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Dynamic model of the interface reactions in an aircraft bomb rack due to an external store

Tim C. Schoppert
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DYNAMIC MODEL OF THE INTERFACE REACTIONS IN AN AIRCRAFT BOMB RACK DUE TO AN EXTERNAL STORE

TIM C. SCHOPPERT

*Dissertation Submitted to the
College of Engineering and Mineral Resources at West Virginia University
in Partial Fulfillment of the Requirements for the Degree of*

DOCTOR OF PHILOSOPHY
IN
ENGINEERING

Department of Mechanical and Aerospace Engineering

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Morgantown, West Virginia
2002

KEYWORDS: BRU-32, Reactions, Lug, Swaybrace

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ABSTRACT

Dynamic Model of the Interface Reactions in an Aircraft Bomb Rack Due to an External Store

Tim C. Schoppert

In today's downsizing environment, more demands than ever are being placed on aircraft flight test programs. To compensate for shrinking budgets and increased requirements, new and more versatile test techniques and data processing systems must be developed. Standard flight test procedures must be reexamined and optimized to maximize the availability of the test asset while processing the collected data more quickly and at a lower cost.

This research demonstrated the ability to predict the reaction loads transmitted to an aircraft bomb rack due to the inertial forces acting on an external store. These load calculations typically require lengthy test programs with strain gage and accelerometer instrumentation placed on the store, suspension equipment and rack interface points. Instrumented testing procedures are cost prohibitive and time consuming, requiring much pre-flight and post-flight work to instrument the test articles and reduce the data, respectively. This research focused on calculating the interface reactions relying only on store mass properties, accelerometer data and geometry, all of which can be collected at minimal effort and cost while allowing real-time data reduction.

Equations were developed from classical theory and the accuracy of the data was proven with actual flight test information. A full-scale static ground test provided data for model improvement and verification. Flight test data for final validation were primarily accumulated during a carrier suitability flight test program conducted at the Naval Air Warfare Center, Patuxent River, Maryland on a fully instrumented F-14, BRU-32/A bomb ejector rack and a GBU-24B/B 2,000-lb. bomb.

In the 300 milliseconds following arrestment, forces and moments up to 15,000 lbs. and 150,000 in-lbs., respectively, were calculated at the store CG. Compared to the measured data, very good agreement was found in form and magnitude for all calculated interface reactions. Critical lug and swaybrace rod reactions averaged less than 7% and 9% absolute error, respectively. Swaybrace rod and vertical lug reactions that were less than 2,000 lbs. and 5,000 lbs., respectively, were considered non-critical and in the noise of the test.

DEDICATION

This project is sincerely and completely dedicated to my patient wife, *Traci*, and my four wonderful children, *Brandon*, *Allison*, *Zachary* and *Tyler*. Their sacrifices minimize my own and each deserves immeasurable credit. My family has undoubtedly worked harder than I have to reach the end of this journey; my research simply could not have been accomplished without their unwavering support. God has blessed me richly through each of them; they are my life.

I LOVE YOU ALL VERY MUCH

ACKNOWLEDGEMENTS

Although this research has been dedicated to my family, there are many people who helped make this project a success. I would like to first thank Dr. Ken Means for his support and unfailing guidance throughout this long and arduous process. As committee chairman, he led me through all aspects of this project, from qualitative discussions as well as technical details. Dr. Means' patience and caring attitude provided the necessary foundation for the completion of this work; every time I thought it just might not be possible, he brought me back on the right path.

I would also like to thank the rest of my advisory committee for their help and service throughout this project: Dr.'s Gary Morris, Victor Mucino, Nithi Sivaneri and Mr. Jack Pratt. Mr. Pratt in particular spent many long hours at the dry-erase board, painstakingly reviewing the myriad of equations while answering my seemingly endless questions. He often spent time at home reading through rough drafts and verifying equation derivations, not just as a member of my advisory committee but as a friend.

I would next like to sincerely thank my colleagues and supervisors at the Naval Air Warfare Center Aircraft Division in Patuxent River, Maryland for their continued understanding of my absences during this lengthy endeavor. Mr. Neal Seigel and Mr. Dave Roberts of the Air Vehicle/Store Compatibility Division faithfully supported my research through their generous allowances of time, resources and flexibility in my workload. Ms. Lori Gallo and Mr. Thomas Carron also provided vital financial support in the final stages of this effort to allow its timely completion.

To my parents, for their love and encouragement – thank you. You always knew I could and would do this.

Finally, none of this would be possible without the innumerable blessings of Jesus Christ; only *through Him* was this project possible and *with Him* was it completed.

“I HAVE FOUGHT A GOOD FIGHT, I HAVE FINISHED MY COURSE, I HAVE KEPT THE FAITH.”

2 Timothy 4:7

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NOMENCLATURE

FROM TEXT:

AR	Aspect Ratio
BRU-32	BRU-32/A Bomb Ejector Rack
CFD	Computational Fluid Dynamics
CG	Center of Gravity
CMS	Component Mode Substitution
FEA	Finite Element Analysis
FEM	Finite Element Model
Fps	Feet per Second
GBU-24	GBU-24B/B
IDL	Interference Distributed Loads
IFM	Influence Function Method
MOI	Moment of Inertia
NAWCAD	Naval Air Warfare Center Aircraft Division
SLW	Spring-Loaded Wedge
Sps	Samples per Second
SRI	Store/Rack Interface
STC	Self-Temperature Compensated
USN	United States Navy
WLS	Wedge-Limiting Spring
α	Angular Acceleration, or Angle of Tilt of swaybrace rod from vertical in y-z plane
v	Linear Velocity
ω	Angular Velocity
a_{cg}	Translational acceleration of store CG
a_m	Measured translational acceleration on store surface
a_{rel}	Relative translational acceleration at store surface with respect to store CG
$F_{x,y,z}$	Forces along x-, y-, and z-axes
L1	Longitudinal (x-axis) distance (positive) from CG to forward lug (in.)
L2	Longitudinal (x-axis) distance (positive) from CG to aft lug (in.)
L5	Vertical (z-axis) distance from CG to lug/hook contact (in.)
$L_{a,x}$	Reaction force on the aft lug along the x-axis (lb.)
$L_{a,y}$	Reaction force on the aft lug along the y-axis (lb.)
$L_{a,z}$; Laz	Reaction force on the aft lug along the z-axis (lb.)
$L_{f,x}$	Reaction force on the forward lug along the x-axis (lb.)
$L_{f,y}$	Reaction force on the forward lug along the y-axis (lb.)
$L_{f,z}$; Lfz	Reaction force on the forward lug along the z-axis (lb.)
$M_{x,y,z}$	Moments along x-, y-, and z-axes
$P_{x,y,z}$	Forces along x-, y-, and z-axes
s1	Longitudinal (x-axis) distance from CG to forward swaybrace (in.)
s2	Longitudinal (x-axis) distance from CG to aft swaybrace (in.)
s3	Lateral (y-axis) distance from CG to port swaybrace (in.)
s4	Lateral (y-axis) distance from CG to starboard swaybrace (in.)
s5	Vertical (z-axis) distance from CG to swaybrace (in.)
$S_{a,l}$; SAP	Overall reaction force on the left aft swaybrace (lb.)
$S_{a,r}$; SAS	Overall reaction force on the right aft swaybrace (lb.)
$S_{f,l}$; SFP	Overall reaction force on the left forward swaybrace (lb.)
$S_{f,r}$; SFS	Overall reaction force on the right forward swaybrace (lb.)

FROM FORTRAN PROGRAM:

a	longitudinal (x-axis) distance (positive) from CG to fwd accelerometer (in.)
alf	angle of tilt of swaybrace from vertical in y-z plane (degrees)
alphax	rotational acceleration of store about x-axis (rad/sec**2)
alphay	rotational acceleration of store about y-axis (rad/sec**2)
alphaz	rotational acceleration of store about z-axis (rad/sec**2)
ax	translational acceleration of store along x-axis (CG) (in/sec**2)
axas	accelerometer reading from aft, stbd accel along x-axis
ay	translational acceleration of store along y-axis (CG) (in/sec**2)
ayas	accelerometer reading from aft, stbd accel along y-axis
ayfs	accelerometer reading from fwd, stbd accel along y-axis
azap	accelerometer reading from aft, port accel along z-axis
azas	accelerometer reading from aft, stbd accel along z-axis
azfs	accelerometer reading from fwd, stbd accel along z-axis
az	translational acceleration of store along z-axis (CG) (in/sec**2)
by	longitudinal (x-axis) distance from CG to aft y-accelerometer (in.)
bz	longitudinal (x-axis) distance from CG to aft z-accelerometer (in.)
ixx	store mass moment of inertia about the x-axis (in-lb-s**2)
iyy	store mass moment of inertia about the y-axis (in-lb-s**2)
izz	store mass moment of inertia about the z-axis (in-lb-s**2)
L1	longitudinal (x-axis) distance (positive) from CG to forward lug (in.)
L2	longitudinal (x-axis) distance (positive) from CG to aft lug (in.)
L5	vertical (z-axis) distance from CG to lug/hook contact (in.)
lmx, lmy, lmx	reaction components on lug due to mx, my, mz (lb.)
lpx, lpy, lpz	reaction components on lug due to px, py, pz (lb.)
mx	store inertial moment around x-axis at the store CG (in-lb.)
my	store inertial moment around y-axis at the store CG (in-lb.)
mz	store inertial moment around z-axis at the store CG (in-lb.)
px	store inertial force along x-axis through store CG (lb.)
py	store inertial force along y-axis through store CG (lb.)
pz	store inertial force along z-axis through store CG (lb.)
ra	radius of reference accelerometer cross-section at accel locations (in.)
ral	overall reaction force on the aft lug (lb.)
ralx	reaction force on the aft lug along the x-axis (lb.)
raly	reaction force on the aft lug along the y-axis (lb.)
ralz	reaction force on the aft lug along the z-axis (lb.)
rfl	overall reaction force on the forward lug (lb.)
rflx	reaction force on the forward lug along the x-axis (lb.)
rfly	reaction force on the forward lug along the y-axis (lb.)
rflz	reaction force on the forward lug along the z-axis (lb.)
rlas	overall reaction force on the left aft swaybrace (lb.)
rlasy	reaction force on the left aft swaybrace along y-axis (lb.)
rlasz	reaction force on the left aft swaybrace along z-axis (lb.)
rlfs	overall reaction force on the left forward swaybrace (lb.)
rlfsy	reaction force on the left forward swaybrace along y-axis (lb.)
rlfsz	reaction force on the left forward swaybrace along z-axis (lb.)
rras	overall reaction force on the right aft swaybrace (lb.)
rrasy	reaction force on the right aft swaybrace along y-axis (lb.)
rrasz	reaction force on the right aft swaybrace along z-axis (lb.)
rrfs	overall reaction force on the right forward swaybrace (lb.)
rrfsy	reaction force on the right forward swaybrace along y-axis (lb.)
rrfsz	reaction force on the right forward swaybrace along z-axis (lb.)
rs	radius of store at swaybrace location (in.)

rxtriax	+/- longitudinal (x-axis) distance from CG to triaxial accelerometer (in.)
rytriax	+/- lateral (y-axis) distance from CG to triaxial accelerometer (in.)
rztriax	+/- vertical (z-axis) distance from CG to triaxial accelerometer (in.)
s1	longitudinal (x-axis) distance from CG to forward swaybrace (in.)
s2	longitudinal (x-axis) distance from CG to aft swaybrace (in.)
s3	lateral (y-axis) distance from CG to port swaybrace (in.)
s4	lateral (y-axis) distance from CG to starboard swaybrace (in.)
s5	vertical (z-axis) distance from CG to swaybrace (in.)
smx, smy, smz	reaction components on swaybrace due to mx, my, mz (lb.)
spx, spy, spz	reaction components on swaybrace due to px, py, pz (lb.)
vx	translation velocity of store CG along x-axis (in/sec)
vy	translation velocity of store CG along y-axis (in/sec)
vz	translation velocity of store CG along z-axis (in/sec)
w	weight of store (lb.)
wx	rotational velocity of store about x-axis (rad/sec)
wy	rotational velocity of store about y-axis (rad/sec)
wz	rotational velocity of store about z-axis (rad/sec)
z	vertical (z-axis) distance from CG to accelerometers (in.)

INTRODUCTION

The demands on aircraft flight-testing have increased exponentially during the past few decades. Significant reductions in the budgets for weapons systems testing require collection of more test information for less money. In addition to the effects of reduced budgets and a downsizing environment, the desire to make rapid production decisions in order to retain program funding is critical. Aircraft flight-testing has traditionally been immune to the unpredictability of the defense budget, but the pressure to streamline must now be considered in all aspects of the flight test process.¹

To compensate for the shrinking budgets and increased requirements, new and more versatile test techniques and data processing systems must be developed. Standard flight test processes must be reexamined to maximize a test asset's availability. Highly complex, expensive aircraft can no longer afford to sit idle while recorded data are being reduced. Each test must be optimized to produce the information which allows the most effective use of the time in the air while contemporaneously processing and analyzing the collected data more quickly and at a lower cost.¹

Concurrently, military aircraft are becoming more versatile in design while the externally carried ordnance has become larger and heavier. With the entrance of the F/A-18E/F as the United States Navy's (USNs) premier fighter *and* attack aircraft of today and the future, the majority of this burden will lie on its wings. Though the aircraft is new, the store/aircraft interface is still approximately the same as originally designed in 1976 by Douglas Aircraft Company. The BRU-32/A Bomb Ejector Rack (BRU-32), figure 1-1, was created for the F/A-18 and, through a number of new features, was better than the state-of-the-art suspension systems of the time.² The BRU-32 is still the primary ejector rack for single, external ordnance on the F/A-18 Hornet and the F-14 Tomcat.

Increases in aircraft capability and ordnance weight and size create larger reaction forces at the BRU-32 interface points. The aerodynamic and inertial loading of the store is transferred to the BRU-32 through six points of contact: two lug/hook connections that

react only tensile forces and four swaybrace rods only able to react in compression. The magnitudes of these reactions have been rising steadily over the past 15 years due to increases in aircraft capability as well as in the mass of the external ordnance. The ability of the BRU-32 to withstand the required forces is often considered marginal based on analytical computations. Accurate predictions of reactions at the store/rack interface (SRI) points are difficult and, in the past, generally shown to be unsuccessful during flight-testing.

FIGURE 1-1: BRU-32/A BOMB EJECTOR RACK

Currently, without accurate and readily available prediction models, all ordnance with the possibility of creating large loads on the BRU-32 must go through a time-consuming and expensive structural flight test program with a fully instrumented store and rack combination. Strain gages, either machined within or mounted on the surface of the lugs, provide data for the lug/hook reactions; instrumented swaybraces have externally mounted gages for data collection. This instrumentation is costly in the application of the gages as well as in the data collection and reduction. Furthermore, the gages are very fragile and, especially during the typical installation and removal procedures of the larger stores, are easily damaged resulting in wasted effort in the delay or repetition of test flights, added costs and can impact critical program milestones.

Although an aircraft's envelope of flight operations is generally quite large and contains a plethora of combinations of airspeed, altitude, etc., many of the largest reactions experienced at the SRI will be found during carrier suitability flight-testing. With maximum sink rates for a typical fighter aircraft over 20 feet per second (fps), the oscillating reactions due to inertial forces immediately after the impact of an arrested landing will almost completely eclipse all aerodynamic load contributions at that same time. Structural flight test programs will typically begin with carrier suitability flight tests.

The objective of this research was to demonstrate the ability to accurately predict the reaction loads at the SRI on an aircraft during an arrested landing. The reaction forces were found without employing specialized SRI instrumentation, thereby avoiding the time and expense associated with installing the delicate strain gages as well as the subsequent calibration of the gages and installation of strain gage signal conditioning. The rack used in this research was a BRU-32, which is the standard parent rack for external stores on USN tactical aircraft. Preloads accumulated at the interface during ordnance loading and handling were also examined and considered.

The approach for this research was to create BRU-32 reaction equations based on inertial loads and preloads only. This was accomplished by theoretically modeling the inertial reactions and comparing the expected results with data from an instrumented ground test as well as an actual flight test. For the ground test, a 2,000-lb. store was hung from an instrumented SRI in a laboratory and subjected to eight predetermined load conditions comprised of single and multiple forces and moments. These data were collected as truth data and used to improve the theoretical models by reducing the number of assumptions originally necessary due to the static indeterminacy of the reactions and parallel nature of the loads.

The newly developed equations were then compared with actual flight test data from carrier suitability flight-testing where, immediately after an arrestment, aerodynamic loads were shown to be negligible. Any differences between the actual data and the predictions were then resolved at a finer resolution by accounting for the small variations

in individual store geometry and loading conditions. Once reasonable inertial predictions were made, aerodynamic load components experienced during normal flight were then considered for further research; lack of available funding prevented acquisition of additional flight test data. The predictions for in-flight SRI reactions due to aerodynamic loads can be found through a similar process as the inertial loads, with modeling and comparisons to actual flight data. The current inertial predictions for arrested landings are also adequate for inertial-only predictions during normal flight.

The flight test data were collected during a test program conducted at the Naval Air Warfare Center Aircraft Division (NAWCAD), Patuxent River, MD with an F-14 aircraft and a fully instrumented BRU-32. The final results provided an accurate prediction model for calculating the loads at the BRU-32 SRI given the store mass properties, store accelerometer data, flight parameters and conditions during the flight test. This research has also discussed implementing the prediction routines as a real-time data processor that will provide the interface loads during flight-testing while receiving the accelerometer data via telemetry from the aircraft as another avenue of future research. Further work may address SRI reactions due to lighter stores, additional aircraft types, or various bomb ejector racks carrying single or multiple stores.

When used prior to flight-testing, this program functions as a loads prediction tool. This method saves money and time through the reduction in the number of flights necessary during a test program by calculating the interface reactions at a specified set of flight conditions *a priori* instead of requiring additional, dedicated flight-testing and the required additional instrumentation and data reduction.

These objectives have been completed in conjunction and cooperation with the USN. Their interest in the successful completion of this project has allowed the use of previous flight test data, as well as funding for the additional ground testing and data reduction required for model development and verification.

OBJECTIVES

The successful completion of this research provides numerous benefits for most structural flight test programs. Time and cost savings are primarily realized through fewer required test flights due to a confident prediction of the results at the necessary test points and hence fewer required flights. Similar savings are obtained by minimizing repeated and cancelled test flights due to instrumentation failures in strain gages, specialized racks, etc. Cost reductions are further achieved through minimizing pre-flight instrumentation (including store and rack) and post-flight data reduction.

2.1 Research Objectives

The objective of this work was to develop and employ a numerical model to calculate the interface reactions in a bomb ejector rack during an arrested landing due to a single, externally carried ordnance using only mass properties, store geometry and store accelerometer data. This objective was accomplished through the following tasks:

1. A literature review was conducted to determine the existing SRI load prediction schemes and modeling techniques, as well as the structural and load characteristics involved in modeling an under-carriage interface on an aircraft in flight.
2. Equations were analytically developed to calculate the interface reactions at the SRI points due to store inertial forces. Reactions due to multiple loads were developed independently and combined using the principle of superposition.
3. Reaction equations were corrected to account for preload in the SRI.
4. A static ground test was conducted in a controlled laboratory with instrumented equipment to assist in accurate model development. Test data were used to verify and correct the inertial reaction equations. Actual SRI equipment, instrumentation and store were incorporated for this test.

5. Equations were analytically developed to calculate the dynamic forces and moments at the store CG during flight, primarily via store accelerations, using Newton's second law and Euler's equations.
6. Actual flight test data was collected using an instrumented SRI on a USN F-14 during carrier suitability flight-testing carrying a GBU-24. Modeled results were compared with experimental data to demonstrate the model's ability to accurately predict the store CG loads and the interface reactions without the need of strain gages or load cells at the SRI.
7. Processes were considered for further research to develop the equations to calculate the interface reactions in the SRI due to the combined aerodynamic and inertial forces during up-and-away flight maneuvers. Additional research could convert the model to a real-time data processor providing all interface reactions instantaneously during flight-testing through telemetry reception of aircraft data. A variety of rack and store hardware may also be pursued.

2.2 Result Objectives

The final objectives of the research results are summarized in the following flowchart:

REVIEW OF RELEVANT LITERATURE

3.1 Store Carriage Loads and Measurements

Data collection during flight-testing can be accomplished in many different ways; finding SRI reactions are no exception although the difficulties become more prevalent. Loads collection at the SRI points have generally been obtained by mounting strain gages on the lugs (figure 3-1) and using specially machined swaybraces as shown in figure 3-2.³

FIGURE 3-1: STANDARD LUG WITH EXTERNAL INSTRUMENTATION

The strain gages on the top of the lugs are in a very awkward and fragile position. If the store is raised too high during normal uploading or downloading, the circuits will be broken and the test delayed. The swaybrace rods must be specifically designed and machined to provide an adequate location for strain gage placement. Both of these difficulties can provide numerous problems to a structures flight test engineer and can significantly impact program schedules.

FIGURE 3-2: STANDARD BRU-32 AND INSTRUMENTED SWAYBRACE

In an attempt to solve the more serious problem of gage placement on the lugs, special lugs were designed by drilling holes in the bottom of each lug and mounting the gages on the interior of the lug rather than the exterior. The drilled lugs were manufactured and instrumented by StrainSert, Inc. and are shown in figure 3-3; a wire umbilical used to transmit the strain data to the aircraft computer is also shown.⁴

FIGURE 3-3: LUG WITH INTERNAL INSTRUMENTATION

The improved, instrumented lugs will help enhance loads flight-testing and reduce the delays associated with broken circuits. However, acquiring and maintaining instrumented lugs and swaybrace rods in a flight test program is a very difficult and expensive requirement.

A number of individual flight test programs have been conducted using instrumented interface points to collect the primary loads data. In the advanced development program of the Tornado combat aircraft, a multi-weapon carriage system has been opted to carry a variety of external stores.⁵ One task of flight-testing was dedicated to the loads measurements of external store configurations during carriage trials, as well as the measurement of reaction loads at the attachment points during jettison trials. In particular, loads data were collected from large, underfuselage stores attached to multiple rack locations as opposed to the traditionally sized weapon carried on an individual rack.

All load-carrying structural components in the Tornado test, including the swaybrace rods and lugs, were instrumented to determine the reactions at the store attachment points. All gages were mounted on the exterior of the interface hardware. Extensive aircraft downtime was required for gage placement and instrumentation. Positive longitudinal loads were found to be reacted primarily by the aft lug while the forward lug only carried a portion of the longitudinal load. Engineers felt the reaction of the forward lug was principally due to the effects of friction. Preflight strain gage calibrations were conducted to determine whether the equations were correctly modeling the statically

indeterminate reactions of a pylon suspension system. After analysis, it was determined that there were small load errors attributed to friction in the suspension system. However, it was assumed that the vibrational environment during flight would provide sufficient dynamic responses to settle any frictional preloads. Major evaluations were also done to accurately solve the lug load equations including nonlinearities and cross-influences for the large underfuselage stores on the Tornado. It was concluded, though, that most load parameters were completely linear for the lug/hook reactions.⁵

The inertial loads for the Tornado flight-testing were computed by the Euler equations. The loads were due to aircraft motion and were calculated at the store using three linear accelerations, three angular velocities and three angular accelerations. The data were collected at the aircraft center of gravity (CG) as opposed to taking measurements at the store CG requiring separate acceleration measurements at the CG of every store during a flight test program. This process was found acceptable for dynamic and quasi-static load cases. It was also determined, by comparing flights conducted with pylon fittings only and monitoring deflection, that lug forces from pylon deflection due to fuselage bending may be neglected. Additionally, pylons were determined not to be affected by aerodynamic forces except in the lateral direction.⁵

The Tornado program concluded that a roller coaster maneuver at 0.9 Mach and an altitude of 5,000 feet provided good aerodynamic loads data. A careful performance of maneuvers with minimum speed variation is essential to accurately collect test data. Calculated results showed lug forces were actually lower than predicted in the forward lug and higher than predicted in the aft lug as the highest aerodynamic load was effectively at the bow of the store.⁵

The USN conducted loads testing in September 1996 at Patuxent River, Maryland, with an F-14 aircraft, a BRU-32 and a GBU-24B/B 2,000-lb. class weapon (GBU-24).⁶ These tests incorporated both lug instrumentation configurations shown in figures 3-1 and 3-3. The flight test program went more smoothly with the new lug design (figure 3-3) when compared to tests with gages mounted on the lug exterior surfaces; fewer broken circuits,

wires, etc., required less delay, expense and data loss. The data from that flight test program was used as the basis for this research.

3.2 Advanced Prediction Models

Computational methods provide an improved ability to create detailed analysis data for use by many disciplines involved in the evaluation of a proposed design. As technology improves, couplings between disciplines will be accounted for and computational methods could be used as a design tool to provide the sensitivity of overall performance characteristics with design changes proposed by the individual disciplines. Therefore, numerical optimization methods used in the design process could lead to improved efficiency and performance of advanced aircraft.⁷ Previous work has demonstrated a variety of beneficial uses of this type of integration method, including incorporating the effects of static aeroelasticity early in the design process,^{8,9} integration with simplified wing geometries,¹⁰ and linear aerodynamics.¹¹

Present configuration trends in the design of high-speed aircraft have created a number of fundamental structural problems in aeroelasticity and structural dynamics. The primary difficulty is to predict, for a given elastic structure, a comprehensive set of load-deflection relationships which can serve as a structural basis for dynamic load calculations, theoretical vibration and flutter analysis, structural deflection, and aeroelastic effects on stability and control.¹² It seems likely that the load-deflection relationships of a practical structure must be expressed in the form of either deflection or stiffness influence coefficients. However, elaborate models are expensive, time consuming and restrictive to changes; therefore, wherever possible, analytical methods are generally preferred.¹²

There are a variety of approaches and methods used in structural analyses. Elementary theories of flexure and torsion are common, yet are limited to lower order modes of elongated structures; therefore, effects such as shear lag and torsion-bending require separate consideration. Wide Beam Theory is applicable to multi-spar wide beams with generally rigid ribs. Although torsion-bending is included in wide beam theory and it is

applicable to static aeroelastic problems (i.e. airframe flexibility in steady airloads, etc.), it is very limited for any vibration or flutter use.¹³

The method of redundant forces and structural deflections can be solved through energy methods, matrix algebra or influence coefficients. These methods are very general and become extremely complicated when many redundancies are present.^{14,15} Plate methods are also very useful in deflection analyses where flexural and torsional rigidities of the shell make a significant contribution to the overall stiffness of a hollow section, or in the deflection of solid plates of variable thickness.^{16,17}

Another approach for solving highly redundant structures is with a direct stiffness calculation. A stiffness matrix is computed for the entire structure as a summation of stiffness matrices; the matrix of deflection influence coefficients is then obtained by inversion. Direct stiffness analysis can be approached in two different ways: in one case, the forces acting in the members of the structure are considered unknown, while the second approach considers the displacements of the joints in the structure as unknown quantities.^{12,18,19}

Recent advances in computational fluid dynamics (CFD) have enabled the analytical calculation of aerodynamic and carriage loads for stores mounted on complex aircraft.^{7,20-24} Specifically, Rosen developed a prediction methodology for external store carriage characteristics at transonic speeds. Finite difference solutions were achieved through an embedded grid arrangement and automatic grid generation. Rosen uses a nonlinear relation scheme of small distribution equations to enhance stability and accuracy. Pressure, load distribution and force/moment correlations showed good agreement with experimental data over several test cases.²⁵

A number of computational efforts have also been directed at predicting transonic flows around wing configurations. These approaches include small disturbance potential,^{26,27} full potential,²⁸ Euler,^{29,30} and Navier-Stokes³¹ equations. Most predictions have been at low transonic Mach numbers while little work has been accomplished to computationally predict near sonic flows on body-of-revolution missile shapes. One approach using grid

generation was found that accurately accounted for the pressure distribution on a body of revolution at 0.95 Mach; the latest CFD results have even demonstrated excellent agreement with test data for the F-15 up to 0.98 Mach.^{32, 33}

In the preliminary design environment, the necessity of generating and validating an Euler grid to fit the aircraft and store arrangements may not be feasible. Therefore, alternative approaches which provide a much quicker solution must be considered.³³ Computational tools which require only a surface description of the aircraft geometry are much easier to use. Although these are presently only capable of solving the full potential equations^{21,22} or their linearized equivalents,²³ that may be all that is necessary since the wing lower surface pylon location may not be subjected to the nonlinear, supercritical effects usually associated with the wing upper surfaces.³³

Aerodynamic concerns on the wing/store/rack combinations are important, but their effects on the SRI have, more recently, been of greater interest. With 2,000-lb. class weapons becoming typical and stores in design exceeding two tons, accurate measurement and prediction of the reactions in the lugs and swaybrace rods are a necessity. Although attempts have been made to predict these loads, most are either very general leading to quite conservative solutions or very complex requiring significant post-flight data analysis. With aircraft and store limits on the edge of the envelope and beyond, extremely conservative estimates are restricting operations, impairing capabilities and requiring more actual flight-testing to verify and validate the loads environment and its impact on the SRI at the expense of a great deal of time and money.

The most accurate load calculation schemes, unfortunately, are too complex to use quickly, much less in real-time, combining CFD and finite element analysis (FEA) methods with large computer routines and lengthy iterations. A balance must be struck between simplicity to allow real-time calculations and accuracy to provide confidence.

One of the more accurate methods for predicting store carriage loads is the Influence Function Method (IFM) which uses the angularity distribution along the store to predict store loads at a horizontal crossing.³⁴ The advantage of the IFM technique is that

estimates of the store carriage loads can be made more quickly than most schemes by knowing the aircraft flowfield near the carriage position.

The IFM technique employs a 3-step process, beginning with the calibration of the IFM equations:

$$C_N - C_{NO} = \sum_{i=1,N} A_i \alpha_i \quad (1)$$

$$C_M - C_{MO} = \sum_{i=1,M} B_i \alpha_i \quad (2)$$

Equations (1) and (2) represent the relationships between the forces and moments, respectively, acting on a store as a function of the local flow angle. The equations are nonlinear due to the angularities α_i as well as the influence coefficient terms (A_i and B_i).³³

Calibrations determine the influence coefficients for each store so that the responses to the aerodynamic flowfields can be estimated. The values C_M , C_N and α_i along an axial line are found either from wind tunnel testing, an analytical CFD approach³⁵ or the Interference Distributed Loads (IDL) code.³⁶ The IDL/IFM code has been shown to have very good results for symmetric stores at a wide range of Mach numbers, as well as some non-symmetric configurations.^{33,37} Equations (1) and (2) may be solved simultaneously for the unknown α_i distributions along an axial line once the influence coefficients have been determined. Since there are fewer unknowns than equations, the angularities can be solved forward and aft of the test data location.

The third step in IFM is combining the α_i flowfield with the influence coefficients of other stores to determine their forces and moments for the same conditions. The IFM permits an estimate of store carriage loads to be made prior to wind tunnel testing and the effects of configuration modifications can be evaluated very quickly. The IFM method, however, cannot be expected to yield *quantitatively* correct results since it ignores the effects of mutual interference.³³ Some test data suggests that the IFM might not even provide useful qualitative information in the carriage position, yielding qualitative accuracy in immediate post-release positions only.³⁸

Component Mode Substitution (CMS), another computational method, reduces a complete structural system into a group of subsystems. This method is useful in reducing the number of generalized coordinates required in a vibrational analysis. The modes of vibration are determined separately and then mathematically combined to create the modes of the complete system. The advantage of CMS is the ability to select fewer generalized coordinates and still retain satisfactory results.³⁹ The range of applications of this method have included statically determinate beam models^{40,41} and complex redundant models.⁴²⁻⁴⁷

A previous flight test program conducted in 1992 by the USN measured the interface reactions and store CG loads for a GBU-24 guided bomb unit attached to a BRU-32 bomb rack.⁴⁸ The mass properties of the GBU-24 used in those tests as well as this research are shown in table 3-1:

TABLE 3-1: GBU-24B/B MASS PROPERTIES

<i>Parameter</i>	<i>Value</i>
Weight	2,370 lb.
I_{xx}	22.6 Slug-Ft ²
I_{yy}	594.2 Slug-Ft ²
I_{zz}	593.1 Slug-Ft ²

The equations of motion must be inspected to identify the required parameters to solve for the inertial loads. The equations include the store angular velocities, angular accelerations and translational accelerations along each axis, as well as store mass properties and geometry. At least 6 in-flight store accelerations are required to be collected to compute the inertial forces (P_x , P_y , P_z) and moments (M_x , M_y , M_z) generated at the store CG.⁴⁹ The contribution of angular velocity and acceleration must also be determined for each maneuver. Reference 50 indicates that the load factors and angular accelerations shall be represented by a half sine wave amplitude profile as shown in figure 3-4. Figure 3-4 extends this profile to include angular velocity.⁵¹

FIGURE 3-4: HALF-SINE WAVE AMPLITUDE PROFILES

Additionally, a variable contact, finite element model (FEM) was used to calculate the inertial loads on the GBU-24. The ABAQUS FEA program was incorporated to perform the calculations and assumed the following two swaybrace and hook variable contact assumptions:

- A. Swaybrace pads react in compression only, along the length of the rod
- B. Hooks react in tension only

The FEM of the GBU-24 and the BRU-32 used in reference 48 is a very simplified model of one-dimensional beam elements and is shown in figure 3-5. The model is flexible and will produce lower, more conservative reactions than an assumed rigid model.

It was found that the flexibility of the guidance control unit and wing assembly of the GBU-24 have negligible effect on the internal loads and therefore it is not necessary to represent flexibility in these components; lumped mass approximations will provide correct and accurate results. These models also allow variable swaybrace preloads from 0 to 2,500 lbs.; hook preloads are calculated from swaybrace preloads.⁴⁸

FIGURE 3-5: ONE-DIMENSIONAL FEM OF GBU-24B/B

3.3 Aerodynamic Concerns of Externally-Carried Objects

The estimation of aerodynamic forces on externally carried ordnance has long been a difficult task. Additionally, with the increase in frequency and variety in the use of external ordnance, wind tunnel application for store load measurement has significantly grown.⁵² Most prediction methods incorporate complex and time-consuming computational methods to solve for the flowfield forces, while other loads estimation schemes assume the user has knowledge of all the aerodynamic loads *a priori*. In general and for the more useable approaches, the aerodynamic loading is determined assuming the flowfield to be in a quasi-static state at the instant the inertial loading is applied.⁵⁰ A basic error, however, in the simpler schemes of external flowfield and store loads estimation is in the perturbation velocity calculations for tapered wings. Flow environment in the fuselage region is also typically quite different from that in the wing region. Even adjacent store carriage stations can have considerable interactive effects which are difficult to predict.⁵³

The equations of motion for aerodynamic loads consist of aircraft true velocity, angle of attack and angle of sideslip as well as other flight and physical parameters. The general procedures identified in reference 50 have been shown to be comprehensive and flexible, specifically with regard to flight load envelopes. Some judgment should be applied when an extremely heavy or lightweight store is carried where a modified envelope might be

more appropriate. However, the midwing pylon and wingtip envelopes may be defined too restrictively for normal loads and potentially not restrictive enough for lateral loads.^{49,51}

Due to the unknown flow phenomenon attributed to differences in certain aerodynamic loads beneath fighter aircraft, loads flight-testing has been conducted by General Dynamics on an F-16 Falcon. During data reduction, the loads predicted for the external stores varied significantly from the measured data. The majority of the error was traced to the non-dimensional aerodynamic coefficients from wind tunnel testing not accurately representing actual aerodynamic loads; therefore, care must be taken for actual derivation and implementation of the aerodynamic coefficients.⁵⁴ Many assumptions can also be made when trying to estimate the aerodynamic coefficients on a store and pylon combination. Testing has shown that scaled wind tunnel testing, which provided the original although incorrect aerodynamic coefficients in reference 54, may not always reflect the true, full-scale aerodynamic loads. Variances in Reynolds number, flexibility, wall and interference effects as well as unknown problems can be significant between a modeled and actual external store and can cause large differences in predicting external store carriage loads.⁵⁴ New wind tunnel approaches could be considered to reduce these errors, including high-pressure testing, higher levels of dimensional analysis, different temperatures or gas compositions, better structure modeling, etc.

Although not for real-time use due to the lengthy and time-consuming calculations involved, a number of advanced aerodynamic loads prediction methods have been developed. Slender Body Theory predicts the normal load on an asymmetric body tapered to a point at both ends is zero. This is the combined effect of lift from the nose canceled out by an equal and opposite lift from the tail. The point of action of both of these components is at the centroid of the area under the curve of dA/dx taken along each tapering portion.⁴⁹ Following this approach, the force coefficients of the nose, tail and cross flow are, respectively, as follows:

$$C_{N,nose} = 2\alpha \quad (\alpha \text{ in radians}) \quad (3)$$

$$C_{N,tail} = -2\alpha(1 - 1.4\sqrt{\sin\alpha}) \quad (\alpha \text{ in radians}) \quad (4)$$

$$C_{N,cf} = 0.7(AR)\sin^2\alpha \quad (\alpha \text{ in radians}) \quad (5)$$

Equation (4) predicts the tail force will be greatly reduced, when compared to the nose force, due to the thickening boundary layers and separations resulting in pressure loss. The aspect ratio (AR) in equation (5) is equal to the quotient l/d for a slender body, and 0.7 is the approximate value for the drag coefficient of a cylindrical body midway between the laminar and turbulent coefficients. $C_{N,cf}$ is applied at the centroid of the plan area. The method in reference 49 yields reasonable results for normal and pitching moments on finned stores in a uniform airstream, although the solutions may only reasonably be assumed accurate up to transonic flow (approximately 0.8 Mach).

An interesting as well as complicated approach to calculating the aerodynamic loads was posed by Teposu (reference 55). His paper determines the aerodynamic and inertial load components in the *OXYZ* reference system (fixed to the aircraft) for longitudinal maneuvers with large variations of incidence angle, altitude, speed and arbitrary initial conditions. Tepuso assumes the aircraft to be a rigid body neglecting the aeroelastic deformations that the aerodynamic and inertial loads transfer to the structure; however, the aeroelastic derivatives are included in his analysis of the force equations. Also, by studying Mach number influences, the effects of variations in dynamic pressure and aerodynamic derivatives are allowed. By starting with the airplane's equations of motion, the equations for the explicit forms of F_x and F_z (forces) and M_y (moment) are derived, retaining all nonlinear terms which are important during maneuvers with large altitude and speed variations.⁵⁵

In this current study, a fine line was drawn in the calculation of the aerodynamic loads. Firstly, flutter was not considered in this research. It has been shown that flutter effects are negligible in a 2,000-lb. class store and rack combination. Accuracy of flutter predictions are also suspect due to their sensitivity to structural nonlinearities associated with store-pylon-wing attachments.⁵⁶ Additionally, all stores are designed such that divergence and flutter are not experienced in the store, its components or at the SRI at

speeds up to 1.15 times the highest limit speed of the store or the aircraft/store combination. This design requirement applies to all aircraft on which the store is carried and for all design ranges of altitudes, maneuvers, loading conditions and aerodynamic heating effects. Therefore, an increase of 15% in the equivalent airspeed at all points on the captive flight limit speed envelope at constant Mach number and constant altitude should not result in flutter or aerodynamic divergence. The total damping coefficient for all altitudes and airspeeds was found to be at least 3% for all modes of vibration.⁵³ Secondly, the more intensive CFD and FEA approaches have also been avoided in this study as the goal of this present research was eventual real-time operation.

In the case of multiple stores carriage, particularly adjacent stores, the interference effects in the flowfield between stores and the aircraft can exceed the summation of individual loads and further degrade aircraft performance.⁵⁷ Therefore, all testing for this research assumes a single, externally carried store per wing or fuselage.

3.4 A Simplified Prediction Model – Military Specification 8591

Military specification 8591H, General Design Criteria for Airborne Stores, Suspension Equipment and Aircraft-Store Interface (Carriage Phase) contains the currently accepted procedures for estimating the reaction forces and interface loads at the SRI. This procedure is simple, although it has many missing components as well as a number of mathematical and conceptual errors. The method considers the entire structure as a rigid body and all assumptions are made conservatively. The general equations are based only on the combination of external loads that subsequently result in the maximum forces generated at each swaybrace and hook as shown in 3-2.⁵⁰

The combinations in 3-2 were possible due to the fact that hooks can react only tensile loads and swaybraces can only react compressive loads. Since all equations in reference 50 are derived from the worst case loadings, all results are conservative while many are extremely moderate. Other errors in reference 50 include the absence of the effects of aerodynamic loads or the effects of preload at the interface points (a non-trivial value at extreme load conditions), as well as a few incorrectly written equations.

**TABLE 3-2: DIRECTION OF EXTERNAL LOADS AND MOMENTS
FOR MAXIMUM REACTION FORCES AT THE SWAYBRACES AND LUGS**

Load Case	Swaybrace Rod				Hook/Lug	
	Forward		Aft			
	Port	Stbd.	Port	Stbd.	Forward	Aft
Px	—	—	+	+	+	—
Py	—	+	—	+	±	±
Pz	+	+	+	+	—	—
Mx	—	+	—	+	±	±
My	+	+	—	—	—	+
Mz	+	—	—	+	±	±

The following assumptions were used in MIL-STD-8591H:

- A. All structures were considered rigid.
- B. Upper store surfaces are symmetric about the x - z plane.
- C. The direction of the swaybrace pad resultant force is perpendicular to the store surface (figure 3-6):

$$S_y = S \cdot \sin(\epsilon) \tag{6}$$

$$S_z = S \cdot \cos(\epsilon)$$

- D. The yaw moment (M_z) is reacted laterally by the swaybrace rods while inducing a vertical reaction in the hooks. Since each hook is designed to withstand the entire maximum longitudinal force (P_x) possible, the lateral hook reaction due to the fraction of the reaction of M_z is neglected.⁵⁰

3.5 BRU-32/A Bomb Ejector Rack

In the 1970s, the USN sent out a design specification for a bomb ejector rack for the F/A-18 aircraft. The specifications included several new features that were non-existent in the current state of the art suspension systems. Douglas Aircraft Company began the design and development of the BRU-32 in 1976 to meet those demands.²

FIGURE 3-6: DIRECTION OF SWAYBRACE RESULTANT REACTION

The BRU-32 Ejector Rack, figure 3-7, combines two sets of hooks, one at 14-inch spacing and one at 30-inch spacing, designed for carriage of stores with suspension lugs.⁵⁰ Stores are automatically swaybraced at the time the hooks become latched and secondary adjustments are not required. Off-loading of stores by normal ejection or by manual release will automatically cock the swaybrace system for the next loading. The automatic swaybracing feature accommodates 10-inch to 28-inch diameter stores.² The rack assembly weighs approximately 76-lbs. and has a pitching moment of 1.52 slugs/ft^2 .⁵⁸

Store release and ejection are accomplished through two electrically initiated CCU-45B explosive cartridges. The cartridges are installed in a centrally located breech. Each cartridge has independent ignition wiring, although firing of either cartridge will sympathetically fire the other. A release piston driven by the cartridge gases provides actuation to open the hook latching mechanism and is configured to restrict the flow of gas to the ejection pistons until after the hook latches are opened.² This provides maximum pressure to unlatch the hooks before any force is used to eject the store. End of stroke velocities and reaction forces are shown in table 3-3.⁵⁸ For example, static ejection acceleration for the 2,370-lb. GBU-24 from the BRU-32 is approximately 11 Gs.⁴⁸

All dimensions in inches.

* Connecting rod pins identified

FIGURE 3-7: BRU-32/A EXTERIOR AND INTERIOR VIEWS

TABLE 3-3: END OF STROKE EJECTION VELOCITIES

STANDARD PISTONS WITH 0.219" ORIFICES AND CCU-45/B CARTRIDGES

Store Weight (lbs.)	End of Stroke Velocity (fps)	Peak Reaction (lbs.)
500	23.40	16,957
1,000	16.71	17,085
1,500	14.21	17,687
2,000	12.83	18,036

One design requirement set forth by the USN was to provide a hook latching system without the use of a toggle lock. The BRU-32 was designed with a device known as the La Roe mechanism (figure 3-8); Douglas developed this device in 1968. Instead of the typical 90° cam rotation needed to unlock the hooks, the La Roe mechanism incorporates an eccentricity that unlocks the hooks at approximately 37 degrees of cam rotation.²

FIGURE 3-8: LA ROE MECHANISM IN THE BRU-32

To achieve automatic swaybracing, a swaybrace crutch with swivel pads is incorporated onto the head of a cylinder. The cylinder is fitted into a structural housing on each end of the ejector unit so that the crutch cylinder is vertically moveable as shown in figure 3-9.²

FIGURE 3-9: SWAYBRACING SYSTEM IN THE BRU-32

Near the top of the swaybrace structural cylinder, two surfaces are machined with an angle small enough to be considered a self-locking taper. Slots are provided in the structural end housing to allow a wedge on each side of the cylinder to move along the top surface. The wedges contain angles that match those on the cylinder. As the store becomes fully hoisted, the lug hooks latch and a pair of spring-loaded wedges (SLWs) are released to seek the upper surface of the crutch cylinder thereby locking the cylinder downward and restraining the store. In this cinched position, side loading on the crutch assembly is translated through the bearing surfaces of the interface and upward loads are

transferred into the end housing through compression of the wedge (figure 3-10) resulting in swaybracing of the store.²

FIGURE 3-10: SWAYBRACE LOAD PATH

Through handling and vibration, the SLW may tighten into an extremely loaded position resulting in a significant increase in swaybrace preload. Figure 3-11 shows the preload obtained with the SLW during a random vibration of a 50-lb. store at 20 to 2,000 hertz. Preload is produced when the external loads are sufficient to allow the BRU-32 self-swaying device to extend and the SLWs to engage. The swaybrace mechanism does not retract and as the external loads are released, residual loads are produced by the hook and swaybrace interaction. The cinching capability becomes quite significant and, although the rack is capable of releasing the store under these circumstances, a high preload against the weapon is undesirable.²

A wedge-limiting device was developed to control the overtightening characteristics of the SLW based on the theory that the wedge is momentarily relieved of load during vibration. A wedge-limiting spring (WLS) was incorporated into the upper surface in order to maintain friction against the wedge-bearing surfaces. Therefore, as vibration causes the wedges to be pulled tighter, the WLS compresses until its friction component

can no longer be exceeded by the SLW and the wedges stop moving relative to each other. As the wedge feels a cyclic load, the fully compressed WLS transfers the swaybrace load into the end housing. Further vibration momentarily relieves the wedge load allowing the WLS to move while maintaining friction against the bearing surface. Since the friction is greater than the SLW load, the wedge cannot tighten further. Figure 3-12 shows the reduced preload in the swaybrace assembly due to the WLS.²

FIGURE 3-11: WEDGE PRELOAD WITHOUT WEDGE LIMITING DEVICE

FIGURE 3-12: SWAYBRACE PRELOAD WITH WEDGE LIMITING DEVICE

Even with preload, it's possible that under certain combinations of high vertical and lateral loading, the swaybraces will cease to be in contact with the store thereby reducing the preload effect to zero. Magnifications of the inertia loads arise due to structural

flexibility of individual aircraft, pylons and suspension equipment. The equations developed to account for swaybrace preload, therefore, will be dependent on the hardware involved. Depending on the load case, the swaybrace assembly will partially or totally react to store yaw and pitching moments in addition to vertical and lateral store loads.⁵⁰

There are a few types of stores that, although having radii between 10- and 28-inches, still cannot be carried on a BRU-32. This is generally due to a lack of design conformance between a store and the tolerances described in reference 50; examples are the B-57 nuclear store, the LAU-68 B/A, the LAU-69 A/A and the Walleye II. Interference problems with these stores include oversized lugs, incorrect lug heights above the store and hardened buildup around the base of the lugs. Tolerances in the lugs must be carefully monitored during design and installation to account for swaybrace travel. If the lug is designed at a height of only 0.092-inches above its allowable height, the maximum diameter of acceptable store on the BRU-32 is only 21-inches instead of 28-inches, even though the hardware is still within design specifications.² As the lug is set higher, the effective and hence allowable diameter of the store, with respect to the rack, becomes smaller. Figure 3-13 shows this relationship:

FIGURE 3-13: APPARENT DIAMETER OF 28" DIAMETER STORES

The contact surfaces between the hook and the lug must be evaluated with concern given to variable lug height to allow the greatest swaybrace range with the shortest swaybrace travel. Similar to the lug height described above, the effects of swaybrace interface tolerances are significant even when they are within the specified tolerances defined in reference 50. Typically acceptable stores may fall out of the swaybracing capabilities of the rack when non-standard conditions are imposed onto the already critical conditions. With specified tolerancing and true control of the interface surface, the capability of the automatic swaybracing can be increased while eliminating some of the current interface difficulties.²

Store CGs are designed to be centered between the suspension lugs within ± 3 inches. Reinforced swaybrace pad areas on the store are designed to be within a minimum of 5.0 inches circumferentially on both sides of the lug centerline (figure 3-14).⁵⁰

FIGURE 3-14: LOCATION OF STORE CASE COMPONENTS (30-INCH)

[illegible]

30

The largest store allowed for carriage on an external rack is a 2,000-lb. class weapon, requiring 2 lugs with 30-inch spacing. This will represent a worst load case with respect to the SRI reaction and will therefore be the only weight class of rack-carried stores to be considered in this research. Other typical store weight classes include 250-, 500- and 1,000-lb. stores.

ANALYTICAL MODELING

4.1 Approach

This dissertation addresses research related to calculating the reactions at SRI points without the need for strain gages. The reaction equations were derived via a classical analysis and the results are primarily a function of directly measured or computed accelerometer data. Once formulated, a FORTRAN program was created to calculate the SRI reactions based on geometry, inertial forces, known preloads, etc. The program determined the translational and rotational accelerations at the store CG using data from accelerometers placed around the surface of the store. The inertial loads at the store CG (three forces and three moments) were then found from the accelerations using Newton's Laws, kinetics of rigid bodies in three dimensions and Euler's Equations of Motion as an extension of d'Alembert's Principle. The store CG loads were distributed to the six SRI interface points and the reactions calculated. Of course, the most accurate analytical tool for determining store carriage loads for all conditions is a solution to the full Navier-Stokes equations.²⁴ Solutions to the complete Euler equations have been solved for various complex shapes by generating a grid to precisely fit the configuration and extending the grid out into the flowfield.^{20,33} Both processes, however, are too difficult and time consuming for most configurations. A simpler method is required to predict real-time SRI reactions during a structural flight-test program.

The store and rack assembly forms a slightly flexible (in the rack), statically indeterminate structure. Rigidities in future designs were not known and the load paths could not be analytically or experimentally determined for an exact solution; therefore, a rigid body assumption was incorporated for all components. It is also important to note that the six interface points at the SRI consist of four swaybrace rods and two lug/hook combinations. The swaybrace rods only take compressive loads in the local y - z (lateral and vertical) plane; the hooks can react along the local x - and y -axes (longitudinal and lateral) and can exert a tensile force along the z -axis.

To test the structural integrity of a store and rack combination, the first consideration is how to interpret the data during testing. Failure can be defined many ways, from almost imperceptible yielding to complete separation.^{64,65} The definition of a failure set forth by the USN with regard to store carriage is constituted by unintended separation of the store from the suspension equipment, separation of any part of the store or suspension equipment at ultimate or lower loads, or material fracture or yielding of the store or suspension equipment. Limit loads are defined as the maximum expected loads in normal operation of the store and suspension equipment including swaybrace and lug loads during carriage. Yield and ultimate loads are defined as 115% and 150% of the limit loads, respectively.⁵⁰

4.2 Accelerations

Although the store and rack were considered rigid bodies, a dynamic analysis was used to create the equations required for inertial load calculations. A number of procedures for complete dynamic analyses have been considered in academia for dynamic loading, including dividing a system into substructures and performing a discrete element idealization on each substructure to obtain the necessary stiffness matrices and mass matrices.⁴⁵ A variety of procedures have also been utilized to obtain the substructure mass matrices, including lumped mass formulations in which the displacement method, a process considering the geometric compatibility along each substructure boundary, is then employed in the final substructure coupling.^{42,66} Substructure methods relying on the displacement method have been employed in analysis of both static^{45,67} and dynamic^{43,44} behavior of structures. Dynamic behavior generally requires a Rayleigh-Ritz procedure to reduce the order of system matrices. Gladwell introduced the Branch-Modes technique with the advantage of a diagonal system stiffness matrix that is easily formed along with the normal-mode analysis of the substructure.⁴² Each of these methods is time-intensive and requires many input parameters.

To more quickly solve for the store's translational and rotational accelerations, equations and methods were developed to compute those accelerations using the individual linear

accelerometer data and location geometry. First principles were incorporated to derive the equations of acceleration from raw accelerometer data.

Considering the general motion of a body in space, the position of one point (B) on a body with respect to another point (A) may be expressed as the vector sum

$$\vec{r}_B = \vec{r}_A + \vec{r}_{B/A} \quad (7)$$

where, in general, for an XYZ inertial coordinate system

$$\vec{r} = r_x \vec{i} + r_y \vec{j} + r_z \vec{k} \quad (8)$$

The expression of $\vec{r}_{B/A}$ in equation (7) is defined as the position of point B relative to a frame $AX'Y'Z'$ attached to point A and of fixed orientation (figure 4-1).

FIGURE 4-1: RIGID BODY IN GENERAL MOTION

The rotation of a rigid body about a fixed axis may be defined by the motion of a slab in a plane perpendicular to the axis of rotation. Since point A is fixed in this frame, the motion of the body relative to $AX'Y'Z'$ is the motion of a body with a fixed point. The motion during a time interval Δt of a rigid body about a fixed point O may be considered as a rotation through $\Delta\theta$ about a certain axis. The instantaneous axis of rotation and the angular velocity $\bar{\omega}$ of the body are found by finding the limit of $\Delta\theta/\Delta t$ as Δt approaches zero.⁷⁵ The angular velocity $\bar{\omega}$ in figure 4-1 is equal in magnitude to the rate of change of the angular coordinate and is directed along the axis of rotation $\bar{u}$ as

$$\bar{v} = \bar{\omega} \times \bar{r} \quad (9)$$

where $\bar{\omega} = \omega\bar{u}$. Considering equation (9), the absolute velocity of a particle on the body with respect to the inertial coordinate system is obtained by differentiating equation (7) with respect to t as

$$\bar{v}_B = \frac{d}{dt} \bar{r}_B = \bar{v}_A + \dot{\bar{r}}_{B/A} + \bar{\omega}_A \times \bar{r}_{B/A} \quad (10)$$

The value of $\dot{\bar{r}}_{B/A}$ in equation (10) is the velocity of point B relative to A . Similarly, differentiating the velocity with respect to time t yields the absolute acceleration $\bar{a}$ of a particle with respect to the inertial coordinate system XYZ .

$$\bar{a}_B = \bar{a}_A + \ddot{\bar{r}}_{B/A} + 2\bar{\omega}_A \times \dot{\bar{r}}_{B/A} + \dot{\bar{\omega}}_A \times \bar{r}_{B/A} + \bar{\omega}_A \times (\bar{\omega}_A \times \bar{r}_{B/A}) \quad (11)$$

The first term on the right hand side of equation (11) is the acceleration of point A , the second term is the acceleration of B relative to A , the third term is the Coriolis acceleration, and the final two terms make up the instantaneous acceleration at point B . The last term $\bar{\omega}_A \times (\bar{\omega}_A \times \bar{r}_{B/A})$ also represents the centripetal acceleration, which points towards the instantaneous axis of rotation.⁷⁶

Equations (10) and (11) can be reduced in complexity by assuming the body is rigid and hence ignoring the small deformations associated with its flexibility. Therefore, the

distance between points A and B will remain constant and any time derivative of the displacement of B with respect to A will also be zero. Additionally, defining angular acceleration as the time derivative of angular velocity

$$\alpha = \frac{d\omega}{dt} \quad (12)$$

equations (10) and (11) were rewritten as

$$\vec{v}_B = \vec{v}_A + \vec{\omega}_A \times \vec{r}_{B/A} \quad (13)$$

$$\vec{a}_B = \vec{a}_A + \vec{\alpha}_A \times \vec{r}_{B/A} + \vec{\omega}_A \times (\vec{\omega}_A \times \vec{r}_{B/A}) \quad (14)$$

Equations (13) and (14) follow Euler's theorem that the general displacement of a rigid body with a fixed point A is equivalent to a rotation of the body about an axis through A .

The general motion of a rigid body is equivalent, at any given instant, to the sum of a translation, in which all of the particles of a body have the same velocity and acceleration of a reference particle A , and of a motion in which particle A is assumed to be fixed. In general, the vectors $\vec{\omega}$ and $\vec{\alpha}$ in figure 4-1 are not collinear and the accelerations of the particles of the rigid body in their motion relative to the frame $AX'Y'Z'$ cannot be determined as if the body were rotating permanently about the instantaneous axis through A . It can further be shown that the motion of the body with respect to a frame attached to a different reference point would also be characterized by the same vectors $\vec{\omega}$ and $\vec{\alpha}$ as its motion relative to $AX'Y'Z'$. The angular velocity and angular acceleration of a rigid body at a given instant are therefore independent of the choice of the reference point.⁷⁵

Considering a large, 2,000-lb. bomb as a rigid body, equation (14) can be rewritten in terms of the acceleration of the store CG, $\vec{a}_{CG}$, and the acceleration measured by an accelerometer on the store surface, $\vec{a}_M$. The term $\vec{a}_{rel}$ represents the relative acceleration felt by the surface accelerometer with respect to the store CG due to the store's angular acceleration or rotational velocity about the CG.

$$\vec{a}_M = \vec{a}_{CG} + \vec{a}_{rel} \quad (15)$$

To find the acceleration at the store CG, equation (15) is rearranged to

$$\vec{a}_{CG} = \vec{a}_M - \vec{a}_{rel} \quad (16)$$

The measured accelerations at each accelerometer $\vec{a}_M$ are known while the relative accelerations require calculation. Allowing $\vec{a}_M$ in equation (16) to coincide with point *B* in figure 4-1 and point *A* to represent the CG, equations (14) and (16) were combined to find the equation of acceleration about the CG based on the measured accelerometer data.

$$\vec{a}_{CG} = \vec{a}_M - \vec{\alpha} \times \vec{r}_{rel} - \vec{\omega} \times (\vec{\omega} \times \vec{r}_{rel}) \quad (17)$$

From equations (16) and (17), the acceleration of an accelerometer on the store relative to the store CG $\vec{a}_{rel}$ is defined as

$$\vec{a}_{rel} = \vec{\alpha} \times \vec{r}_{rel} + \vec{\omega} \times (\vec{\omega} \times \vec{r}_{rel}) \quad (18)$$

Since $\vec{\omega}$, $\vec{\alpha}$ and $\vec{a}$ are all three-dimensional vectors, they can be expressed as the combination of their $\vec{i}$, $\vec{j}$ and $\vec{k}$ directional components similar to equation (8):

$$\vec{\omega} = \omega_x \vec{i} + \omega_y \vec{j} + \omega_z \vec{k} \quad (19)$$

$$\vec{\alpha} = \alpha_x \vec{i} + \alpha_y \vec{j} + \alpha_z \vec{k} \quad (20)$$

$$\vec{a} = a_x \vec{i} + a_y \vec{j} + a_z \vec{k} \quad (21)$$

By expanding equation (18) with equation (8) and equations (19) through (21), the three final equations for relative acceleration broken down by component along the *X'*-, *Y'*- and *Z'*-axes are found, as felt by the accelerometer with respect to the store CG.

$$a_{rel,X} = r_y (\omega_x \omega_y - \alpha_z) + r_z (\omega_x \omega_z + \alpha_y) - r_x (\omega_y^2 + \omega_z^2) \quad (22)$$

$$a_{rel,Y} = r_z (\omega_y \omega_z + \alpha_x) + r_x (\omega_x \omega_y - \alpha_z) - r_y (\omega_x^2 + \omega_z^2) \quad (23)$$

$$a_{rel,Z} = r_x (\omega_x \omega_z - \alpha_y) + r_y (\omega_y \omega_z + \alpha_x) - r_z (\omega_x^2 + \omega_y^2) \quad (24)$$

The final equations to calculate the components of translational acceleration at the store CG based on the measured accelerations, geometry, angular velocities and angular accelerations were found by combining equation (17) with equations (22), (23) and (24):

$$a_{CG,X} = a_{M,X} - r_y(\omega_x\omega_y - \alpha_z) - r_z(\omega_x\omega_z + \alpha_y) + r_x(\omega_y^2 + \omega_z^2) \quad (25)$$

$$a_{CG,Y} = a_{M,Y} - r_z(\omega_y\omega_z + \alpha_x) - r_x(\omega_x\omega_y - \alpha_z) + r_y(\omega_x^2 + \omega_z^2) \quad (26)$$

$$a_{CG,Z} = a_{M,Z} - r_x(\omega_x\omega_z - \alpha_y) - r_y(\omega_y\omega_z + \alpha_x) + r_z(\omega_x^2 + \omega_y^2) \quad (27)$$

Equations (25) through (27) contain scalar quantities vice vector expressions; therefore correct sign convention is critical. The values of r_x , r_y and r_z physically relate the store CG to the locations of the accelerometers and need to follow the global sign conventions instead of simply being positive distance values. Accelerometers are fastened to an orthogonal riser block and not necessarily fastened directly on the surface of the store.

The translational accelerations calculated in equations (25) through (27) are functions of the rotational velocities ($\bar{\omega}_x$, $\bar{\omega}_y$ and $\bar{\omega}_z$) and rotational accelerations ($\bar{\alpha}_x$, $\bar{\alpha}_y$ and $\bar{\alpha}_z$). If the length $\bar{r}$ and the axis of rotation along $\bar{\omega}$ are mutually perpendicular as in the rotation of a slab, the magnitude of the velocity $\bar{v}$ is $v = r\omega$ from equation (9). If the slab axis of rotation is labeled $\bar{k}$, the now collinear $\bar{\omega} = \omega\bar{k}$ and $\bar{\alpha} = \alpha\bar{k}$ may be substituted into equation (18) and by setting $\bar{r} = \bar{r}_{rel}$, it can be shown that

$$\bar{a} = \alpha\bar{k} \times \bar{r} - \omega^2\bar{r} \quad (28)$$

Resolving equation (28) into components tangential and normal to the center of rotation and in the plane of rotation yields

$$\bar{a}_t = \alpha\bar{k} \times \bar{r} \quad a_t = r\alpha \quad (29)$$

$$\bar{a}_n = -\omega^2\bar{r} \quad a_n = r\omega^2 \quad (30)$$

From equation (29) the magnitude of the angular acceleration is equal to the ratio of the tangential acceleration and the distance from the acceleration to the center of rotation.

For accelerometer data, the measured accelerations were all tangential allowing the calculation of the angular accelerations when combined with the store and instrumentation geometry. The physical locations of the accelerometers on the store were critical to avoid coupling effects of the angular, centripetal and translational accelerations that could not analytically be separated. The measured accelerations were generally labeled and defined as shown in table 4-1. Redundant use of accelerometers allows the required minimum of six accelerometers (i.e. sharing a z -accelerometer for pitch, roll and vertical acceleration calculations, etc.). All coupled accelerometers (i.e. $a_{YF,yaw}$ and $a_{YA,yaw}$, etc.) should be placed at the necessary and identical coordinates to minimize error due to acceleration coupling (i.e. a roll acceleration producing false pitch acceleration readings due to uneven lateral placement, etc.).

TABLE 4-1: PHYSICAL ACCELEROMETER DATA (MINIMUM REQUIREMENTS)

Mnemonic	General Accelerometer Descriptions and Locations
a_x	X-axis accelerometer measuring longitudinal acceleration. Located anywhere on store, but prefer at the store longitudinal CG.
$a_{YF,yaw}$	Y-axis accelerometer used for yaw measurement. Located at or forward of longitudinal store CG and forward of $a_{YA,yaw}$.
$a_{YA,yaw}$	Y-axis accelerometer used for yaw measurement. Located at or aft of longitudinal store CG and aft of $a_{YF,yaw}$.
$a_{ZS,roll}$	Z-axis accelerometer used for roll measurement. Located on starboard side of store, preferably at store CG across from $a_{ZP,roll}$.
$a_{ZP,roll}$	Z-axis accelerometer used for roll measurement. Located on port side of store, preferably at store CG across from $a_{ZS,roll}$.
$a_{ZF,pitch}$	Z-axis accelerometer used for pitch measurement. Located forward of longitudinal store CG and forward of $a_{ZA,pitch}$.
$a_{ZA,pitch}$	Z-axis accelerometer used for pitch measurement. Located aft of longitudinal store CG and aft of $a_{ZF,pitch}$.

The magnitude of the store roll acceleration α_x was computed using two linear z -axis accelerometers placed on opposite sides of the store's longitudinal centerline although not necessarily in the same longitudinal coordinate. Equation (31) provides the average

reading of roll acceleration of the store CG. The second term in equation (31) removes an effective roll acceleration component due to pitch acceleration for the case when the two accelerometers are at different longitudinal locations. Yaw acceleration does not effect this parameter and translational acceleration along the z -axis is canceled out via subtraction within both terms in equation (31). The value of $L_{Y,roll}$ corresponds to the positive lateral distance between the accelerometers used for the roll acceleration calculations, which are typically located just above the surface of the store on orthogonal blocks. $L_{X,roll}$ and $L_{X,pitch}$ correspond to the positive longitudinal distances between the z -axis accelerometers measuring roll and pitch, respectively. With the store rigid body assumptions imposed to this point, the roll accelerometers do not have to be equidistant laterally or vertically from the store CG or center of rotation.

$$\alpha_X = \frac{a_{ZS,roll} - a_{ZP,roll}}{|L_{Y,roll}|} - \frac{a_{ZF,pitch} - a_{ZA,pitch}}{|L_{X,pitch}|} \left(\frac{|L_{X,roll}|}{|L_{Y,roll}|} \right) \quad (31)$$

The magnitude of the store pitch acceleration α_Y was computed using two linear z -axis accelerometers placed on the same side of the store with one forward and one aft of the longitudinal store CG. Equation (32) provides the average reading of pitch acceleration about the store CG. The second term in equation (32) removes an effective pitch acceleration component due to roll acceleration for the case when the two accelerometers are at different lateral locations. Yaw acceleration does not effect this parameter and translational acceleration along the z -axis is canceled out in equation (32). $L_{Y,roll}$ and $L_{Y,pitch}$ correspond to the positive lateral distances between the z -axis accelerometers measuring roll and pitch, respectively. Due to the store rigid body, the pitch accelerometers do not have to be equidistant longitudinally or vertically from the store CG or center of rotation.

$$\alpha_Y = \frac{a_{ZF,pitch} - a_{ZA,pitch}}{|L_{X,pitch}|} - \frac{a_{ZS,roll} - a_{ZP,roll}}{|L_{Y,roll}|} \left(\frac{|L_{Y,pitch}|}{|L_{X,pitch}|} \right) \quad (32)$$

The magnitude of the store yaw acceleration α_Z was computed using two linear y -axis accelerometers placed on the same side of the store's longitudinal centerline with one positioned forward of the store CG and the other aft of the store CG. Equation (33)

provides the average reading of yaw acceleration of the store CG. The second term in equation (33) removes an effective yaw acceleration component due to roll acceleration for the case when the two accelerometers are at different vertical locations. Pitch acceleration does not affect this parameter and translational acceleration along the y-axis is canceled out in equation (33). The values of $L_{X,yaw}$ and $L_{Z,yaw}$ correspond to the positive longitudinal and vertical distances, respectively, between the accelerometers used for the yaw acceleration calculations. The yaw accelerometers do not have to be equidistant laterally or longitudinally from the store CG or center of rotation due to the rigid body.

$$\alpha_Z = \frac{a_{YA,yaw} - a_{YF,yaw}}{|L_{X,yaw}|} - \frac{a_{Y,up,yaw} - a_{Y,dn,yaw}}{|L_{Y,roll}|} \left(\frac{|L_{Y,pitch}|}{|L_{X,pitch}|} \right) \quad (33)$$

To find the forces and moments at the store CG, accurate acceleration data must be found. Data for equations (31) through (33) are from accelerometers placed on the store in such a way to eliminate interference from other accelerometers. Translational accelerations (equations 25 through 27) are already corrected for interference effects. Typical store accelerometer placements are depicted in figure 4-2.

FIGURE 4-2: TYPICAL STORE ACCELEROMETER LOCATIONS

4.3 Inertial Loads

The angular momentum of a mass particle dm is the movement of its linear momentum about the origin of the coordinate system and is given by the following expression⁷⁶:

$$\vec{r} \times (\vec{v}_O + \vec{\omega} \times \vec{r}) dm \quad (34)$$

The angular momentum of the rigid body about the origin O is obtained as

$$\vec{H}_O = \int \vec{r} \times (\vec{v}_O + \vec{\omega} \times \vec{r}) dm = -\vec{v}_O \times \int \vec{r} dm + \int \vec{r} \times (\vec{\omega} \times \vec{r}) dm \quad (35)$$

since localized deformations are assumed negligible. If the reference point O of the body is a fixed point in inertial space, then $\vec{v}_O = 0$.

$$\vec{H}_O = \int \vec{r} \times (\vec{\omega} \times \vec{r}) dm \quad (36)$$

By choosing the origin of the coordinate system either at its center of mass or at a fixed point of the body, if it exists, the rotational equations uncouple from the translational. The product of $\vec{r} \times (\vec{\omega} \times \vec{r})$ may be expanded to yield the following expression:

$$\begin{aligned} \vec{r} \times (\vec{\omega} \times \vec{r}) = & \vec{i} [y(\omega_x y - \omega_y x) - z(\omega_z x - \omega_x z)] \\ & + \vec{j} [z(\omega_y z - \omega_z y) - x(\omega_x y - \omega_y x)] \\ & + \vec{k} [x(\omega_z x - \omega_x z) - y(\omega_y z - \omega_z y)] \end{aligned} \quad (37)$$

Substituting equation (37) into (36) it can be shown⁷⁶

$$\vec{H}_O = \vec{i} H_x + \vec{j} H_y + \vec{k} H_z \quad (38)$$

where

$$H_x = \omega_x \int_m (y^2 + z^2) dm - \omega_y \int_m xy dm - \omega_z \int_m xz dm \quad (39)$$

$$H_y = -\omega_x \int_m xy dm + \omega_y \int_m (x^2 + z^2) dm - \omega_z \int_m yz dm \quad (40)$$

$$H_z = -\omega_x \int_m xz dm - \omega_y \int_m yz dm + \omega_z \int_m (x^2 + y^2) dm \quad (41)$$

Incorporating the moment and product of inertia relationships defined as

$$I_x = \int_m (y^2 + z^2) dm \quad I_y = \int_m (x^2 + z^2) dm \quad I_z = \int_m (x^2 + y^2) dm \quad (42)$$

$$I_{xy} = I_{yx} = -\int_m xy dm \quad I_{yz} = I_{zy} = -\int_m yz dm \quad I_{xz} = I_{zx} = -\int_m xz dm$$

equations (39), (40) and (41) can be written in the following matrix form:

$$\begin{Bmatrix} H_x \\ H_y \\ H_z \end{Bmatrix} = \begin{bmatrix} I_x & I_{xy} & I_{xz} \\ I_{xy} & I_y & I_{yz} \\ I_{xz} & I_{yz} & I_z \end{bmatrix} \begin{Bmatrix} \omega_x \\ \omega_y \\ \omega_z \end{Bmatrix} \quad (43)$$

Equation (43) can be simplified as the single matrix equation

$$\{H\}_o = [I]_o \{\omega\}_o \quad (44)$$

Both $\bar{H}_o$ and $\bar{\omega}$ are independent of the orientation of the $OXYZ$ coordinate frame. The elements of the matrix arrays in equation (43) or (44), however, depend on the orientation of the coordinate system. If a different coordinate frame is used ($OX'Y'Z'$), the vectors $\bar{H}_o$ and $\bar{\omega}$ will not change even though the column matrices $\{H'\}_o$ and $\{\omega'\}_o$ will contain different elements. The inertia matrix in equation (44), $[I]_o$, contains the moment and product of inertias with respect to a particular coordinate system. If the $OX'Y'Z'$ frame is used, $[I']_o$ will also have different matrix elements.⁷⁶

A coordinate system fixed on the body was assumed in the development of equation (44) so that the angular velocity of the coordinate system is the same as that of the body. For

a rigid body, it is possible to choose a coordinate system that has a different angular velocity than that of the body $\bar{\Omega}$. Because of the reference frame rotation, the derivatives of the coordinate components in equation (43) are only changes measured relative to the local frame. By defining $\bar{\tilde{\Omega}} = \bar{\omega}_{B/F} + \bar{\omega}$, equation (44) may be modified to account for the relative angular velocities:

$$\{H\}_o = [I]_o \{\tilde{\Omega}\}_o \quad (45)$$

To arrive at the six equations of motion defining six degrees of freedom, first recall that $\bar{\tilde{\Omega}} = \bar{\omega}$ for an unconstrained rigid body. Three equations of motion represent the translation of the center of mass of the body and three equations represent the rotation about the center of mass. Since the angular velocity throughout a rigid body is constant, Newton's second law can be used to express the resultant of the external forces acting on the body as $\bar{F}$ and the resultant moment of external forces and couples about the body mass center (c) as $\bar{M}_c$.

$$\frac{d}{dt}(m\bar{v}_c) = m \frac{d}{dt} \bar{v}_c = \bar{F} \quad (46)$$

$$\frac{d}{dt} \bar{H}_c = \bar{M}_c \quad (47)$$

where $\bar{v}_c$ is the velocity vector of the mass center and $\bar{H}_c$ is the angular momentum vector defined in equation (36) about the mass center. With the center of mass as the origin of the coordinate system, the rotational equations of motion, equation (47), are uncoupled from the translational equations, equation (46).

As $\bar{H}_c$ and $\bar{v}_c$ have been expressed in terms of the rotating angular coordinate system XYZ with an angular velocity $\bar{\omega}$, equations (9) and (36) were used to write

$$\begin{aligned} \frac{d\bar{v}_c}{dt} &= \dot{v}_x \bar{i} + \dot{v}_y \bar{j} + \dot{v}_z \bar{k} + \bar{\omega} \times \bar{v}_c \\ &= (v_z \omega_y - v_y \omega_z) \bar{i} + (v_x \omega_z - v_z \omega_x) \bar{j} + (v_y \omega_x - v_x \omega_y) \bar{k} \end{aligned} \quad (48)$$

and

$$\frac{d\vec{H}_c}{dt} = \dot{H}_x \vec{i} + \dot{H}_y \vec{j} + \dot{H}_z \vec{k} + \vec{\omega} \times \vec{H}_c \quad (49)$$

Since the inertia terms are constant with time, the time derivative of equation (43) yields the three expressions:

$$\begin{aligned} \dot{H}_x &= I_x \dot{\omega}_x + I_{xy} \dot{\omega}_y + I_{xz} \dot{\omega}_z \\ \dot{H}_y &= I_{xy} \dot{\omega}_x + I_y \dot{\omega}_y + I_{yz} \dot{\omega}_z \\ \dot{H}_z &= I_{xz} \dot{\omega}_x + I_{yz} \dot{\omega}_y + I_z \dot{\omega}_z \end{aligned} \quad (50)$$

Substituting equation (48) into equation (46), the translational equations of motion are given by⁷⁶

$$\begin{aligned} F_x &= m(\dot{v}_x + v_z \omega_y - v_y \omega_z) \\ F_y &= m(\dot{v}_y + v_x \omega_z - v_z \omega_x) \\ F_z &= m(\dot{v}_z + v_y \omega_x - v_x \omega_y) \end{aligned} \quad (51)$$

Expanding the last term in equation (49) as

$$\vec{\omega} \times \vec{H}_c = (\omega_y H_z - \omega_z H_y) \vec{i} + (\omega_z H_x - \omega_x H_z) \vec{j} + (\omega_x H_y - \omega_y H_x) \vec{k} \quad (52)$$

and combining equation (52) with equations (47), (49) and (50) yields the three rotational equations of motion for a rigid body:

$$\begin{aligned} M_x &= I_x \dot{\omega}_x + I_{xy} (\dot{\omega}_y - \omega_x \omega_z) + I_{xz} (\dot{\omega}_z - \omega_x \omega_y) + (I_z - I_y) \omega_y \omega_z + I_{yz} (\omega_y^2 - \omega_z^2) \\ M_y &= I_y \dot{\omega}_y + I_{xy} (\dot{\omega}_x - \omega_y \omega_z) + I_{yz} (\dot{\omega}_z - \omega_x \omega_y) + (I_x - I_z) \omega_z \omega_x + I_{xz} (\omega_z^2 - \omega_x^2) \\ M_z &= I_z \dot{\omega}_z + I_{yz} (\dot{\omega}_y - \omega_x \omega_z) + I_{xz} (\dot{\omega}_x - \omega_y \omega_z) + (I_y - I_x) \omega_x \omega_y + I_{xy} (\omega_x^2 - \omega_y^2) \end{aligned} \quad (53)$$

If the body coordinate axes XYZ in equation (53) are selected such that they are the principal axes with origin at the body mass center or at a point fixed in inertial space, and

if the angular velocity $\bar{\omega}$ of the coordinate system is the same as that of the body, the product of inertia terms can be removed in equations (53) to yield a simpler form:

$$\begin{aligned} M_1 &= I_1 \dot{\omega}_1 + \omega_2 \omega_3 (I_3 - I_2) \\ M_2 &= I_2 \dot{\omega}_2 + \omega_1 \omega_3 (I_1 - I_3) \\ M_3 &= I_3 \dot{\omega}_3 + \omega_1 \omega_2 (I_2 - I_1) \end{aligned} \quad (54)$$

Equations (54) are known as *Euler's equations of motion for body-fixed principal axes* and are often used in describing the rotational motion of a rigid body, where I_1 , I_2 and I_3 are the principal moments of inertia; ω_1 , ω_2 and ω_3 are the components of the angular velocity vector along the principal axes; and M_1 , M_2 and M_3 represent the components of the moment vector along the principal axes.

Equations (51) and (54) can now be written in terms of the currently-known parameters. The time derivatives of the linear velocities in equations (51) can be replaced with the translational accelerations in equations (25) through (27) as

$$\begin{aligned} F_x &= m(a_{CG,X} + v_z \omega_y - v_y \omega_z) \\ F_y &= m(a_{CG,Y} + v_x \omega_z - v_z \omega_x) \\ F_z &= m(a_{CG,Z} + v_y \omega_x - v_x \omega_y) \end{aligned} \quad (55)$$

Additionally, the principal axes of the bomb body correspond to the XYZ body axes and, from equation (12), the time derivatives of angular velocity can be replaced with the angular accelerations shown in equations (31) through (33). The simplified Euler's equations (55) can then be shown as

$$\begin{aligned} M_X &= I_X \alpha_X + \omega_Y \omega_Z (I_Z - I_Y) \\ M_Y &= I_Y \alpha_Y + \omega_X \omega_Z (I_X - I_Z) \\ M_Z &= I_Z \alpha_Z + \omega_X \omega_Y (I_Y - I_X) \end{aligned} \quad (56)$$

The values for mass moments of inertia (I_X, I_Y and I_Z) are found from experimental mass property measurements and discussed in detail in Chapter 5. The values for translational velocities (v_X, v_Y and v_Z) and angular velocities (ω_X, ω_Y and ω_Z) cannot be found directly and must be approximated numerically. Integrating equation (12) for the rotational velocities and the corresponding equation for the translational velocities, the approximations over any time step ($t_2 - t_1$) may be solved as

$$v_2 = v_1 + a_{avg}(t_2 - t_1) \quad (57)$$

$$\omega_2 = \omega_1 + \alpha_{avg}(t_2 - t_1) \quad (58)$$

where

$$a_{avg} = \frac{a_1 + a_2}{2} \quad \alpha_{avg} = \frac{\alpha_1 + \alpha_2}{2} \quad (59)$$

Equations (57) through (59) must be solved in each direction X , Y , and Z .

Newton's Second Law of Motion (equation 46) states that if the resultant force acting on a particle is not zero and mass is constant, the particle will have an acceleration proportional to the magnitude of and in the direction of the resultant force. The forces resisting the inertial loads, as calculated with equations (55) and (56), are therefore equal in magnitude but opposite in direction to the inertial forces as found with the accelerations experienced by the store during any particular maneuver.⁵⁰ The external reactions resisting a particle undergoing a maneuver must then be in the opposite direction of the resisting force, or in the same direction as the acceleration of the particle. Therefore, equations (55) and (56) not only represent the forces and moments felt by the store due to the measured and calculated accelerations, these equations also represent the reactions experienced externally by the bomb rack unit that are resisting the stores inertial loads. The coordinate system used for the store geometry as well as all inertial loads and reactions is defined by the right-hand convention shown in figure 4-3.

FIGURE 4-3: THREE-DIMENSIONAL FLIGHT ENVELOPE AND CONVENTION

4.4 Aerodynamic Loads

In all situations, regardless of how complex the maneuver or chaotic the atmosphere, aerodynamic forces and moments on a body stem from only two sources: pressure distributions and shear stress distributions over the surface of a body. The net effect of the normal pressure and tangential shear stress distributions integrated over the complete body surface produces a resultant aerodynamic force R and moment M on the body. With the flow velocity far ahead of the body designated as the relative wind, or V_∞ , the components of R perpendicular and parallel to V_∞ are known as lift (L) and drag (D), respectively.⁵⁷

The equations to calculate L , D and M can be found from the definitions of their respective dimensionless coefficients C_L , C_D and C_M , respectively.

$$C_L \equiv \frac{L}{qS} \quad C_D \equiv \frac{D}{qS} \quad C_M \equiv \frac{M}{qSl} \quad (60)$$

Equations for lift, drag and moment are therefore found as

$$L = C_L qS \quad D = C_D qS \quad M = C_M qSl \quad (61)$$

In equations (60) and (61), the values of q , S and l represent dynamic pressure, reference area and reference length, respectively. The aerodynamic coefficients C_L , C_D and C_M are the most difficult to evaluate. A number of objects have known aerodynamic coefficients found through extensive wind tunnel modeling, while others require theoretical calculations and additional modifications based on actual test data or historical experience.

From the Buckingham pi theorem, a dimensional analysis proves that all three dimensionless coefficients in equations (60) and (61) are functions of Reynold's number Re , Mach number M and angle of attack α . The lift equation given in equations (61) is used to define the vertical aerodynamic lifting force, $P_{Z,aero}$, as well as the lateral lifting force, $P_{Y,aero}$. The angle of attack used to define the aerodynamic coefficients can be either the traditional aircraft angle of attack in the x - z plane, α , or the aircraft's angle of sideslip in the x - y plane, β , depending on if the calculation is for $P_{Z,aero}$ or $P_{Y,aero}$, respectively. Similarly, the lift calculations in equations (61) can either be used with the lift coefficient or the side-force coefficient depending on whether the desired calculation is for $P_{Z,aero}$ or $P_{Y,aero}$, respectively.⁵⁷

The drag equation in equations (61) is used only for drag calculations which are the aerodynamic forces along the x -axis, $P_{X,aero}$. This equation can have two forms as well: one incorporating α and one β to calculate the drag force components coupled with $P_{Z,aero}$ and $P_{Y,aero}$, respectively. If the moment equation in equations (61) is used for the aerodynamic moment calculation about the y -axis, $M_{Y,aero}$, the moment coefficient and the angle of attack will become the pitching moment coefficient and α , respectively. Similarly, for the aerodynamic moment calculation about the z -axis, $M_{Z,aero}$, the moment

coefficient and the angle of attack will become the yawing moment coefficient and β . For this research, the length l in equations (61) is the reference length of the store.

The coefficients of lift and drag must be found from both experimental and theoretical data. If an object involved in testing has known aerodynamic coefficients, the known values will be incorporated and modified as necessary. If some or all of the coefficients are not known, useful values must be determined from known data.

4.4.1 Generalized Lift and Drag Coefficients

A streamlined body operating at an angle of attack develops a lifting force similar to that of a low aspect ratio wing. This lifting force is composed of cross-flow and circulation components.⁶⁸ Circulation theory predicts that in a slender body of revolution, as in a aircraft store, lift develops corresponding to local cross forces by

$$\frac{dF}{dx} = q \left(\frac{dS_0}{dx} \right) \sin(2\alpha) \quad (62)$$

In equation (62), the term dS_0/dx represents the rate of change of the cross-sectional area.⁶⁹ Considering a circular cone with a finite length and blunt base, the lift coefficient would be dependent on the frontal area S and could be found with equation (63). Lift of this type, however, is more typical in wings and airfoil sections than missile bodies.⁶⁸

$$C_{L,0} = \sin(2\alpha) \quad (63)$$

According to Hoerner, for a closed, streamlined body with an approximately circular cross-section, the only procedure for obtaining lift is statistical and is a function of body drag.⁶⁸ Characteristics of a streamlined body tested in an open-jet wind tunnel show that lift increases with drag produced by surface roughness.⁷⁰ It was noted that cross-sectional shape more than any other physical parameter or ratio determines the lift and longitudinal moment on a body. A pointed nose and cylindrical body combination is theoretically not expected to produce any lift, particularly at small angles of attack. Evidence does show the existence of lift, which is generally explained with the growth of

the boundary layer or possibly the mass of air within the boundary layer and wake added to that which was originally deflected by the body. For cylindrical bodies, the lift increment was found to be approximately 10% of that predicted by equations (62) and (63).⁶⁸

As the angle of attack or fineness ratio l/b is increased, a second and nonlinear component of lift develops. When the angle of attack is less than 90° , the normal force is proportional to the cross-flow dynamic pressure.⁶⁸

$$q_w = \frac{1}{2} \rho V^2 \sin^2 \alpha \quad (64)$$

The component of V parallel to the cylinder axis does not contribute to the cross-flow pattern around the body. Disregarding the small component of skin friction drag in longitudinal flow, there are only normal forces N acting on the cylinder so that

$$D = N \sin \alpha \quad L = N \cos \alpha \quad (65)$$

By defining the maximum coefficient of the store in cross-flow as C_{CF} , which corresponds to an angle of attack of 90° , the normal force coefficient becomes

$$C_N = \frac{N}{q} dl = C_{CF} \sin^2 \alpha \quad (66)$$

From equations (65) and (66), the coefficients of lift and drag due to cross-flow are

$$C_L = C_{CF} \sin^2 \alpha \cos \alpha \quad (67)$$

$$C_D = C_{CF} \sin^3 \alpha \quad (68)$$

4.4.2 Moment Coefficients

For an isolated body of revolution, the forces and moments due to an angle of attack will be of the same magnitude of those due to a similar angle of sideslip. Within small angles of pitch or yaw, the moment coefficient in equation (60) reduces to:

$$C_M = \frac{M}{qV} = 2k\alpha \quad (69)$$

where α is expressed in radians and

$$k = 1 - \frac{b}{l} \quad (70)$$

For larger angles, the volume of air affected by a streamlined body corresponds to its thickness as measured normal to the plane of angular displacement. Since the volume of the body isn't always available, the moment coefficient in equation (69) can be written as

$$C_M = \frac{M}{qb^2l} \quad (71)$$

In equation (71), the parameter b corresponds to the span when the object is at an angle of attack, or the thickness when at an angle of sideslip.⁶⁸

4.4.3 Subsonic Drag Coefficient

Contrary to C_L , the coefficient of drag has many contributors. The total drag on a body is generally found by combining the parasite drag at zero lift $C_{D,0}$ and the induced drag due to lift $C_{D,i}$. Parasite drag, however, has many components and is usually obtained from airfoil-type data. The induced drag can be obtained from finite wing theory.⁵⁷

In subsonic cruise, most well-designed aerodynamic objects will have parasite drag that is predominantly skin-friction drag with a small addition of separation pressure drag.⁷¹

From reference 71, subsonic parasite drag can be found with the following equation:

$$(C_{D,0})_{subsonic} = \frac{C_f(FF)(Q)S_{wet}}{S_{ref}} + C_{D,misc} + C_{D,L\&P} \quad (72)$$

The values of C_f , FF and Q in equation (72) represent the flat-plate skin friction coefficient, the subsonic form factor and the interference factor, respectively. The value

of C_f is a function of M , Re and skin roughness. The most critical factor affecting skin friction drag is the amount of laminar flow over the surface of the body.⁷¹ The skin friction coefficient can be estimated by equation (73) or (74) for any surfaces in laminar or turbulent flow, respectively. Laminar flow, however, is not likely to occur in transonic or supersonic flow.⁷¹

$$C_f = \frac{1.328}{\sqrt{Re}} \quad (laminar \ flow) \quad (73)$$

$$C_f = \frac{0.455}{(\log(Re_{min}))^{2.58} (1 + 0.144M^2)^{0.65}} \quad (turbulent \ flow) \quad (74)$$

The value of Re_{min} in equation (74) is determined by the minimum Reynolds number when considering the actual Reynolds number and the cutoff Reynolds number, Re_{cutoff} , as

$$Re_{cutoff,subsonic} = 38.21 \left(\frac{l}{k} \right)^{1.053} \quad (75)$$

$$Re_{cutoff,transonic} = Re_{cutoff,supersonic} = 44.62 \left(\frac{l}{k} \right)^{1.053} M^{1.16} \quad (76)$$

Table 4-2 provides typical k values of skin roughness used in equations (75) and (76).

TABLE 4-2: TYPICAL SKIN ROUGHNESS VALUES

Surface Type	k value (in)
Camouflage Paint on Aluminum	40×10^{-5}
Smooth Paint	25×10^{-5}
Production Sheet Metal	16×10^{-5}
Polished Sheet Metal	6×10^{-5}
Smooth Molded Composite	2×10^{-5}

The form factors FF in equation (72) for subsonic drag estimation of an external store are found through equations (77) and (78).⁷¹

$$FF = 1 + \left(\frac{0.35}{f} \right) \quad (77)$$

where

$$f = \frac{l}{d} = \frac{l}{\sqrt{\frac{4A_{\max}}{\pi}}} \quad (78)$$

The parasite drag on the body is also increased due to mutual interference of components. For an external store mounted directly on the fuselage or wing, the interference factor Q is approximately 1.5. If the store is mounted less than or greater than one store diameter from the aircraft, Q is approximately 1.3 or 1.0, respectively.⁷¹

Miscellaneous drag $C_{D,misc}$ is composed of the drag of the various items attached to the body and needs to be considered in the parasite drag calculation of equation (72). These miscellaneous items include the store's unusual design characteristics, fins, etc. Leakage and protuberance drag $C_{D,L\&P}$, also shown in equation (72), is always difficult to predict. Leakage drag is the result of air going into the store at high-pressure zones while exhausting at a much lower pressure. This has a two-fold negative effect: the momentum loss of the air entering contributes directly to drag while the escaping air produces additional airflow separation effectively reducing lift. Protuberances include antennas, wires, protruding rivets, shell misalignments, etc. Typically, leakage and protuberance drag can be estimated at 2% - 15% of the total parasite drag.⁷¹

4.4.4 Supersonic Drag Coefficients

4.4.4a Parasite Drag

Supersonic parasite drag is calculated similarly to that in subsonic flow in equation (72):

$$(C_{D,0})_{supersonic} = \frac{C_f S_{wet}}{S_{ref}} + C_{D,misc} + C_{D,L\&P} + C_{D,wave} \quad (79)$$

Equation (79) differs from equation (72) with the absence of the form factor FF and interference effects Q , as well as the addition of the wave drag coefficient $C_{D,wave}$ which accounts for pressure drag due to the formation of shock waves. Skin friction is found similarly to the subsonic flow calculation in equation (74), but incorporates equation (76) vice (75). The calculations of $C_{D,misc}$ and $C_{D,L\&P}$ will also be found similarly as in subsonic flow with the same approximate percentage estimations. However, the wave drag for supersonic flight will often be the largest contributor to parasite drag.⁷¹

4.4.4b Wave Drag

In finding the wave drag coefficient $C_{D,wave}$ for supersonic flow, the linear area-rule theory predicts that wave drag is dependent on cross-sectional shape at any longitudinal location regardless of cross-sectional area. Wave drag is minimized when the aircraft's volume distribution is identical to that of a Sears-Haack body, figure 4-4.⁷²

FIGURE 4-4: SEARS-HAACK VOLUME DISTRIBUTION

It is unlikely that any aircraft will ever have a volume distribution identical to a Sears-Haack body, although it would be much easier for an external store to follow this pattern than an aircraft. If it were possible for a given body, the wave drag would then be at a theoretical minimum value, $D_{wave, SH}$, and could be found through equation (80).⁷¹

$$D_{wave,SH} = \frac{9\pi}{2} q \left(\frac{A_{max}}{l} \right)^2 \quad (80)$$

A_{max} represents the maximum cross-sectional area of the object. It is interesting to note that the cross-sectional shape does not appear in equation (80).

To use equation (80) for a realistic body vice a body of revolution, a wave drag efficiency factor E_{wd} may be introduced into equation (80) in the form of the ratio between the actual wave drag and the Sears-Haack value. E_{wd} values range from approximately 1.2 – 1.4 for clean aircraft with smooth volume distributions to 1.4 – 2.0 for a typical supersonic fighter. Values of E_{wd} from 2.0 – 3.0 are generally considered poor design; the F-15, optimized for the dogfight as opposed to supersonic flight, has an E_{wd} of 2.9.⁷¹

4.4.4c Induced Drag

Again, the total drag coefficient is not only composed of a parasite drag term at zero lift, but also an induced drag term due to lift. Drag due to lift involves components of drag directly related with the generation of lift. As the airflow over a wing, for example, rolls over the wingtip, the difference in pressures above and below the wing causes the flow to spiral rearward. Trailing vortices due to the decrease of circulation towards the wing tips form. These vortices create a deflection of the airflow which effectively changes the angle of attack by adding an induced angle α_i . These changes cause the lifting force to deflect aft through α_i , resulting in an effectively smaller lifting force and a new, additional drag component that increases the magnitude of the total drag. The minimum possible value of the induced drag coefficient, $C_{D,i}$, is found from theory to be⁷³

$$C_{D,i} = \frac{C_L^2}{\pi AR} \quad (81)$$

Classical aerodynamic theory predicts that the induced drag coefficient of a 3-D wing will be represented by an elliptical lift distribution. Since few wings actually have a perfect elliptical lift distribution, a factor was developed to modify equation (81). The additional drag due to a non-elliptical lift distribution, as well as the wing separation

drag, can be accounted for by incorporating an Oswald span efficiency factor, e . This addition effectively reduces the aspect ratio, producing a modification to equation (81).⁵⁷

$$C_{D,i} = \frac{C_L^2}{\pi e AR} \quad (82)$$

4.4.4d Experimental Drag Coefficients

Aerodynamic or flowfield anomalies may be encountered under the aircraft fuselage that cannot be modeled through classical aerodynamics or accepted formulas. Through an abundance of actual aerodynamic and aircraft flight test data, correction factors and computer models can be created to help define any difficult situations. These models will consist of algorithms based on aircraft and flowfield parameters, which were shown above to fundamentally consist of Re , M and α .

One effort to develop and correlate overall drag coefficient with M is via experimental flight-testing. Reference 74 describes ballistic testing of a 2,000-lb. store at the Naval Air Warfare Center in Patuxent River, MD. This analysis succeeded in finding the total drag coefficient of the GBU-24 B/B on an F/A-18 aircraft as a function of M . Data reduction and analysis were combined with theoretical models and flight test results. The final drag curve is shown in figure 4-5.

FIGURE 4-5: C_D VERSUS MACH FOR THE GBU-24B/B

4.5 Generalized Form of the Combined Dynamic Equations

The general equations representing aerodynamic loads due to external body forces in equations (61) were modified to calculate the forces on a store in straight and level flight with respect to V_∞ .

$$D_{x,aero,\alpha} = qS_{ref}C_{D,\alpha} \quad D_{x,aero,\beta} = qS_{ref}C_{D,\beta} \quad (83)$$

$$L_{y,aero} = qS_{ref}C_{L,\beta} \quad (84)$$

$$L_{z,aero} = qS_{ref}C_{L,\alpha} \quad (85)$$

The reference area S_{ref} and reference length L_{ref} are derived during the evaluation of the lift, drag and moment coefficients and are typically equivalent to the cross-sectional area and length of the store, respectively. The terms $C_{D,\alpha}$ and $C_{D,\beta}$, and similarly for $C_{L,\alpha}$ and $C_{L,\beta}$, are the aerodynamic coefficients found for a given range of angle of attack and angle of sideslip, respectively.

The forces in equations (83) through (85) need to be translated to the body axes of the store with respect to the angles of attack and sideslip. Figure 4-6 shows the aerodynamic forces on the store in relation to the freestream direction and the body axes of the store, for both the x - z plane with angle of attack and the x - y plane with angle of sideslip.

FIGURE 4-6: RESULTANT AERODYNAMIC FORCES ON A STORE IN FLIGHT

Translating the forces at the store CG (equations 83 through 85) due to the presence of angles of attack and sideslip as shown in figure 4-6 provided the final form of the aerodynamic force equations with respect to the body axes of a store in flight. The moment equations are also included as expanded from equations (61).

$$F_{x,aero} = D_{x,aero,\alpha} \cos \alpha - L_{z,aero} \sin \alpha + D_{x,aero,\beta} \cos \beta - L_{y,aero} \sin \beta \quad (86)$$

$$F_{y,aero} = D_{x,aero,\beta} \sin \beta + L_{y,aero} \cos \beta \quad (87)$$

$$F_{z,aero} = D_{x,aero,\alpha} \sin \alpha + L_{z,aero} \cos \alpha \quad (88)$$

$$M_{x,aero} = qS_{ref}L_{ref}C_{M,roll} \quad (89)$$

$$M_{y,aero} = qS_{ref}L_{ref}C_{M,pitch} \quad (90)$$

$$M_{z,aero} = qS_{ref}L_{ref}C_{M,yaw} \quad (91)$$

The dynamic equations due to inertial loads presented in equations (55) and (56) were combined with the equations due to the external aerodynamic forces on the surface of the store (equations 86 through 91) to yield the final expressions for loads at the store CG. The complete equations for the forces and moments at the store CG during any flight condition are therefore

$$F_x = m(a_{CG,X} + v_z\omega_y - v_y\omega_z) + D_{x,aero,\alpha} \cos \alpha - L_{z,aero} \sin \alpha + D_{x,aero,\beta} \cos \beta - L_{y,aero} \sin \beta \quad (92)$$

$$F_y = m(a_{CG,Y} + v_x\omega_z - v_z\omega_x) + D_{x,aero,\beta} \sin \beta + L_{y,aero} \cos \beta \quad (93)$$

$$F_z = m(a_{CG,Z} + v_y\omega_x - v_x\omega_y) + D_{x,aero,\alpha} \sin \alpha + L_{z,aero} \cos \alpha \quad (94)$$

$$M_X = I_X\alpha_X + \omega_Y\omega_Z(I_Z - I_Y) + qS_{ref}L_{ref}C_{M,roll} \quad (95)$$

$$M_Y = I_Y\alpha_Y + \omega_X\omega_Z(I_X - I_Z) + qS_{ref}L_{ref}C_{M,pitch} \quad (96)$$

$$M_Z = I_Z\alpha_Z + \omega_X\omega_Y(I_Y - I_X) + qS_{ref}L_{ref}C_{M,yaw} \quad (97)$$

4.6 Reactions at the SRI

During flight testing, a store will experience various combinations of forces and accelerations resulting in three forces F_x , F_y , F_z and three moments M_x , M_y , M_z at the store's CG. The accurate distribution of these loads from the store CG to the SRI was critical in calculating the reactions at the rack. Once the loads at the store CG were dynamically calculated for each time step as described in equations 55, 56 and 61, the resulting reactions at the individual interface points were found through a quasi-static assumption of force and moment equilibrium. Using the principle of superposition, each of the six load cases was considered independently at every time step and the resulting interface reactions were combined to form the overall interface reactions at that time step.

There are six points of contact between a store and a typical aircraft bomb rack: four swaybrace rods and two lug/hook combinations. The swaybrace rods can only be loaded via compressive forces and unloaded during a reduction of compressive forces. The swaybrace rods cannot support tensile loads and the ball-and-socket design prohibits any moment reactions; physical separation between the store and swaybrace pad is possible. The hook reactions can only support tensile loading from the lugs; enough reduction in the tensile forces could result in separation between the hook and lug.

The BRU-32 bomb rack is composed of steel members and has rigid body characteristics. Figures 4-7 and 4-8 show the sign convention and layout geometry of a typical SRI assuming the requisite 30-inch lug spacing of a larger store (vice smaller stores requiring 14-inch lug spacing between the 20-inch spaced swaybrace assemblies). The lateral distance between two swaybrace contact points within a single assembly (figure 4-8) is typically 4.24 inches.

Preloads in the interface points will typically be found in the hooks and swaybrace rods during loading of a store onto a bomb rack. The magnitude of the preloads might change or redistribute during taxiing and flight maneuvers but will generally return to the original values in steady state flight. These loads can be based on historical averages and use of consistent loading techniques and must be accounted for in the reaction equations.

FIGURE 4-7: TYPICAL STORE INTERFACE GEOMETRY IN X-Z PLANE

FIGURE 4-8: TYPICAL STORE INTERFACE GEOMETRY IN Y-Z PLANE

Although the swaybrace rods cannot react in tension or lugs react in compression, the swaybrace rods are not restricted from *unloading* due to the presence of a tensile reaction and thereby having the compressive reaction reduced as if the rods were responding in tension. Furthermore, the lugs could effectively react in a compressive fashion if there were already a sufficient tensile reaction present as to not allow the lugs to go into an overall compressive state. Therefore, the magnitudes of the reactions at the interface points were changed to maintain equilibrium with the unloading reactions. To account for unloading, the reactions calculated for each interface point were split equally between

the reacting component and the unloading component. Throughout the equations outlined below, the interaction locations experiencing an unload during either a positive or negative load will have the magnitude of that reaction reduced until the reaction has reached zero (fully unloaded) at which point the entire load in that direction will be only reacted by the interface point that is increasing in magnitude.

4.6.1 Interface Reactions Due to a Longitudinal Load P_x at the Store CG

Longitudinal reactions due to a positive P_x should only be reacted in the two hooks as the swaybraces were not designed to react longitudinally. The lugs share the total longitudinal reaction, although the percentage of the longitudinal reaction for each lug is undeterminable and must be found with experimental procedures. Previous flight-test programs have found that longitudinal loads were primarily reacted by the aft lug,⁵ but without experimental data an even reaction distribution was assumed.

Figure 4-9 is the free body diagram for a **positive** longitudinal load at the store CG, showing the tensile reaction in the forward hook and compressive reactions in the aft swaybrace rods. When preloads are present, some interface points may unload as a result of the loading at the store CG as also shown in Figure 4-9.

FIGURE 4-9: REACTIONS AT SRI DUE TO LONGITUDINAL LOAD $+P_x$

The moment created by P_x in figure 4-9 increases the reactions in the aft swaybrace rods in compression and the forward lug in tension. Finding equilibrium along the x -, y - and z -directions with respect to the geometry shown in figures 4-7 and 4-8 yields the following three relationships for the forward hook vertical reaction $L_{f,z}$, the aft swaybrace reactions along each rod $S_{a,l}$ and $S_{a,r}$, and the longitudinal lugs reactions $L_{f,x}$ and $L_{a,x}$:

$$L_{f,x} = L_{a,x} = \frac{P_x}{2} \quad (98)$$

$$L_{f,z} = \frac{P_x L_5}{L_1 + S_2} \quad (99)$$

$$S_{a,l} = S_{a,r} = \frac{P_x L_5}{2(L_1 + S_2) \cos \alpha} \quad (100)$$

The left and right aft swaybrace reactions are assumed to be symmetrical due to store design and load placement. The longitudinal lug reactions are also assumed to be symmetrical unless experimental methods prove otherwise.

Similarly, the aft lug will react in tension while the forward swaybrace pair will react in compression due to the presence of a longitudinal load in the **negative** direction. The longitudinal lug reactions will be the same as found in equation (98), while the remaining lug and swaybrace reaction equations are similar but slightly different in geometry and direction as

$$L_{a,z} = \frac{P_x L_5}{L_2 + S_1} \quad (101)$$

$$S_{f,l} = S_{f,r} = \frac{P_x L_5}{2(L_2 + S_1) \cos \alpha} \quad (102)$$

4.6.2 Interface Reactions Due to a Lateral Load P_y at the Store CG

Figure 4-10 is the free body diagram for a **positive** lateral load P_y at the store CG, showing the tensile reactions in the hooks and compressive reactions in the starboard swaybrace rods. When preloads are present, interface points may unload as a result of the loading at the store CG as also shown in Figure 4-10. During a purely lateral load condition, only the swaybrace rods will react the lateral load to maintain equilibrium at the store CG. Both lugs will react vertically in tension.

FIGURE 4-10: REACTIONS AT SRI DUE TO LATERAL LOAD $+P_y$

Finding equilibrium along the x -, y - and z -directions with respect to the geometry shown in figures 4-7 and 4-8 yields the following four relationships for the forward hook vertical reaction $L_{f,z}$, the aft hook vertical reaction $L_{a,z}$, and the starboard swaybrace reactions along each rod $S_{f,r}$ and $S_{a,r}$:

$$L_{f,z} = \frac{P_y L_2}{(L_1 + L_2) \tan \alpha} \quad L_{a,z} = \frac{P_y L_1}{(L_1 + L_2) \tan \alpha} \quad (103)$$

$$S_{f,r} = \frac{P_y S_2}{(S_1 + S_2) \sin \alpha} \quad S_{a,r} = \frac{P_y S_1}{(S_1 + S_2) \sin \alpha} \quad (104)$$

For a lateral load in the **negative** direction, the lug reactions will be identical (including sign) to equations (103) while the starboard swaybrace rods will remain in a zero-load state. The port swaybrace compressive reaction equations are equivalent to their starboard counterparts in equations (104) as

$$S_{f,l} = \frac{P_y S_2}{(S_1 + S_2) \sin \alpha} \quad S_{a,l} = \frac{P_y S_1}{(S_1 + S_2) \sin \alpha} \quad (105)$$

4.6.3 Interface Reactions Due to a Vertical Load P_z at the Store CG

Vertical reactions due to a **positive** vertical load P_z should only be reacted in the four swaybrace rods as the two hooks can not react to compressive loading. Figure 4-11 is the free body diagram for a positive P_z at the store CG, showing the compressive reactions in the swaybrace rods and the possible unloading in the hooks if a preload is present.

FIGURE 4-11: REACTIONS AT SRI DUE TO VERTICAL LOAD $+P_z$

Equilibrium along the x -, y - and z -directions with respect to the geometry shown in figures 4-7 and 4-8 yields the following four relationships for the swaybrace rod reactions:

$$S_{f,l} = S_{f,r} = \frac{P_z S_2}{2(S_1 + S_2) \cos \alpha} \quad (106)$$

$$S_{a,l} = S_{a,r} = \frac{P_z S_1}{2(S_1 + S_2) \cos \alpha} \quad (107)$$

The left and right aft swaybrace reactions are assumed to be symmetrical due to store design and load placement. The SRI reactions due to negative vertical load P_z are quite different since the lugs will now react in tension and the swaybrace rods can only unload if a preload is present as shown in figure 4-12:

FIGURE 4-12: REACTIONS AT SRI DUE TO VERTICAL LOAD $-P_z$

Finding equilibrium along the x -, y - and z -directions with respect to the geometry shown in figures 4-7 and 4-8 yields the following two relationships for the lug reactions:

$$L_{f,z} = \frac{P_z L_2}{L_1 + L_2} \quad (108)$$

$$L_{a,z} = \frac{P_z L_1}{L_1 + L_2} \quad (109)$$

4.6.4 Interface Reactions Due to a Rolling Moment M_x at the Store CG

Figure 4-13 is the free body diagram for a **positive** rolling moment M_x at the store CG (counterclockwise looking forward), showing the tensile reactions in the hooks and compressive reactions in the starboard swaybrace rods. When preloads are present, SRI points may unload as a result of the loading at the store CG as also shown in Figure 4-13.

FIGURE 4-13: REACTIONS AT SRI DUE TO ROLLING MOMENT $+M_x$

Finding equilibrium along the x -, y - and z -directions with respect to the geometry shown in figures 4-7 and 4-8 yields the following three relationships for hook vertical and lateral reactions and the reactions along the swaybrace rods:

$$S_{f,r} = S_{a,r} = \frac{M_x}{2L_5 \sin \alpha} \quad (110)$$

$$L_{f,y} = L_{a,y} = \frac{M_x}{2L_5} \quad (111)$$

$$L_{f,z} = L_{a,z} = \frac{M_x}{2L_5 \tan \alpha} \quad (112)$$

For a rolling moment in the **negative** direction (clockwise looking forward), the reactions in the lugs will remain the same magnitude as with a positive moment although the reacting swaybrace rods will change.

$$S_{f,l} = S_{a,l} = \frac{M_x}{2L_5 \sin \alpha} \quad (113)$$

4.6.5 Interface Reactions Due to a Pitching Moment M_y at the Store CG

Figure 4-14 is the free body diagram for a **positive** pitching moment M_y at the store CG (nose up), showing the tensile reactions in the aft hook and compressive reactions in the forward swaybrace rods. When preloads are present, interface points may unload as a result of the loading at the store CG as also shown in Figure 4-14.

FIGURE 4-14: REACTIONS AT SRI DUE TO PITCHING MOMENT $+M_y$

Finding equilibrium along the x -, y - and z -directions with respect to the geometry shown in figures 4-7 and 4-8 yields the following three relationships for the aft hook vertical reactions and the reactions along the forward swaybrace rods:

$$S_{f,l} = S_{f,r} = \frac{M_y}{2(S_1 + L_2) \cos \alpha} \quad (114)$$

$$L_{a,z} = \frac{M_y}{S_1 + L_2} \quad (115)$$

For a pitching moment in the **negative** direction (nose down), the reactions will be in the aft swaybrace rods and the forward hook.

$$S_{a,l} = S_{a,r} = \frac{M_y}{2(S_2 + L_1) \cos \alpha} \quad (116)$$

$$L_{f,z} = \frac{M_y}{S_2 + L_1} \quad (117)$$

4.6.6 Interface Reactions Due to a Yawing Moment M_z at the Store CG

Figure 4-15 is the free body diagram for a **positive** yawing moment M_z at the store CG (nose left), showing the tensile reactions in both hooks and compressive reactions in the forward port and aft starboard swaybrace rods. When preloads are present, interface points may unload as a result of the loading at the store CG as also shown in figure 4-15.

FIGURE 4-15: REACTIONS AT SRI DUE TO YAWING MOMENT $+M_z$

Finding equilibrium along the x -, y - and z -directions with respect to the geometry shown in figures 4-7 and 4-8 yields the following six relationships for the vertical and lateral hook reactions and the forward port and aft starboard swaybrace rods:

$$S_{f,l} = \frac{M_z S_1}{[L_1 (L_1 + L_2) - S_1 (S_1 + S_2)] \sin \alpha} \quad (118)$$

$$S_{a,r} = \frac{M_z S_2}{[L_2 (L_1 + L_2) - S_2 (S_1 + S_2)] \sin \alpha} \quad (119)$$

$$L_{f,z} = \frac{M_z S_1}{[L_1 (L_1 + L_2) - S_1 (S_1 + S_2)] \tan \alpha} \quad (120)$$

$$L_{a,z} = \frac{M_z S_2}{[L_2 (L_1 + L_2) - S_2 (S_1 + S_2)] \tan \alpha} \quad (121)$$

$$L_{f,y} = \frac{M_z L_1}{[L_1 (L_1 + L_2) - S_1 (S_1 + S_2)] \sin \alpha} \quad (122)$$

$$L_{a,y} = \frac{M_z L_2}{[L_2 (L_1 + L_2) - S_2 (S_1 + S_2)] \sin \alpha} \quad (123)$$

For a yawing moment in the **negative** direction (nose right), the reactions in the hooks will be the same as equations (120) through (123). The swaybrace reactions will remain the same magnitude but now be located in the forward starboard and aft port swaybrace rods.

$$S_{f,r} = \frac{M_z S_1}{[L_1 (L_1 + L_2) - S_1 (S_1 + S_2)] \sin \alpha} \quad (124)$$

$$S_{a,l} = \frac{M_z S_2}{[L_2 (L_1 + L_2) - S_2 (S_1 + S_2)] \sin \alpha} \quad (125)$$

4.7 Generalized Reaction Equations at the SRI

The reactions at each interface point due to each load type as shown in the above equations represent the total magnitude of each reaction expected in the SRI while in a state of zero preload. However, some preload is present during all flight-testing and will generally be of sufficient magnitude to keep the interface points from ever reaching zero during typical flight maneuvers. As the store experiences external forces, opposing reactions will simultaneously load and unload equally to maintain equilibrium. In all six load cases, the four swaybrace rods will have a loading and unloading portion. For example, a positive pitching moment M_y will proportionally add to the forward swaybrace reactions while decreasing the aft swaybrace reactions; likewise, a positive

lateral load P_y will increase the reactions on the two starboard swaybrace rods while proportionally decreasing the port swaybrace rod reactions. The reaction due to a vertical load P_z must be split between the swaybrace rods and the hooks and is the only load case to do so. Similar to the swaybrace rods, the forward and aft lugs will split the reactions between loading and unloading portions due to a pitching moment M_y as well as the vertical reaction due to a longitudinal force P_x . The loads of P_y , M_x and M_z will be reacted in the lugs with the full magnitude of the calculated results, as there are no unloading counterparts within the lugs for these loads.

Although the reaction equations at each interface point were obtained from combining equations (98) through (125) via superposition and considering equilibrium modifications, specific equations at the SRI required knowledge of the direction of each load case. As shown in section 4.6, different equations are used and different interface points are affected depending upon what direction each load at the store CG is acting. However, assuming all loads at the store CG are acting in a positive sense and preloads are sufficient to maintain reactions at all interface points, the equations representing the SRI reactions were found as

$$S_{f,l} = \frac{1}{2} \left(\begin{aligned} & -\frac{P_x L_5}{2(L_2 + S_1) \cos \alpha} - \frac{P_y S_2}{(S_1 + S_2) \sin \alpha} + \frac{P_z S_2}{2(S_1 + S_2) \cos \alpha} - \frac{M_x}{2L_5 \sin \alpha} \\ & + \frac{M_y}{2(S_1 + L_2) \cos \alpha} + \frac{M_z S_1}{[L_1(L_1 + L_2) - S_1(S_1 + S_2)] \sin \alpha} \end{aligned} \right) + S_{f,l,preload} \quad (126)$$

$$S_{f,r} = \frac{1}{2} \left(\begin{aligned} & -\frac{P_x L_5}{2(L_1 + S_2) \cos \alpha} + \frac{P_y S_2}{(S_1 + S_2) \sin \alpha} + \frac{P_z S_2}{2(S_1 + S_2) \cos \alpha} + \frac{M_x}{2L_5 \sin \alpha} \\ & + \frac{M_y}{2(S_1 + L_2) \cos \alpha} - \frac{M_z S_1}{[L_1(L_1 + L_2) - S_1(S_1 + S_2)] \sin \alpha} \end{aligned} \right) + S_{f,r,preload} \quad (127)$$

$$S_{a,l} = \frac{1}{2} \left(\begin{aligned} & \frac{P_x L_5}{2(L_1 + S_2) \cos \alpha} - \frac{P_y S_1}{(S_1 + S_2) \sin \alpha} + \frac{P_z S_1}{2(S_1 + S_2) \cos \alpha} - \frac{M_x}{2L_5 \sin \alpha} \\ & - \frac{M_y}{2(S_2 + L_1) \cos \alpha} - \frac{M_z S_2}{[L_2(L_1 + L_2) - S_2(S_1 + S_2)] \sin \alpha} \end{aligned} \right) + S_{a,l,preload} \quad (128)$$

$$S_{a,r} = \frac{1}{2} \left(\begin{aligned} & \frac{P_x L_5}{2(L_1 + S_2) \cos \alpha} + \frac{P_y S_1}{(S_1 + S_2) \sin \alpha} + \frac{P_z S_1}{2(S_1 + S_2) \cos \alpha} + \frac{M_x}{2L_5 \sin \alpha} \\ & - \frac{M_y}{2(S_2 + L_1) \cos \alpha} + \frac{M_z S_2}{[L_2(L_1 + L_2) - S_2(S_1 + S_2)] \sin \alpha} \end{aligned} \right) + S_{a,r,preload} \quad (129)$$

$$L_{f,x} = L_{a,x} = \frac{P_x}{2} \quad (130)$$

$$L_{f,y} = \frac{M_x}{2L_5} + \frac{M_z L_1}{[L_1(L_1 + L_2) - S_1(S_1 + S_2)] \sin \alpha} \quad (131)$$

$$L_{a,y} = \frac{M_x}{2L_5} + \frac{M_z L_2}{[L_2(L_1 + L_2) - S_2(S_1 + S_2)] \sin \alpha} \quad (132)$$

$$L_{f,z} = \frac{P_x L_5}{2(L_1 + S_2)} + \frac{P_y L_2}{(L_1 + L_2) \tan \alpha} - \frac{P_z L_2}{2(L_1 + L_2)} + \frac{M_x}{2L_5 \tan \alpha} \\ - \frac{M_y}{2(S_2 + L_1)} + \frac{M_z S_1}{[L_1(L_1 + L_2) - S_1(S_1 + S_2)] \tan \alpha} + L_{f,z,preload} \quad (133)$$

$$L_{a,z} = -\frac{P_x L_5}{2(L_2 + S_1)} + \frac{P_y L_1}{(L_1 + L_2) \tan \alpha} - \frac{P_z L_1}{2(L_1 + L_2)} + \frac{M_x}{2L_5 \tan \alpha} \\ + \frac{M_y}{2(S_1 + L_2)} + \frac{M_z S_2}{[L_2(L_1 + L_2) - S_2(S_1 + S_2)] \tan \alpha} + L_{a,z,preload} \quad (134)$$

4.8 Program to Calculate Reactions at the SRI

A FORTRAN program was created to calculate the SRI reactions at each time step using all necessary equations as derived and listed throughout Chapter 4; a complete printout is included in appendix A. The program can be used with ground or flight testing, as all necessary data must be entered for each test. The program requires the following information: the physical parameters of the store, including weight, radius, accelerometer layout, CG, moment of inertias, etc.; the store and aircraft aerodynamic

parameters; the raw accelerometer data; and the preflight preloads at the SRI. A list of all read and written parameters is included with the program in appendix A. The model was modified and verified with ground and flight test data as discussed in chapters 5 and 6, respectively, of this research.

Once all of the necessary data was entered into the program, the translational and rotational accelerations at the store CG were found with equations (25) – (27) and equations (31) – (33), respectively. Inertial forces and moments at the store CG were then calculated with equations (55) and (56), respectively; aerodynamic forces may be added later with equations (61). The reactions at the SRI were found using superposition via the equations derived in section 4.6. Finally, the hook and swaybrace rod reactions were saved to data files for review and graphing.

4.9 Chapter 4 Summary

This chapter used a classical analysis to develop a methodology to calculate the reactions at the SRI using only accelerometer data and geometry and without the need for fragile, costly strain gages. The translational (equation 25 – 27) and rotational (equations 31 – 33) accelerations were found at the store CG using raw accelerometer data recorded around the surface of the store. The equations required for the inertial force (equations 55) and moment (equations 56) calculations at the store CG were derived dynamically using the calculated accelerations and integrated rates with Newton's Laws, kinetics of rigid bodies in three dimensions and the simplified Euler's Equations of Motion. Aerodynamic loads were discussed in section 4.4 but not incorporated in the present data analysis, thereby limiting this discussion to high inertial load cases only. If aerodynamic forces were available, they would be added to the inertial forces creating an overall load state as shown in equations (92) through (97).

The final store CG loads calculated in this analysis were distributed to the six interface points and the reactions calculated via the principle of superposition in equations (98) through (125). Due to the statically indeterminate nature of the SRI, the reactions could not be completely resolved based only on the equations of equilibrium from the free body

diagram. Consequently, assumptions and geometric similarities were incorporated and will be evaluated using experimental data in the next chapter. Finally, a FORTRAN program was written to incorporate all of the necessary equations with accelerometer data, preload measurements and geometry to calculate the complete loading and unloading reactions at the SRI.

EXPERIMENTAL METHODS & ANALYSIS: GROUND TEST

Various experimental procedures were required to collect the ground and flight test data and validate the derived reaction equations. After solving for the theoretical equations in chapter 4, the first stage of the experimental investigation was to develop and conduct a ground test to verify the distribution of loads at the store CG to the six SRI points due to inertial loads only. The ground test data would therefore validate the original assumptions in the SRI reaction equations or support empirical modifications.

5.1 Static Ground Test Setup

For the static ground test, a rigid test cell was assembled in Hangar 101 at NAWCAD. A MK 84 bomb body with a conical tail fin was mounted on a BRU-32 affixed to steel I-beams. Large, rigid beams were used to ensure that no flexibility would be present in the testing apparatus. Additional lugs were welded at various locations on the MK 84 and cables attached to hydraulic presses applied loads to the store via the new lugs. The locations of the welded lugs were based on specified distances from the store CG, which was determined by prior mass properties testing of the store at the Strike Ordnance complex at NAWCAD. Loads were applied at these various lug locations to mimic inertial loads through the CG, creating known force and moment combinations. Loads data were recorded, as well as strain gage data from instrumented lugs and swaybrace assemblies, and reduced into reaction forces.

5.1.1 Mass Properties Measurements

After the lugs were welded and the store was ready for testing, the mass properties of the MK 84 were found at the Firing Tunnel Complex at the Strike Aircraft Division of NAWCAD. The weapon was placed on a mass property table developed by Space Electronics, Inc., Model KSR6000, shown in figure 5-1. The KSR6000 can measure weight, CG and moments of inertia (MOIs) simultaneously.

FIGURE 5-1: MASS PROPERTY SYSTEM; SPACE ELECTRONICS KSR6000

A special cradle for the MK 84 was placed on the mass property table, which was then calibrated and reset to zero. The MK 84 was placed in the cradle with the lugs facing up and the store weight was measured. The values for CG_x , CG_z and I_{zz} were found by the system through computer-controlled, left to right oscillations which calculated the mass properties based on the mass, accelerations, etc. The store was then rotated by hand 90° around the longitudinal axis so that the lugs faced to the side and the process was repeated, solving for CG_x , CG_z and I_{yy} . The final task was to stand the store vertically on its tail and repeat the process once last time, solving for CG_y , CG_z and I_{xx} . The final mass properties of the MK 84 with welded lugs are shown in table 5-1. CG offsets are with respect to the center of the forward standard lug on the upper surface of the MK 84.

TABLE 5-1: MASS PROPERTIES OF MK 84 WITH CONICAL FIN

<i>Parameter</i>	<i>Value</i>
Weight	1,975 lb.
CG_x offset	14.4 in.
CG_y offset	0.16 in.
CG_z offset	-8.84 in.
I_{xx}	18.7 Slug-Ft ²
I_{yy}	374.9 Slug-Ft ²
I_{zz}	374.5 Slug-Ft ²

5.1.2 MK 84 Instrumentation

Six lugs were welded to the bomb body; three on each side of the store and vertically centered on the longitudinal axis. One lug on either side of the MK 84 was located at the store CG_x and CG_z intersection and the remaining two lugs per side were symmetrically placed 36-inches forward and aft of this point. Each lug weld was rated for a minimum 10,000 lbs. of shear or tensile load and was attached perpendicular to the CG axes vice normal to the local store surface. Figure 5-2 shows a typical welded lug on the MK 84.

FIGURE 5-2: WELDED LUG ON MK 84 FOR PULL TEST

Loads were applied to the welded lugs via braided steel cables. To simulate single axis loading or specific force-moment couples, one or more lugs were loaded simultaneously with one or more hydraulic hand pumps (figure 5-3). Spreader bars were used to symmetrically load two lugs simultaneously using only one pump when necessary.

FIGURE 5-3: HYDRAULIC PUMPS FOR PULL TEST

The BRU-32 was also fully instrumented; strain gages were installed on the lugs and the swaybrace assemblies. Data were captured on an Astro-med computer system at 100 samples per second (sps) during all tests and saved digitally and on strip charts. Figure 5-4 shows the MK 84 and the instrumented rack attached to the I-beam. Figure 5-5 shows the Astro-med, various computers and the data collection system.

FIGURE 5-4: INSTRUMENTED RACK DURING PULL TEST

FIGURE 5-5: COMPUTER SYSTEM FOR PULL TEST

Multiple load cells and systems were required to apply and record the loads being applied from the multiple hydraulic pumps. Loads were recorded and tracked with the voltmeters shown in the right of figure 5-5 and a typical load cell is shown in figure 5-6; appendix B contains the complete load cell specifications. Figure 5-6 also shows a typical block setup to attach the load cell to a welded lug and the necessary wiring to record loads data.

FIGURE 5-6: TYPICAL LOAD CELL FOR PULL TEST

5.1.3 Steel Beam Test Cell for Ground Pull Test

The MK 84 and BRU-32 were attached to a rigid, steel I-beam test cell to provide a foundation for the test loads. The I-beams were assembled at Hangar 101 at NAWCAD with a forklift and fastened together with 1-inch bolts and doubler plates. A total of eighteen 10-foot beams, seven 20-foot beams and two 8-foot beams were used in the construction. The complete test cell with MK 84 in place is shown in figures 5-7 and 5-8.

5.1.4 Ground Pull Test of MK 84 and BRU-32

After the instrumented BRU-32 was attached to the I-beams, the MK 84 was attached to the BRU-32 via standard USN ordnance loading procedures. Swaybrace rods were in extended position and not additionally tightened. Real-time loads data were captured at all test points at 100 sps, as well as voltage and reaction data from the four instrumented swaybrace rods and two instrumented lugs. The Test Article Preparation Group at NAWCAD calibrated all equipment before testing and after each load case.

5-7: TEST CELL FOR MK 84 GROUND PULL TEST, FRONT VIEW

FIGURE 5-8: TEST CELL FOR MK 84 GROUND PULL TEST, SIDE VIEW

Before each test point, a settling load of 2,500 lb. was applied to remove any slack in the instrumentation, cables or rack. A load matrix of eight test points was prepared for the test and is shown in table 5-2. Test point 6 shows a combined load point whereas all other load cases were attempts at pure force conditions through the store CG. During each test point, all load cases applied a consistent load to the store from 0 lbs. to the maximum of 10,000 lbs. (equivalent to approximately 5 Gs of translational acceleration) and back to 0 lbs. again. For the load cases requiring the use of two hydraulic pumps, only 5,000 lbs. was applied from each pump. Also, as both pumps increased in load output, the load values were monitored using the voltmeters to allow consistent and symmetric buildup on the welded lugs.

TABLE 5-2: LOAD MATRIX FOR MK 84 GROUND TEST

<i>Test Point</i>	<i>Simulated Load Case</i>
1	+F_x
2	+F_y
3	+F_z
4	-F_z
5	-M_x
6	-F_y, +M_y, +M_z
7	+M_y
8	+M_z

Load case 1 simulated a pure longitudinal force at the store CG. This test point required loading the store CG directly along the x-axis. Two hydraulic pumps each applied 5,000 lbs. of force simultaneously to the two, middle welded lugs located symmetrically on the sides of the store. Figure 5-9 shows the setup for this load case.

Load case 2 consisted of a pure lateral pull of 10,000 lbs. through the store CG via one of the middle, welded lugs. Figure 5-10 shows this pull from the starboard side of the store.

FIGURE 5-9: MK 84 GROUND TEST LOAD CASE 1–LONGITUDINAL PULL

FIGURE 5-10: MK 84 GROUND TEST LOAD CASE 2 – LATERAL PULL

Load case 3 consisted of a pure vertical pull of 10,000 lbs. upward through the store CG. One hydraulic pump was connected to a spreader bar over the store CG that in turn was connected to the two middle, welded lugs. The full load was spread equally between the two lugs, pulling on each with 5,000 lbs. of force. Figure 5-11 shows this pull, although only the starboard-side vertical cable can be seen. A port side vertical pull is also present, symmetrically attached to the opposite side of the spreader bar overhead.

FIGURE 5-11: MK 84 GROUND TEST LOAD CASE 3 – VERTICAL PULL UP

Load case 4, similar to load case 3, applied a 10,000 lb. downward force through the store CG using the two middle welded lugs and a spreader bar with one hydraulic pump. Figure 5-12 shows the setup for this load case, looking aft below the store.

FIGURE 5-12: MK 84 GROUND TEST LOAD CASE 4 – VERTICAL PULL DOWN

Load case 5 modeled a pure moment about the longitudinal axis (M_x) by simultaneously pulling up with 5,000 lbs. on the middle lug on the starboard side of the store and pulling down on the middle lug on the port side of the store. Two separate hydraulic pumps were used and monitored during this test. Figure 5-13 shows both load cells for load case 5.

FIGURE 5-13: MK 84 GROUND TEST LOAD CASE 5 – ROLL MOMENT

As can be seen in figure 5-14, load case 6 was the only combined load to be modeled. A hydraulic pump and spreader bar were used to pull the nose upward with 5,000 lbs. of force using the two forward, welded lugs. An additional 5,000 lb. lateral load was applied to the middle, welded lug on the port side. The two external loads were monitored with voltmeters for a symmetric buildup.

FIGURE 5-14: MK 84 GROUND TEST LOAD CASE 6 – COMBINED LOAD

Load case 7 modeled a pure moment about the lateral axis (M_y) by simultaneously pulling up with 5,000 lbs. on the two forward, welded lugs via a spreader bar while also pulling down on the two aft, welded lugs via another spreader bar. Both sets of lugs are symmetrically located about the store CG. Two separate hydraulic pumps were again used for this load case and load buildup was monitored via the voltmeters to allow consistent loading. Figure 5-15 shows the setup for this load case.

FIGURE 5-15: MK 84 GROUND TEST LOAD CASE 7 – PITCH MOMENT

The final load case is shown in Figure 5-16. Load case 8 is a model of a pure moment about the vertical axis (M_z) by simultaneously pulling laterally with 5,000 lbs. of force on the aft welded lug on the port side of the store while pulling in the opposite direction with an equal load on the forward welded lug on the starboard side of the store. Two separate pumps and voltmeters were used for this load case.

5.2 Static Ground Test Data Analysis

Before the test cases were conducted, the distances from the CG of the MK 84 to the SRI interface points and the six welded lugs were measured. Table 5-3 summarizes the various distances from the store using the sign convention presented earlier. The lugs were not exactly on the CG lines but as close as possible.

FIGURE 5-16: MK 84 GROUND TEST LOAD CASE 8 – YAW MOMENT

TABLE 5-3: INSTRUMENTATION GEOMETRY OF MK 84 AND CONICAL FIN

<i>Hardware</i>	<i>Distance from Store CG (in.)</i>		
	<i>x-axis</i>	<i>y-axis</i>	<i>z-axis</i>
Forward Port Swaybrace	-9.40	-2.12	6.95
Forward Stbd Swaybrace	-9.40	2.12	6.95
Aft Port Swaybrace	10.60	-2.12	6.95
Aft Stbd Swaybrace	10.60	2.12	6.95
Forward Lug	-14.40	0.00	8.60
Aft Lug	15.60	0.00	8.60
Welded Lug 1 (Port, Fwd)	-36.00	-8.63	0.38
Welded Lug 2 (Port, Mid)	0.00	-11.00	0.00
Welded Lug 3 (Port, Aft)	36.00	-10.38	-0.38
Welded Lug 4 (Stbd, Fwd)	-36.00	8.63	0.38
Welded Lug 5 (Stbd, Mid)	0.00	11.00	0.00
Welded Lug 6 (Stbd, Aft)	36.00	10.38	-0.38

5.2.1 Measured Ground Test Data

Two modified lugs were instrumented with 5 strain gage circuits as shown in figure 5-17; each lug contained one internal, proprietary circuit from StrainSert, Inc. measuring vertical reaction and four external circuits. The external gages were manufactured by Vishay and consisted of three shear circuits (model number EA-06-125TR-350) and one bending circuit (model number CEA-06-250UN-350). All circuits were self-temperature-compensated (STC) for steel with a nominal resistance of 350 ohms.

FIGURE 5-17: MK 3 Mod 0 LUG WITH STRAIN GAGE INSTRUMENTATION

The four swaybrace rods were also instrumented with Vishay strain gage circuits (model number CEA-06-062UT-350) as shown in figure 5-18; these gages were STC for steel with 350 ohms resistance. The gages on each rod were connected in four-circuit bridges (figure 5-19) to eliminate bending load and friction measurements via cancellation of terms. Specifications for each type of strain gage circuit are included in appendix B.

Although the swaybrace rod is threaded into the swaybrace assembly (figures 3-2 and 3-10), the rod is either engaged in a fully extended or fully retracted position; for stores with 30-inch lug spacing, the swaybrace rods are typically set in the fully extended position. Generally, once in this position, the rod is not additionally tightened or torqued further after the store is loaded in the rack. During some flight test programs, the rods will be set to a certain preload after loading (generally 1,000 lbs. each) if an initial preload is necessary for the program, though it is not usually required.

FIGURE 5-18: SWAYBRACE ROD WITH STRAIN GAGE INSTRUMENTATION

FIGURE 5-19: STRAIN GAGE BRIDGE DESIGN

Each rod was fitted into a ball-and-socket pad that was in contact with the store as shown in figure 5-20. As with all ball-and-socket joints, moments could not be reacted in the swaybrace rods.

For each load case listed in table 5-2, the buildup to the maximum external load was accomplished in two to three minutes while unloading took an average of less than 30 seconds. During the test, the data from the lug and swaybrace strain gages were recorded in millivolts at 100 sps. Reduced data output files for each load case were included in appendices C through F showing data from a total of 21 evenly spaced points per load case. Appendix C contains the external loads applied to the store during each load case by one or more actuators and calculations of the resulting forces and moments at the store CG. Appendix D contains the raw strain gage data recorded for all five gages per lug per time step, while the strain gage data for the swaybrace rods was included in appendix E.

FIGURE 5-20: BALL-AND-SOCKET PAD FOR SWAYBRACE ROD

The swaybrace gage data were combined in the bridge shown in figure 5-19 and recorded as one overall strain reading per swaybrace per time step. The lug strain data, when considered versus total external force, defined the linearity and sensitivity of each gage to the particular load type and was useful in determining which gages were to be included for the reaction force calculations. Figure 5-21 provides an example of the strain output for Ground Test Load Case 1 showing data from the five strain gages on the forward lug.

FIGURE 5-21: FORCE VERSUS STRAIN FOR LOAD CASE 1; FORWARD LUG

The raw strain data from the instrumented lugs and swaybrace rods were combined and converted to the reaction data for each interface point. The tables of forces representing the measured lug and swaybrace reactions derived from raw strain data are included in appendix F. The reaction forces shown are the actual reactions at each time step and therefore contain any preload in the interface points before the external load was applied. Preloads for each load case for the lugs and swaybrace rods are shown in table 5-4. Lug preloads were calculated using the recorded swaybrace preload data and weapon weight.

TABLE 5-4: MK 84 GROUND TEST PRELOAD DATA – ALL LOAD CASES

Test Load Case	Swaybrace Rods (lbs.)				Lugs (lbs.)			
	Forward		Aft		Forward		Aft	
	Port	Stbd.	Port	Stbd.	Vert.	Lateral	Vert.	Lateral
1	-185	-382	-336	-200	1,564	1,466	41	-24
2	-405	-542	-336	-200	1,867	1,526	27	-26
3	-106	-790	-322	-213	1,826	1,517	161	7
4	-810	-1,678	-349	-186	3,095	1,771	204	3
5	-1,154	-1,705	-270	-213	3,382	1,788	132	13
6	-2,149	-3,117	-209	-140	5,279	2,065	233	30
7	-2,474	-3,090	0	0	5,461	1,835	150	30
8	-1,964	-3,064	-270	-186	5,106	2,113	264	33

Notes: 1. For swaybrace rods: Negative values are compressive reactions along the axis of the rod
2. For lugs: Positive vertical preloads are tensile reactions; Positive lateral preloads are starboard reactions
3. Preload values include contribution of weapon weight

5.2.2 Calculated Ground Test Data Analysis

Using equations (98) through (125), the interface reactions were calculated based on the known preloads, external loads, mass properties and geometry of the store and instrumentation. The calculations were completed with the FORTRAN program created for this research and included as appendix A. This program incorporates the equations outlined in chapter 4 for converting store accelerations into forces and moments and distributing the forces and moments from the store CG to the SRI. Tabular results of the FORTRAN reaction calculations for the reduced data series are shown in appendix G.

5.3 Model Verification with Ground Test Data

The reaction data in the lugs along the longitudinal axis did not show an equal split between the lugs due to a longitudinal load as was assumed in equations (98). Using the measured data, it was calculated that, on average, 38.5% of the longitudinal load was reacted by the forward lug while 60.6% of the data was reacted by the aft lug. The remaining 0.9% of longitudinal load was attributed to a bending reaction in the swaybrace rods which was not recorded due to the circuit design. The longitudinal lug reactions due to a longitudinal force P_x (equations 98) were corrected to

$$L_{f,x} = 0.385(P_x) \quad (135)$$

$$L_{a,x} = 0.606(P_x) \quad (136)$$

During the buildup of the external load, the interface points reacted the load and other areas would unload a stored reaction as predicted. It was noted, however, that during a lateral external force P_y the two swaybrace rods opposite those reacting in compression did not unload but held the preload as a constant value. Also, the assumption of the swaybrace rods reacting the entire lateral portion of the lateral load and the lugs not reacting in a lateral response proved to be correct.

One point not predicted with the classical analysis was the reaction of the swaybrace rods due to a yawing moment about the vertical z -axis. The data in appendix G showed that a positive yawing moment (nose left) was laterally reacted in the forward lug in the starboard direction and in the port direction for the aft lug as predicted, although higher in magnitude. The forward starboard and aft port swaybrace rods reacted in compression, however, instead of the assumed reactions in the forward port and aft starboard swaybrace rods. Since the store is a rigid body and much more so than the bomb rack itself, it was determined that the rack was twisting into the opposite swaybrace rods creating the unpredicted reactions. Due to the unusually high yawing moment imposed for this test, this behavior has not been seen, or at least not been recognized, before. The equations were corrected to allow the full yawing moment to be reacted by the lugs while the opposite swaybrace rods were given a very small and empirically determined amount

of reaction due to rack twist based on the amount of lug reaction. For a positive yawing moment M_z , equations (118) through (123) were revised based on this data as

$$S_{f,l} = S_{a,r} = 0 \quad (137)$$

$$S_{f,r} = S_{a,l} = \frac{4M_z}{(L_1 + L_2)^2 \sin \alpha} \quad (138)$$

$$L_{f,z} = L_{a,z} = \frac{M_z}{(L_1 + L_2) \tan \alpha} \quad (139)$$

$$L_{f,y} = L_{a,y} = \frac{M_z}{(L_1 + L_2)} \quad (140)$$

For a negative yawing moment (nose right), equations (124) and (125) were similarly corrected to

$$S_{f,r} = S_{a,l} = 0 \quad (141)$$

$$S_{f,l} = S_{a,r} = \frac{4M_z}{(L_1 + L_2)^2 \sin \alpha} \quad (142)$$

The SRI reactions to the externally applied load during buildup, while all interface points still contained preload, was reduced to allow half of the predicted reaction to go towards the reacting points (increasing in load) and half to go to the respective unloading points. Unlike actual flight tests, however, the dominance of the one specific load type in each ground test load case quickly overpowered the preloads and was fully reacted by the necessary points. The equilibrium adjustment shown by example in equations (126) through (134) was only necessary until all of the unloading reactions went to zero and the reactions to the applied load were born by the interface points already increasing in load.

Appendix H contains overlay graphs of the measured and calculated reactions for all eight load cases. Three graphs showing the reactions in the forward and aft swaybrace assemblies and the vertical lug represent each load case. Additionally, load case 1 shows

the only occasion the lugs react longitudinally as it is the only test case with an external longitudinal load. The reaction distribution of approximately 38.5% and 60.6% of the external load to the forward and aft lug, respectively, can also be seen in figure 5-22. The total applied force for load case 1 was approximately 10,000 lb. in the aft direction.

FIGURE 5-22: LUG LONGITUDINAL REACTIONS FOR LOAD CASE 1

Additional graphs in appendix H show the only two load cases where the lugs react laterally. Figure 5-23 shows the lateral lug reactions to an applied M_x in load case 5.

FIGURE 5-23: LUG LATERAL REACTIONS FOR LOAD CASE 5

Figure 5-24 shows the lateral lug reactions in response to the approximately 360,000 in-lb. yawing moment in load case 8. It can be seen in figure 5-24 that the lugs react very symmetrically and linearly as predicted, reaching a much larger reaction than shown in figure 5-23 due primarily to a doubling of the externally applied moment.

FIGURE 5-24: LUG LATERAL REACTIONS FOR LOAD CASE 8

Appendix H shows that the lug reactions were primarily linear in response, especially in the critical high load areas. This matches previous testing which showed linearity in the response of the hook/lug reaction.⁵ The results of flight testing presented in reference 5 verified that a longitudinal load would be unevenly reacted between the lugs and was supported by this research.

5.4 Chapter 5 Summary

This chapter focused on the static ground test conducted to uncover the true distribution equations relating loads at the store CG to the six points in a SRI. A MK 84 instrumented with welded lug attachment points allowed external loads to be applied to the store to simulate pure forces and moments at the store CG. Collected test data included strain gage output from 42 gages affixed to the lugs and swaybrace rods in the bomb rack. The applied forces were also collected with respect to time. Test points included eight different load cases, including forces through the store CG along the x -, y -, and $\pm z$ -axes,

moments along the three axes and one combined load case. The final, measured data was reduced to 21 point sets for each load case, 10 points during build up and 10 points during the unload in addition to the point of maximum applied load, for ease of comparison and calculation.

The swaybrace assemblies by design can not react in tension and the lugs cannot react in compression, yet both can unload and reduce the current load state. The corrections to the reaction equations to allow concurrent loading and unloading reactions until the unloading reaction reached zero matched well with observation. The direct solving of a full set of loading and unloading equations was impossible due to the parallel nature of the loads and reactions and an indeterminate system of equations.

The FORTRAN program created to calculate the interface reactions using the equations developed in chapter 4 was corrected based on the above observations; predicted results generally matched the measured reactions, with a few exceptions. It was noted that the only axial reaction exhibited by the lugs was in the presence of a longitudinal load, but the reaction was not evenly split. The forward lug carried 38.5% of the total longitudinal load while the aft lug reacted over 60%. The lugs reacted laterally only during the application of roll and yaw moments as seen in load cases 5 and 8, respectively. The swaybrace rods reacted differently than predicted during the application of a yaw moment, although the reactions were quite low and were due to a twisting of the bomb rack. Most of these variations in reaction were shown to be possible in reference 5, which also stated deflections in the pylon would not noticeably affect lug reactions. This does not predict the twisting of the rack as proposed in this research, but does show that structural problems might occur regardless of the rigidity of the store being tested.

Unlike flight-testing where multiple load combinations on the store are always present, a single dominant load in one direction was unique to this ground test. With the exception of load case 2, each load case completely diminished the preloads in the unloading interface points very quickly and the reacting points would bear the entire load. During the ground test, this was seen in the initial swaybrace rod reactions and in the vertical lug

reactions as predicted in chapter 4. Calculated and measured data showed high correlation as reaction slopes typically increased early into the applied load buildup.

As this analysis focused on the high-reaction loads and results, SRI reactions near zero were negligible. The maximum reaction magnitudes acceptable during flight-testing are currently approximately 20,000 lb. and 50,000 lb. per swaybrace rod and vertical lug, respectively, although the ultimate loads for both interface points are much higher. To quantify error observations, it was decided that the critical reaction points for this research would be any reaction equal to at least 10% of the maximum reaction magnitude for flight-testing. To that end, reactions below 2,000 lbs. in the swaybrace rods and 5,000 lbs. in the vertical lugs were considered to be in the noise of the data and consequently neglected in the final error analysis.

EXPERIMENTAL METHODS & ANALYSIS: FLIGHT TEST

Flight-testing was used to validate the overall inertial model of the SRI reactions. The analytical models of inertial forces at the store CG found in chapter 4 via Newton's Second Law and Euler's equations were first verified with the accelerations found from store instrumentation data. The SRI interaction relationships were derived empirically by modeling the SRI reaction equations found via the ground test and comparing the expected results with actual flight test data from carrier suitability flight testing. Aerodynamic loads immediately after an arrestment or catapult were considered negligible when compared to the inertial forces at this same time. Assuming typical arrestment airspeed of 150 knots (approximately 250 ft/sec), the dynamic pressure at sea level is approximately $\frac{1}{2}$ psi. Assuming a reference area of 165 in^2 for the GBU-24 cross-section, the aerodynamic load is approximately 80 lb. Compared to nominal landing accelerations immediately after arrestment of approximately 8Gs and -2Gs in the vertical and longitudinal directions, respectively, the percent of total load attributed to aerodynamics for a 2,000 lb. class store is approximately $\frac{1}{2}\%$ and 2% respectively.

Once reasonable inertial reaction predictions were found, aerodynamic components could be added to the equations with the results compared to actual up-and-away flight test data. Due to a lack of the required flight test data, the equations were only developed for inertial load predictions although the aerodynamic theory was discussed and explored.

6.1 Arrestment Flight Test

As only the predictions of the worst case interface loads were necessary, data for larger, heavier stores were desired. Therefore, this research only considered a 2,000-lb. class store, the largest store class, with 30-inch lug spacing. Smaller stores have inherent problems due to radius and were not examined here.^{50,51} Flight test data were available for carrier suitability testing of a GBU-24 on an F-14 aircraft. Rigid body assumptions were possible, as the tested GBU-24 consisted of a BLU-109 bomb body; the BLU-109

has a store diameter and wall thickness of 14.5” and 1.125,” respectively, and is approximately 14 feet long.⁵⁹

For the required equations of motion as derived in chapter 4 and corrected in chapter 5, data collection was dependent on the accelerometer data and locations. The GBU-24 flight test program incorporated ten servo-accelerometers on the store. These accelerometers were selected to perform in the frequency range optimal for store analysis with 100G amplitude. The store/rack/pylon assembly natural frequency is typically in the 20Hz – 40Hz range and generally always less than 60Hz. The store itself, being much stiffer, has natural frequencies of vibration much higher than that of the assembly. Detailed specifications for the accelerometers are provided in appendix B.

Accelerometers are generally placed on orthogonal blocks vice directly on the store, allowing all of the acceleration vectors to line up in one of the three orthogonal axes and not have to be individually corrected. Typically at least one block per store will contain three accelerometers, one operating along each of the three axes. If this triaxial accelerometer block is located in a plane intersecting the store CG, typically on the port or starboard side of the store, the cross-over effect between accelerations is minimized; the acceleration equations (25) through (27) are therefore less complicated.

Experience has shown that the accelerometers placed on the less rigid tail and nose sections of a GBU-24 are more difficult to align, calibrate and obtain accurate information than those placed directly on the rigid BLU-109 portion of the GBU-24. Additionally, the nose and tail sections also have an inconsistent geometry when compared to the main section of the BLU-109 bomb body, requiring geometric corrections when used with the remaining six accelerometers. Therefore, the six accelerometers on the main body of the GBU-24 were used solely for the calculations and predictions in this research. A triaxial accelerometer group located longitudinally at the store CG also allowed ease in translational acceleration calculations with minimal coupling effects from other motions or accelerations along or about other axes. The mass properties of the GBU-24 were presented in table 3-1 of this report. The physical characteristics of the GBU-24 with a BLU-109 bomb body are shown in figure 6-1, as

well as the accelerometer placement used for flight-testing. The two lugs at 30-inch spacing are also shown as a reference.

FIGURE 6-1: GBU-24B/B WITH ACCELEROMETERS

In similar experimental flight testing, reference 48 tested a 2,000-pound class weapon on several aircraft. The inertial load envelope of the store for captive flight found in reference 50 was proven to be very accurate in estimating inertial point loads for these tests. Swaybrace preload values ranged from 1 lb. to 2,500 lbs.; hook preload was calculated from swaybrace preload and store weight. For flights pulling negative G_s in the z -direction, lateral loads on the hooks weren't zero as expected but generally remained less than 5% of the vertical load. The lateral hook load also averaged approximately 5% of vertical load for negative lateral loads in combination with positive M_z , while averaging less than 2% for other load combinations. These data were recorded during a variety of flight tests, including captive carriage, catapults and arrestments.⁴⁸ Reference 5 also showed that in similar large store testing, flutter and frictional effects

are negligible. There is sufficient dynamic response during a typical flight environment, due primarily to vibrations, to eliminate any frictional loads and preloads in the SRI.⁵

6.2 Arrestment Flight Test Data and Analysis

The flight test chosen for data collection was a typical arrestment flight verifying the capability of the F-14 to carry the GBU-24. Accelerations just prior to through just after the arrestment were recorded; the x - and z -accelerations at the triaxial accelerometer block are shown in figure 6-2. The data plot provides the approximate time of the initial arrestment as well as when the inertial loads have been significantly dampened, allowing a minimal time interval for data analysis.

FIGURE 6-2: ACCELERATIONS FOR F-14/GBU-24 DURING ARRESTMENT

To keep the inertial loads at least 95% of the total load on the store and consequently neglect aerodynamic loads, as well as capture all of the peaks in the accelerations, the time immediately after arrestment, between 43.80 and 44.10 seconds, was chosen for this research. Figures 6-3 and 6-4 show the acceleration data from the six accelerometers on the BLU-109 bomb body during that time span. The instrumentation includes: x -, y - and z -accelerometers on the starboard side of the store in the x - z plane intersecting the store CG; y - and z -accelerometers on the starboard side of the store, forward but on the vertical

axis of the store CG; and a z-accelerometer on the port side of the store on the vertical and longitudinal axes of the store CG. All accelerometers were placed above the store surface on 0.87” thick orthogonal blocks; the instrumentation has an effective diameter of approximately 16.24” vice the store diameter of 14.5”.

FIGURE 6-3: X- AND Y-ACCELERATIONS FOR F-14/GBU-24

FIGURE 6-4: Z-ACCELERATIONS FOR F-14/GBU-24

The six accelerations shown in figures 6-3 and 6-4 were then used to find the forces and moments at the store CG using equations (55) and (56). The FORTRAN program used

for ground test data calculations (appendix A) was modified to accept the accelerometer flight-test data and calculate the forces and moments at the store CG prior to the SRI reactions. The translational and angular rates used in these equations to calculate accelerations were integrated between each pair of timesteps. The F-14 flight test team had USN accepted programs used in a post-flight analysis to accurately calculate forces and moments at the store CG. These calculations were used to validate the calculations in the FORTRAN program. Figures 6-5 through 6-7 show the post-flight calculations of forces at the CG of the GBU-24 compared to the predicted values of this research.

FIGURE 6-5: P_x COMPARISON AT STORE CG FOR F-14/GBU-24

FIGURE 6-6: P_y COMPARISON AT STORE CG FOR F-14/GBU-24

FIGURE 6-7: P_z COMPARISON AT STORE CG FOR F-14/GBU-24

Figures 6-8 through 6-10 show the post-flight calculations of moments at the CG of the GBU-24 compared to the predicted values of this research. The predicted moment values have approximately the same accuracy as seen in the force calculations. The moment magnitudes, however, are much higher and more sensitive to geometry, etc.

FIGURE 6-8: M_x COMPARISON AT STORE CG FOR F-14/GBU-24

FIGURE 6-9: M_y COMPARISON AT STORE CG FOR F-14/GBU-24

FIGURE 6-10: M_z COMPARISON AT STORE CG FOR F-14/GBU-24

Figures 6-3 through 6-10 show the dynamic nature of the arrestment and the violent inertial loads the GBU-24 was experiencing under the F-14 aircraft. Within a few hundred milliseconds, accelerations near +9 Gs and -5 Gs created forces and moments of approximately 15,000 lbs. and 150,000 in-lbs, respectively. Once the inertial load calculations were completed, the FORTRAN program used the information to predict the reactions at the SRI. As with the ground test data, preload values must be used to accurately predict interface reactions. For this project, preloads were measured and

known. Unfortunately, in a real-time flight test environment with only accelerometers on the store, real-time preload information will not be available. Although the ambient conditions prior to arrestment, as the aircraft settled in for the approach, were generally near steady state, 1 G flight, the total load state including aerodynamic effects was still approximately 0.2 Gs vice 0.0 Gs and 1.1 Gs vice 1.0 G in the x - and z -directions, respectively. This imbalance caused some SRI points to have an increased reaction and others a decreased reaction. As the total load case will not be known in an uninstrumented flight, even the correct calculation of aerodynamic loads during this time will not allow computation of the preload values. Figure 6-2 showed the approximate ambient accelerations prior to the arrestment; however, a baseline will be established.

As errors in preloads can lead to inaccuracies in the interface reaction calculations, careful consideration must be given to their estimation. Fortunately, past preload data has shown that for similar flight tests, historical averages can be used without inducing large errors since preload values are at least an order of magnitude less than the total reactions observed at the peak accelerations. The *percentage* errors at low reactions may be large if preloads are used incorrectly, but the results at those levels are not critical.

Additionally, the swaybrace rods are generally in the extended position for all stores with a 30-inch lug spacing, yielding approximately the same preload given the same store weight. Flight maneuvers, however, effect preload by redistribution until the reactions have a chance to settle and return to steady state conditions within the dynamic environment.

Finally, when preload estimation is deemed critical, specialized swaybrace rods may be used that allow use of a torque wrench. These swaybrace rods, once set in place and the store loaded in the rack, may be additionally torqued to an arbitrary, initial setting (typically 1,000 lb. each). The magnitude of the steady state preload may change after completion of each flight maneuver, but as normal, steady state flight is resumed the swaybrace and lug preloads will typically redistribute to values near to their original settings. Using an average preload based on empirical data, any errors present will generally be even less than an order of magnitude smaller than the peak reactions.

6.3 Model Verification with Flight Test Data

The FORTRAN program was again used to calculate the six interface reactions at each time step and graphs were created comparing the results to the reactions directly measured by the instrumented rack. Unlike the ground test points involving loads in a single direction, the flight test points were composed of combined load cases and the interactions between the various directions of loads were examined.

For this test, constant preloads were known from the measured data and were entered directly into the analysis. The FORTRAN program in appendix A was modified to divide each reaction into the contributing components before they were combined by superposition. The breakdown allowed the interaction of the various, directional load types to be seen to allow for better data predictions if necessary. Figure 6-11 shows one breakdown using the forward, starboard swaybrace rod as an example.

FIGURE 6-11: REACTION BREAKDOWN FOR FWD, STBD SWAYBRACE ROD

As can be seen in figure 6-11, the largest contributor for compression in the forward, starboard swaybrace rod during this timeframe is the rolling moment M_x . The vertical force P_z is seen primarily in an unloading capacity while the yawing moment M_z and longitudinal force F_x have little effect. Another example of reducing the reactions into

separate components is shown in figure 6-12 with the aft, port swaybrace during the same, 300-millisecond time interval. It is again shown that the primary contributor to the compressive reaction in the swaybrace rod is the rolling moment that quickly peaked then damped out with time.

FIGURE 6-12: REACTION BREAKDOWN FOR AFT, PORT SWAYBRACE ROD

Figures 6-13 through 6-16 show the interface reactions for the four swaybrace rods comparing measured and calculated data.

FIGURE 6-13: INTERFACE REACTIONS AT THE FORWARD PORT SB ROD

FIGURE 6-14: INTERFACE REACTIONS AT THE FORWARD STBD SB ROD

FIGURE 6-15: INTERFACE REACTIONS AT THE AFT PORT SB ROD

FIGURE 6-16: INTERFACE REACTIONS AT THE AFT STBD SB ROD

Figures 6-17 and 6-18 compare the measured and calculated vertical reactions for the two lugs. The lugs for this flight test were not instrumented with the strain gages necessary to collect reaction data in the longitudinal or lateral directions. As shown in figure 3-3, the standard instrumentation lug can only measure strain in the vertical direction.

FIGURE 6-17: VERTICAL INTERFACE REACTIONS AT THE FORWARD LUG

FIGURE 6-18: VERTICAL INTERFACE REACTIONS AT THE AFT LUG

The swaybrace rod and lug reaction predictions generally matched well with the measured reactions, especially for the critical reactions. Critical reactions were defined conservatively as those reactions above 10% of the typical maximum allowable reaction in the swaybrace rods and lugs, or greater than 2,000 lbs. compression and 5,000 lbs. tension, respectively. The main areas of poor agreement between measured and calculated values were in the very low reaction range (less than 1,000 lbs.) of the swaybrace rods. This is attributed to the noise associated with near-zero values in the accelerometer data, as well as not being able to more accurately model the conditions involved in the final unloading and release of reactions within the SRI; however, this area was not of primary concern due to its very nature. The higher compressive reactions in the swaybrace rods were predicted much more accurately, and in all cases there was a high correlation in overall shape, general response and magnitude between the measured and predicted data. Similar correlation was found in the vertical lug reactions for overall shape, magnitude and response.

Appendix I shows the absolute errors for all critical reactions in the swaybrace rods and lugs. The average swaybrace rod reaction error was 239 lbs. or 9% of the measured reactions; all swaybrace reaction errors were less than 900 lbs. Only 6 out of the 154 critical swaybrace reaction errors were greater than 600 lbs. and only 10 errors were greater than 20% of the measured values. The average lug reaction error was 443 lbs. or 7% of the measured reactions; all lug reaction errors were less than 1,500 lbs. Only 6 out of the 78 critical lug reaction errors were greater than 1,000 lbs. and only 8 errors were greater than 15% of the measured values.

Figure 6-19 provides a scatter plot of the absolute value errors for the critical reactions for the four swaybrace rods and the two vertical lug reactions between the calculated and measured data during the 300-millisecond post-arrestment interval used for the reaction plots in figures 13 through 18. The average and maximum error values can be clearly seen, as most errors in the lug and swaybrace reactions are shown to be less than 400 lbs. Figure 6-20 is similar to figure 6-19 but plots percentage error for both the lug and swaybrace reactions. Additionally, an error band of approximately 10% that includes the majority of the errors can be seen in figure 6-20 along with the absolute error values.

FIGURE 6-19: REACTION ERRORS AT THE CRITICAL POINTS (LBS.)

FIGURE 6-20: REACTION ERRORS AT THE CRITICAL POINTS (%)

In calculating the reactions, preloads were combined with the new reactions at each time step and the total load state examined. If the reaction in a lug or swaybrace rod was negative or positive, respectively, the reaction was defined as zero since the interface point was at the point of complete unload. The total load state for a lug reaction must be positive (tension) or zero, while swaybrace rods must stay in a total state of zero or negative (compression) load.

6.4 Free Flight Inertial Loads

Although appropriate free flight data was unavailable for this research, reference 50 provided the envelope of flight conditions required for the design of stores on high performance aircraft. Table 6-1 summarizes the most extreme requirements:

TABLE 6-1: FLIGHT CONDITIONS FOR DESIGN OF STORES ON HIGH PERFORMANCE AIRCRAFT (MIL-A-8591 LIMIT LOADS)

Flight Condition	Linear Accelerations (Gs)			Angular Rates (rad/sec)			Angular Accelerations (rad/sec^2)		
	a_x	a_y	a_z	ω_x	ω_y	ω_z	α_x	α_y	α_z
Pullout	1.5	1.0	10.0	0.0	0.0	0.0	0.5	0.5	0.0
Rolling Pullout (low Q)	1.5	0.5	7.0	5.0	0.0	0.0	11.0	3.0	2.0
Rolling Pullout (high Q)	1.5	0.25	6.0	4.5	0.0	0.0	17.0	1.0	1.0
Pushover	1.5	1.0	-6.0	0.0	0.0	0.0	0.5	0.0	0.0

Note: Angular rates and accelerations are peak values and not intended to occur simultaneously.

Assuming a standard preload of 1,000 lbs. per swaybrace rod and the mass properties of the GBU-24, the reactions to the free-flight inertial loads were calculated. Although the flight conditions given in table 6-1 should include aerodynamic components, the results given in table 6-2 were provided for insight into only the dynamic reactions during free-flight. The results are conservative since the accelerations and rates for each maneuver were assumed to act simultaneously for the purposes of calculation whereas the data in table 6-1 were peak values and intended for independent evaluation.

TABLE 6-2: DYNAMIC REACTIONS TO FREE FLIGHT CONDITIONS

Flight Condition	Swaybrace Rods (lbs.)				Lugs (lbs.)	
	Forward		Aft		Forward	Aft
	Port	Stbd.	Port	Stbd.	Vertical	Vertical
Pullout	0	0	0	0	13,874	11,995
Rolling Pullout (low Q)	0	0	-301	0	12,147	10,293
Rolling Pullout (high Q)	0	0	-160	0	9,164	8,626
Pushover	-4,523	-1,101	-3,720	-536	2,855	3,983

Notes: 1. For swaybrace rods: Negative values are compressive reactions in the swaybrace rod; 0 indicates complete unload
2. For lugs: Positive values in the lugs are tensile reactions
3. Mass properties of a standard GBU-24 were used for the reaction calculations
4. Standard preloads of 1,000 lbs. per swaybrace rod (compression) have been assumed
5. Lug preloads were calculated from swaybrace preloads and weapon weight
6. All results are conservative in that simultaneous peak value flight conditions were used in the calculations
7. Results do not include aerodynamic effects

6.5 Chapter 6 Summary

This chapter focused on a flight test event of a 2,000 lb. GBU-24 on an F-14 Tomcat aircraft. The event used for analysis was an arrestment to allow the dynamic inertial loads to be dominant and aerodynamic loads to be considered negligible. The GBU-24 was instrumented with accelerometers and the BRU-32 had instrumented lugs and swaybrace rods. A time interval of 300 milliseconds was chosen to capture all peak accelerations beginning immediately after arrestment.

Accelerometer readings ranged from -1.8 Gs to $+1.1$ Gs in the x -direction, -0.8 to $+0.8$ Gs in the y -direction and -4.5 Gs to $+8.7$ Gs in the z -direction. The FORTRAN program used to calculate the reactions at the SRI for the ground test was modified to accept the accelerometer and flight test data. The forces and moments at the store CG were calculated using Newton's second law and Euler's equations; linear and angular rates were integrated across consecutive time intervals. The program also allows the use of a variety of accelerometer locations as well as the use of six to ten accelerometers to provide flexibility for each store tested and other testing requirements. Using accepted post-flight programs to calculate loads at the store CG, the results calculated in this

research matched almost exactly to the verified solutions providing an independent verification of the results. In the 300 milliseconds following arrestment, forces and moments up to approximately 15,000 lbs. and 150,000 in-lbs., respectively, were found.

The forces and moments at the store CG were distributed to the interface points, allowing half of each reaction to go towards the unloading interface points and the remaining half to go to the loading points. Comparing the calculated reactions to the measured data, very good agreement was found in form and magnitude for all interface points. Critical reaction points were conservatively designated as those points whose reactions were more than 10% of the typical interface test limit were analyzed for error. When compared to the measured data, all lug and swaybrace rod reactions averaged less than 9% error. Points whose reactions were less than the critical points were considered in the noise of the test.

CONCLUSIONS AND RECOMMENDATIONS

The objective of this research was to demonstrate the ability to accurately predict the reaction loads at the SRI in real-time on an aircraft during an arrested landing without using strain gages or post-flight data reduction. Classical analyses, ground tests and flight tests were all incorporated to successfully accomplish the task.

7.1 Conclusions

A classical analysis was used to calculate the reactions at the SRI using only measured accelerometer data and known mass properties and geometry and without the need for delicate strain gages. The translational and rotational accelerations were found at the store CG using the accelerometer data recorded around the surface of the store. Using the calculated accelerations and integrated rates, the equations required for the inertial force and moment calculations at the store CG were derived dynamically with Newton's Laws, kinetics of rigid bodies in three dimensions and the simplified Euler's Equations of Motion. The calculated loads at the store CG were distributed to the six interface points using the principle of superposition to sum the individual reactions, allowing for both loading and unloading at each interface. Elastic effects were considered negligible for this analysis due to the rigid body assumptions and high reaction loads. Finally, a FORTRAN program was written to incorporate all of the necessary equations to predict or calculate the dynamic loads and their distribution to the SRI using only accelerometer data, and known SRI preloads, mass property and geometry data.

A full-scale ground test incorporated a MK 84, specially instrumented with welded lug attachment points to allow external loads to be applied to the store to simulate pure forces and moments at the store CG. Collected test data included strain gage output from 42 gages affixed to the lugs and swaybrace rods in the bomb rack. The externally applied forces were also collected with respect to time and test points included eight different load cases. The theoretical calculations matched the measured data with a few noted exceptions. The only axial reaction exhibited by the lugs was in the presence of a longitudinal load, but the reaction was not equally split as originally assumed. The

forward lug carried 38.5% of the longitudinal load while the aft lug reacted 60.6% of the total load; the remaining 0.9% was attributed to an unmeasured friction in the swaybrace rods. Additionally, the lugs reacted laterally only due to roll and yaw moments as seen in ground test load cases 5 and 8, respectively. Lateral loads were reacted by the swaybrace rods alone for all other load cases. Lastly, the swaybrace rods reacted in a manner opposite to the initial prediction during the yaw moment load case, loading up the opposite rods in both swaybrace assemblies due to twisting of the bomb rack. The reaction equations were corrected to allow only a primary lug reaction (forward and aft) in the lateral direction due to the presence of the yawing moment, with the opposite side swaybrace rods responding proportionally and with a much smaller magnitude reaction.

The flight test included an arrested landing to create a load case where the dynamic inertial loads were dominant and the aerodynamic loads were considered negligible. The GBU-24 was instrumented with ten servo-accelerometers and the bomb rack included was instrumented with strain gages on the lugs and swaybrace rods. A time interval of 300 milliseconds was chosen to capture all peak accelerations beginning immediately after arrestment. Accelerometer readings ranged from -1.8 Gs to $+1.1$ Gs in the x -direction, -0.8 to $+0.8$ Gs in the y -direction and -4.5 Gs to $+8.7$ Gs in the z -direction. The forces and moments at the store CG were calculated using Newton's second law and Euler's equations; linear and angular rates were integrated over consecutive time intervals. Using accepted and proven post-flight programs to calculate loads at the store CG, the results calculated from this research were identical to the verified solutions providing independent verification of the results. In the 300 milliseconds following arrestment, forces and moments up to approximately 15,000 lbs. and 150,000 in-lbs., respectively, were calculated. Excellent correlation was observed in form and magnitude for all interface points when comparing the calculated reactions to the measured data for all critical reaction points. Critical reaction points were conservatively designated as those points whose reactions were more than 10% of the typical interface test limit. When compared to the measured data, all lug and swaybrace rod reactions averaged less than 9% absolute error for the critical reaction points. Non-critical reaction points provide the most visible indication of the complex, non-linear SRI reactions, albeit at levels of no

concern, and consequently were not taken into consideration in the development of the final reaction equations.

By design, the swaybrace assemblies cannot react in tension and the lugs cannot react in compression, yet both can unload and reduce the current load state. Corrections to the derived reaction equations to allow concurrent loading and unloading reactions until the unloading reaction reached zero matched well with observation. The complete solution of the loading and unloading equations at the SRI was impossible due to the parallel nature of the loads and reactions as well as an indeterminate system of equations. This research focused on a simpler method of analysis by incorporating initial assumptions that were later empirically proved or disproved through ground and flight testing, yielding a very accurate set of equations for the critical load points.

The primary goal of this research was to create a real-time method to predict or calculate the dynamic reactions at the six SRI points in an effort to save time and money while improving the accuracy and consistency of results. This task was successfully accomplished for critical reaction points during carrier-suitability flight-tests.

7.2 Contributions

The ability to calculate SRI reactions without costly and delicate instrumentation, as well as having the opportunity to predict the reactions before a flight is of great interest to the flight test community. Since flight-testing will always be required for a variety of reasons, 100% accuracy in reaction prediction is not necessary although a confident error band for critical points is essential. The importance of this research goes beyond the easily appreciated savings of cost and time in flight test instrumentation design, maintenance and documentation.

7.2.1 Primary Contribution

The principal contribution of this research is the development of the first real-time, fully dynamic analysis of store reactions in an aircraft bomb rack without the reliance on strain gages or instrumented suspension equipment. The resulting program has not been accurately derived before due its complexity in development; conservative predictions are

currently used to assist in structural flight test planning but have extremely high errors impossible to estimate. The effort continually put forth in military standards like reference 50 qualifies the active interest in reaction prediction methodologies. Allowing a flight test program to calculate the SRI reactions during planning stages as well as during actual flight tests within a confident band of error will save critical time and money; this research documents the first usable, accurate and repeatable version of those interests.

7.2.2 Secondary Contributions

The successful completion of this research provides numerous benefits for most structural flight test programs; time and cost savings being the largest. The following are the secondary, although crucial, contributions of this project:

- The FORTRAN program developed for this research is unique and allows calculations of all necessary information for the loading and unloading reactions at the SRI using ground or flight test data. For flight tests, only the accelerometer data, and known preload, mass property and geometry data are necessary. The program can be set up to calculate forces and moments at the store CG based on six to ten accelerometers and provides flexibility in their placement. The program also calculates the reaction distributions from the loads at the store CG to the six interface points. The accelerometer data may be read from a file or entered individually, and all of the input and output data are saved to files for verification. The components that make up the final reactions are also saved to a file for a graphical display of reaction components.
- Cost savings are primarily realized through fewer required test flights due to a confident prediction of the results at the necessary test points and hence fewer required flights. Similar savings are obtained by minimizing repeated and cancelled test flights due to instrumentation failures in strain gages, specialized racks, etc. Cost reductions are further achieved through

minimizing pre-flight instrumentation (including store and rack) and post-flight data reduction.

- Another advantage is the lack of required strain gages. These gages are costly in the application and require specialized and limited suspension equipment. The gages are very fragile and, especially during the typical installation and removal procedures for larger stores, are easily damaged resulting in poor data collection, wasted effort in the delay or repetition of test flights and overall added costs.
- An up-front reduction in the flight hour testing requirements (at rates known to exceed \$20,000/hr) can have significant program impact.
- As an additional benefit, the prediction routines may be used as a secondary reaction calculation device if similar required hardware fail in flight, reducing the cost incurred for repeating flight testing because of instrumentation hardware failure. Currently there is no backup for an instrumented swaybrace in flight and flight tests are often terminated for loss of that data; using this research even as a redundant system could save flight cancellation. Spread out over a number of projects and test programs, even small cost savings for each set of flight tests will become significant.
- The results of this research will allow for computation of the critical reaction points prior to an actual flight test program, thus allowing the flight test team to target a specific flight envelope instead of wasting test resources on irrelevant test points or repeated flights.
- Additionally, implementation of this research in a store's development phase can provide design engineers with unique and critical SRI loading conditions and to be addressed before the store ever gets to testing.
- It was determined through this research that there was no standard for accelerometer placement on stores for structural flight-testing. Each separate

flight test program would mount the accelerometers where desired and write new equations for their use, making it difficult to use a set of equations or program data more than once. Standardized placement, to the extent possible given project needs and store geometry, would help data collection and save time in calculations. The program written for this research, however, allows for easy manipulation of the number and locations of accelerometers.

- From the results of the ground test data, the uneven reactions in the lugs due to a positive longitudinal load was shown and empirically determined to be 38.5% and 60.6% in the front and aft lugs, respectively. The assumptions of which loads were reacted by the lugs and which by the swaybrace rods were also finalized with the observation that the swaybrace rods solely react to a lateral force while the lugs will react laterally only due to a rolling or yawing moment. The bomb rack bending (specifically, its bending characteristics due to relatively low xz -plane stiffness) during a high yawing moment is also significant and stiffening of the center section of the BRU-32 should be considered.

7.3 Recommendations for Further Research

The present research has shown that, in a limited form, the SRI reactions can be predicted and calculated real-time. Future work should consider four key areas:

- adding aerodynamic load calculations
- incorporating the program into a real-time telemetry system for flight-testing
- gathering a larger database of flight data to verify or improve the equations
- improvements in preload estimation and calculation

The aerodynamic equations are discussed in this research, but many details would have to be considered including the force and moment coefficients, typically from wind tunnel data, for each store and rack combination desired. However, once derived, the aerodynamic reaction equations would simply be combined with the inertial equations already developed with this research. A larger database for inertial reactions would also

be valuable, as only one flight event with all necessary instrumentation was available for this research. Moreover, creating modified equations to predict reactions using different bomb racks, different aircraft or different/lighter stores are possible. Improvements in any of these areas would greatly enhance the model's usefulness and reliability as a reaction prediction tool for flight-testing as well as design and analysis. Although preload information is historical and can generally be treated consistently when compared to the much larger peak reactions during carrier suitability flight testing, the percentage error becomes larger for simple flight maneuvers. Preload data and averages are being constantly updated, as they are part of the evolving process bridging the gap between post-flight, complex data reduction and real-time calculations. A method to accurately estimate or calibrate preloads in flight would be beneficial. However, a notable observation from this research is that the application of a conservatively high preload value causes a negligible but conservative change in the SRI reaction loads computations developed for critical points. For the present time, using the typical preload averages measured from past flight tests for the same store and rack combination will be sufficient, as are the preloads given for this research an acceptable estimate for future BRU-32/GBU-24B/B flight testing.

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APPENDIX A: *FORTRAN Program to Calculate Reactions
at the Store/Rack Interface*

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!
! Program REACTIONS
!
!
! *****!
!
! Computer Program to Calculate Interface Reaction Loads at BRU-32 Interface Points
!
!
! Tim C. Schoppert
! May 2002
!
! *****!
!
!
! character(8) ap*10, bp, cp, dp, ep, fp, gp, hp, ip
! character(9) al, bl, cl, dl, el, fl, gl, hl, TODAY
! character(9) ah, bh, ch, dh, eh, fh, gh, hh, ih
! character(15) accelin, accelout, react, groundcg, grnddata, groundpl, fltcglds
! character(15) lfzcheck, sascheck, lazcheck, sfscheck, sfpcheck, sapcheck
!
! real sfp(1000), sfs(1000), sap(1000), sas(1000)
! real lfw(1000), lfl(1000), law(1000), lal(1000)
! real pxg(1000), pyg(1000), pzg(1000), mrg(1000), mpg(1000), myg(1000)
! real azas(1000), ayfs(1000), azfs(1000), ayas(1000)
! real azmp(1000), axms(1000), azms(1000), ayms(1000)
! real ralx(1000), raly(1000), ralz(1000), rflx(1000), rfly(1000), rflz(1000)
! real rras(1000), rlas(1000), rrfs(1000), rlfs(1000)
! real rrfsy(1000), rrfsz(1000), rlfsy(1000), rlfsz(1000)
! real rrasy(1000), rrasz(1000), rlasy(1000), rlasz(1000), dtime(1000)
!
! real lpx, lpy, lpz, lmx, lmy, lmz, mx, my, mz, ixx, iyy, izz, L1, L2, L5
!
! integer loadcase(1000), point(1000), loadpre(1000), testtype
!
! CALL DATE(TODAY) ! call today's date and send to output files
!
! The following question directs the program to use Static Ground Test Data or Flight Test Data:
!
! 10 print *, 'Enter 1 for Ground Test Data or 2 for Flight Test Data'
! read *, testtype
! write (*,200)
!
! if (testtype.eq.1) goto 50
! if (testtype.ne.2) goto 10
!
!
! FLIGHT TEST DATA
!
! The following 13 lines of code are used for manual entry of input and output
! filenames. Note that the input file must be *.csv, which has comma-delimited
! fields (found through the Save-As command in Excel)
!
! 20 print *, 'Enter title (file.ext) of the accelerometer data file to input (raw data):'
!
! read *, accelin
! write (*,200)

```

```

print *, 'Enter title (file.ext) of accelerations data file to create (raw data):'
read *, accelout
write (*,200)
print *, 'Enter title (file.ext) of the reactions file to create (calculated data):'
read *, react
write (*,200)

!
!

open(unit=1, file=accelin)
open(unit=2, file=accelout)

!
read (1,*) ah, bh, ch, dh, eh, fh, gh, hh, ih      ! headings for the accelerometer data
!
!Read in the accelerometer data and write it to a file versus time for verification
!
write (2,*) ' (ACCELOUT was created on ', today, ')'
write (2,200)
write (2,*) '      RAW ACCELEROMETER DATA IMMEDIATELY AFTER ARRESTMENT'
write (2,200)
write (2,210) ah, bh, ch, dh, eh, fh, gh, hh, ih
i=1
30  read (1,*,end=40) dtime(i),azms(i),ayfs(i),azfs(i),azmp(i),axms(i),ayms(i),ayas(i),azas(i)
!
! The GBU-24 data used a left hand sign convention with positive Ny left and must be corrected.
!
axms(i) = -1.0*axms(i)
ayfs(i) = -1.0*ayfs(i)
ayms(i) = -1.0*ayms(i)
ayas(i) = -1.0*ayas(i)
!
write (2,220) dtime(i), azms(i), ayfs(i), azfs(i), azmp(i),axms(i),ayms(i),ayas(i),azas(i)
i=i+1
goto 30
!
40  k=i-1
i=1
!
close (unit=1)
rewind (unit=2)
close (unit=2)
!
!
!BEGIN the program to calculate the forces at the store CG then the reactions at the six interface points:
!
! Sign Convention (for accelerations, velocities, loads and reactions):
!
! Forces and translational accelerations are POSITIVE aft, starboard, up.
! Moments and rotational accelerations are POSITIVE right wing up, nose up, nose left.
!
! Store Physical Parameters and Units - must be known beforehand
! ** All geometric information should be entered as positive values **
!
! rs = radius of store at swaybrace location (in)
! ra = radius of reference accelerometer cross-section at accel locations (in)
!      (the accels are usually place above the surface of the store on blocks)
! w = weight of store (lb)

```


! a = longitudinal (x-axis) distance (positive) from CG to fwd accelerometer (in)
! The 'b' distance was broken into 2 segments, by and bz, to allow differences
! in the physical 'x' locations between the aft z-accel and the aft y-accel (i.e. if one
! was on the CG and the other was aft of CG). Enter both distances as positive values.
! by = longitudinal (x-axis) distance from CG to aft y-accelerometer (in)
! bz = longitudinal (x-axis) distance from CG to aft z-accelerometer (in)
! The rxtriax, rytriax and rztriax values represent the physical distances from the store
! CG to one triax to allow accel calculations. The triax contains three of the six
! currently required accels, but can be located at either a forward, aft or mid (CG)
! location. If no triax is used, the x-, y-, and z-distances to one each x-, y-, and z-
! accelerometer must be used. ** These distances must follow GLOBAL SIGN CONVENTION **
! rxtriax = +/- longitudinal (x-axis) distance from CG to triaxial accelerometer (in)
! rytriax = +/- lateral (y-axis) distance from CG to triaxial accelerometer (in)
! rztriax = +/- vertical (z-axis) distance from CG to triaxial accelerometer (in)
! z = vertical (z-axis) distance from CG to accelerometers (in)
! alf = angle of tilt of swaybrace from vertical in y-z plane (degrees)
! s1 = longitudinal (x-axis) distance from CG to forward swaybrace (in)
! s2 = longitudinal (x-axis) distance from CG to aft swaybrace (in)
! s3 = lateral (y-axis) distance from CG to port swaybrace (in)
! s4 = lateral (y-axis) distance from CG to starboard swaybrace (in)
! s5 = vertical (z-axis) distance from CG to swaybrace (in)
! L1 = longitudinal (x-axis) distance (positive) from CG to forward lug (in)
! L2 = longitudinal (x-axis) distance (positive) from CG to aft lug (in)
! L5 = vertical (z-axis) distance from CG to lug/hook contact (in)
! ixx = store mass moment of inertia about the x-axis (in-lb-s**2)
! iyy = store mass moment of inertia about the y-axis (in-lb-s**2)
! izz = store mass moment of inertia about the z-axis (in-lb-s**2)
! Instrumentation Parameters (in Gs)
! Currently, for the acceleration equations to be valid, the following geometric
! conditions must be satisfied (although there are allowances in the acceleration
! equations discussed later for some deviation):
! 1. axas, ayas, azas, azap must have the same x-coordinate
! 2. ayfs and azfs must have the same x- and y-coordinates
! 3. axas, ayas, azas must have the same y-coordinate
! 4. azas and azap must have the same magnitude but opposite y-coordinates
! 5. All accels must have the same z-coordinate
! azfs = accelerometer reading from fwd, stbd accel along z-axis
! azap = accelerometer reading from aft, port accel along z-axis
! azas = accelerometer reading from aft, stbd accel along z-axis
! ayfs = accelerometer reading from fwd, stbd accel along y-axis
! ayas = accelerometer reading from aft, stbd accel along y-axis
! axas = accelerometer reading from aft, stbd accel along x-axis
! Calculated Store Parameters (full sign convention provided previously)
! ax = translational acceleration of store along x-axis (CG) (in/sec**2)
! ay = translational acceleration of store along y-axis (CG) (in/sec**2)
! az = translational acceleration of store along z-axis (CG) (in/sec**2)
! vx = translation velocity of store CG along x-axis (in/sec)

```

! vy   = translation velocity of store CG along y-axis (in/sec)
! vz   = translation velocity of store CG along z-axis (in/sec)
! alphax = rotational acceleration of store about x-axis (rad/sec**2)
! alphay = rotational acceleration of store about y-axis (rad/sec**2)
! alphaz = rotational acceleration of store about z-axis (rad/sec**2)
! wx   = rotational velocity of store about x-axis (rad/sec)
! wy   = rotational velocity of store about y-axis (rad/sec)
! wz   = rotational velocity of store about z-axis (rad/sec)
!
! Calculated Store Forces and Moments (sign convention provided previously)
!
! px   = store inertial force along x-axis through store CG (lb)
! py   = store inertial force along y-axis through store CG (lb)
! pz   = store inertial force along z-axis through store CG (lb)
! mx   = store inertial moment around x-axis at the store CG (in-lb)
! my   = store inertial moment around y-axis at the store CG (in-lb)
! mz   = store inertial moment around z-axis at the store CG (in-lb)
!
! Calculated Reaction Components on Rack
!
! spx, spy, spz = reaction components on swaybrace due to px, py, pz (lb)
! smx, smy, smz = reaction components on swaybrace due to mx, my, mz (lb)
! lpx, lpy, lpz = reaction components on lug due to px, py, pz (lb)
! lmx, lmy, lmz = reaction components on lug due to mx, my, mz (lb)
!
! rlfsy = reaction force on the left forward swaybrace along y-axis (lb)
! rlfsz = reaction force on the left forward swaybrace along z-axis (lb)
! rlfs  = overall reaction force on the left forward swaybrace (lb)
! rrfsy = reaction force on the right forward swaybrace along y-axis (lb)
! rrfsz = reaction force on the right forward swaybrace along z-axis (lb)
! rrfs  = overall reaction force on the right forward swaybrace (lb)
!
! rlasz = reaction force on the left aft swaybrace along z-axis (lb)
! rlas  = overall reaction force on the left aft swaybrace (lb)
! rrasz = reaction force on the right aft swaybrace along z-axis (lb)
! rras  = overall reaction force on the right aft swaybrace (lb)
!
! rflx  = reaction force on the forward lug along the x-axis (lb)
! rflz  = reaction force on the forward lug along the z-axis (lb)
! rfl   = overall reaction force on the forward lug (lb)
!
! ralx  = reaction force on the aft lug along the x-axis (lb)
! raly  = reaction force on the aft lug along the y-axis (lb)
! ralz  = reaction force on the aft lug along the z-axis (lb)
! ral   = overall reaction force on the aft lug (lb)
!
! Enter GBU-24 mass properties and physical data from actual flight test (all defined above)
!
50      s1      =      7.79
        s2      =      12.21
        L1      =      12.79
        L2      =      17.21
        s3      =      2.12

```

```

s4      =      2.12
s5      =      6.95
L5      =      8.60
alf     =      17.00
rs      =      7.25
ra      =      8.12
a       =      31.00
by      =      51.56
bz      =      51.56
z       =      0.00
w       =      2370.00
ixx     =      271.44
iyy     =      7131.60
izz     =      7116.96
rxtriax =      0.0
rytriax =      ra
rztriax =      0.0
!
! The next section provides the necessary truth data from the MK 84 ground test.
!
  if (testtype.eq.1) then
    s1      =      9.40
    s2      =      10.60
    L1      =      14.40
    L2      =      15.60
    s3      =      2.12
    s4      =      2.12
    s5      =      6.95
    L5      =      8.60
    rs      =      9.00
    w       =      1975.00
  endif
!
! Positive distances were used to create the reaction equations and signs must be checked
!
    s1      =      abs(s1)
    s2      =      abs(s2)
    s3      =      abs(s3)
    s4      =      abs(s4)
    s5      =      abs(s5)
    L1      =      abs(L1)
    L2      =      abs(L2)
    L5      =      abs(L5)
    a       =      abs(a)
    by      =      abs(by)
    bz      =      abs(bz)
    alf     =      abs(alf)
    z       =      abs(z)
    ixx     =      abs(ixx)
    iyy     =      abs(iyy)
    izz     =      abs(izz)
!
    pi      =      4.0*atan(1.0)      ! Need to define the value of PI
!
    if (testtype.eq.1) goto 70      ! Skip the acceleration calculations for ground testing
!

```

```

!
!EQUATIONS FOR ACCELERATIONS AND RATES
!
! First find the rotational accelerations (converted from Gs to rad/sec**2):
!
! The '0.0' term near the end of the 'alphax' equation represents the x-distance between
! the two z-accelerometers that are measuring roll. There is currently no variable
! representing this distance as it is forced to zero by setting the roll accels at the
! same x-coordinate. If an x-distance exists, it should be entered here as the
! equations have been derived to account for it when necessary.
!
! Similarly, the '0.0' terms near the end of the 'alphay' and 'alphaz' equations
! represent the y-distance between the two z-accelerometers that are measuring roll and
! pitch, respectively. These distances are also currently forced to zero by setting the
! roll accels at the same y-coordinate. If a y-distance exists, it should be entered here
! as the equations have been derived to account for it when necessary.
!
60    alphax=386.4*((azms(i)-azmp(i))/(2.0*ra)-(azfs(i)-azas(i))/(a+bz)*(0.0)/(2.0*ra))
    alphay=386.4*((azfs(i)-azms(i))/(a)-(azms(i)-azmp(i))/(2.0*ra)*(0.0)/(a+bz))
    alphaz=386.4*((ayms(i)-ayfs(i))/(a)-(ayms(i)-ayfs(i))/(2.0*ra)*(0.0)/(a+bz))
!
! Second, find the rotational velocities through a numerical integration approximation (rad/sec):
!
    if (i.eq.1) then
        wx = 0.0
        wy = 0.0
        wz = 0.0
    else
        wx = wx + (alphax + alphaxprev)/2.0*(dtime(i)-dtime(i-1))
        wy = wy + (alphay + alphayprev)/2.0*(dtime(i)-dtime(i-1))
        wz = wz + (alphaz + alphazprev)/2.0*(dtime(i)-dtime(i-1))
    endif
!
! Set the current values of rotational acceleration to be used as the previous timestep
! values in the next iteration
!
    alphaxprev = alphax
    alphayprev = alphay
    alphazprev = alphaz
!
! Third find the translational accelerations (Gs):
!
    ax = axms(i)-(rytriax*(wx*wy-alphaz)+rztriax*(wx*wz+alphay)-rxtriax*(wy**2+wz**2))/386.4
    ay = ayms(i)-(rztriax*(wy*wz+alphax)+rxtriax*(wx*wy-alphaz)-rytriax*(wx**2+wz**2))/386.4
    az = azms(i)-(rxtriax*(wx*wz-alphay)+rytriax*(wy*wz+alphax)-rztriax*(wx**2+wy**2))/386.4
!
!
!EQUATIONS FOR FORCES AND MOMENTS
!
! Calculate the inertial loads (resisting acceleration) from flight test data. Inertial
! loads act opposite of acceleration. The reaction loads on the Lugs and Swaybrace Pads
! are opposite inertial loads and therefore in the direction of acceleration. Hence, the
! reaction loads acting on the store due to the inertial forces must be equal and opposite
! to the inertial loads within the store to satisfy equilibrium, and therefore acting in
! the same direction as the acceleration.
!

```

```

! Units are lbs. and in-lbs. for forces and moments, respectively.
!
! The Translational Velocities are approximated through a numerical integration timestep
! similar to the rotational velocities.
!
      if (i.eq.1) then
        vx = 0.0
        vy = 0.0
        vz = 0.0
      else
        vx = vx + (ax + axprev)/2.0*(dtime(i)-dtime(i-1))
        vy = vy + (ay + ayprev)/2.0*(dtime(i)-dtime(i-1))
        vz = vz + (az + azprev)/2.0*(dtime(i)-dtime(i-1))
      endif

!
! Set the current values of translational accelerations to be used as the previous timestep
! values in the next iteration
!
      axprev = ax
      ayprev = ay
      azprev = az

!
! Solve for the Forces (lbs) at the store CG using Newton's Second Law of Motion. The (-1.0)
! term allows inertial force to act opposite of acceleration:
!
      px = -1.0*w/386.4*(ax*386.4+vz*wy-vy*wz)
      py = -1.0*w/386.4*(ay*386.4+vx*wz-vz*wx)
      pz = -1.0*w/386.4*(az*386.4+vy*wx-vx*wy)

!
! Solve for the Moments (in-lbs) about the store CG using Euler's Equations of Motion for a
! Body-Fixed Principal Axis. The (-1.0) term allows inertial moment to act opposite of accel:
!
      mx = -1.0*(ixx*alphax + wy*wz*(izz-iyy))
      my = -1.0*(iyy*alphay + wx*wz*(ixx-izz))
      mz = -1.0*(izz*alphaz + wx*wy*(iyy-ixx))

!
!
! Write all of the Forces and Moments calculated at the store CG to a file
!
      if (i.eq.1) then

!
        fltcglds='fltcglds.dat'
        open(unit=9, file=fltcglds)

!
        write (9,*) '(FLTCGLOADS was created on ', today, ' )'
        write (9,200)
        write (9,*) '          Loads at Store CG Calculated from Accelerometer Data '
        write (9,200)
        write (9,230) 'Dtime ', Px ', ' Py ', ' Pz ', ' Mx ', ' My ', ' Mz '
        write (9,230) '(sec) ',(lb) ',(lb) ',(lb) ',(in-lb) ',(in-lb) ',(in-lb) '
      endif

!
      write (9,240) dtime(i),px, py, pz, mx, my, mz

!
      lcase=1          ! This sets the load case for the ground test when necessary
!

```

```

! The following preloads were provided with the flight test data of estimates prior to
! the arrested landing. Store weight is not included in these preload estimates.
! Swaybrace preloads are along the axis of the swaybrace rod (17-degree rotation
! from vertical) while lug preloads are along the lug vertical axis.
!
      sfp(lcase)      =      -1800.0
      sfs(lcase)      =      -1200.0
      sap(lcase)      =      -2100.0
      sas(lcase)      =      -2200.0
      lfw(lcase)      =      2100.0
      law(lcase)      =      2300.0
!
      goto 110
!
!
!GROUND TEST DATA: Need to read in the experimental ground test data now if necessary.
!
70      groundpl='grndplww.csv' ! ground test preload data
      groundcg='grndcgnw.csv' ! ground test externally applied loads through CG
      grnddata='grnddata.dat' ! output file of ground test loads for verification
      react='react.dat' ! calculated ground test interface reactions
!
      open(unit=6, file=groundpl)
      open(unit=7, file=groundcg)
      open(unit=8, file=grnddata)
!
!
! Preload is assumed to be in the form of negative values for the resultant swaybrace
! preload and positive values for the resultant vertical lug preload. Also note that
! preload for ground tests must include the weight contribution since all readings are
! zeroed out to begin each test. Since ground tests remain at a 1G loading condition,
! the weight should then not be redundantly accounted for once the tests begin.
!
! For flight tests, preload values should not include a store weight contribution since
! the weight of the store will depend on the accelerations present and should be part
! of the calculations at each time slice.
!
      read (6,*) ap, bp, cp, dp, ep, fp, gp, hp, ip ! preload header data
      write (*,200)
      print *, 'Enter number of load cases for preload conditions:'
      write (*,200)
      read *, numpre ! read in the number of load cases
!
      do m=1,numpre
      read (6,*) loadpre(m),sfp(m),sfs(m),sap(m),sas(m),lfw(m),lfl(m),law(m),lal(m)
!
! Since SB preloads must be negative and lug preloads positive, must check to set false
! preloads to 0. (lfl and lal are lateral preloads and have no required sign)
!
      if (sfp(m).gt.0.0) sfp(m)=0.0
      if (sfs(m).gt.0.0) sfs(m)=0.0
      if (sap(m).gt.0.0) sap(m)=0.0
      if (sas(m).gt.0.0) sas(m)=0.0
      if (lfw(m).lt.0.0) lfw(m)=0.0
      if (law(m).lt.0.0) law(m)=0.0
      end do

```

```

!
      read (7,*) al, bl, cl, dl, el, fl, gl, hl          ! headings for the CG loads data
!
      write (8,*) ' (GRNDDATA was created on ', today, ')'
      write (8,200)
      write (8,*) '      Loads at Store CG from Ground Test Data (without weight) '
      write (8,200)
      write (8,250) al, bl, cl, dl, el, fl, gl, hl
      j=1
!
!Read in the CG loads data and write the output file versus time
!
80      read (7,*,end=90) loadcase(j),point(j),pxg(j),pyg(j),pzg(j),mrg(j),mpg(j),myg(j)
!
      if (loadcase(j).gt.loadcase(j-1)) write (8,200)          ! separates loadcases by 2 blank lines
!
      write (8,260) loadcase(j),point(j),pxg(j),pyg(j),pzg(j),mrg(j),mpg(j),myg(j)
!
      j=j+1
      goto 80
90      k=j-1
      j=1
!
      close (unit=7)
      close (unit=8)
!
! The following lines simply rename the loads from the ground test to the correct
! variable names before entering the reaction equations
!
100     px=pxg(j)
        py=pyg(j)
        pz=pzg(j)
        mx=mrg(j)
        my=mpg(j)
        mz=myg(j)
!
        i=j
        jj=j-1
!
        if (j.eq.1) then      ! tracks of the loadcase to allow for calling the correct preload
            lcase=1
        else
            if(loadcase(j).ne.loadcase(jj)) lcase=loadcase(j)
            continue
        endif
!
!
!REACTION CALCULATIONS at the interface points
!
!Calculate the reactions at the interface points based on the total loads. The
!assumption is made that there can be no longitudinal load on a swaybrace as they
!are not designed to carry load in that direction. All longitudinal loads are
!assumed to be carried by the lugs. Also, the swaybraces can only react in
!compression, therefore any tensile-type of reactions acts to unload the swaybrace
!and gets reacted by the lugs. Likewise, the lugs can only react in tension, therefore
!any compressive-type loading unloads the lugs and is reacted by the swaybraces.

```

```

!
! Load contributions are found at each interface point (SB, Lug) for each unique
! loadcase (Px, My, ...) then added together using superposition of the components.
! Preloads are added in as the last step of each component (sfp, sfs, etc.).
!
! All reaction components (spx, spy, etc.) follow the standard sign convention given
! earlier for loads (px, py, etc.) which are positive aft, right, up.
! Preloads also remain as stated earlier (positive tension, negative compression).
! When reactions are converted along the swaybrace axis, they are made to conform to
! the correct preload sign convention (positive tension, negative compressions).
!
! All reaction load components are combined, resulting in the Y- and Z-direction loads
! reacting on each swaybrace before zeroing anything out. The calculated loads are
! now situated along the global Y- and Z-axes and need to be transferred to the axes
! parallel and perpendicular to the swaybrace rods. The resultant reaction loads are
! then multiplied by the sin(alf) or cos(alf) for the y- and z-direction totals to
! obtain the component along the SB rod, as well as a plus or minus sign to match the
! compressive or tensile sense of the preloads. Reactions tangential to swaybrace pad
! are not maintained. Once the resultant parallel to the rod is obtained, it is added
! with the preload to find the overall reaction in the swaybrace.
!
! Reaction equations include the following empirical corrections:
!
! 1. The forward lug reacts 38.5% of the longitudinal load, the aft lug reacts 60.6%
! of the longitudinal load and 0.9% is attributed to friction in the swaybrace rods.
! This effect can't generally be seen in the swaybrace rods since they are reacting the
! moment. Swaybrace gages are bridged to not allow calculation of any bending/friction.
! Ground test points 1.3 through 1.16 were used for this average.
!
! 2. The swaybrace rods (and not the lugs) react an applied lateral load in the lateral direction.
!
! 3. Lugs alone react a yawing moment while swaybrace rods react to a twisting of the rack
! in proportion to the lug load.
!


---


!A. FIND the overall reaction at left, forward swaybrace along the y-axis (Sfly):
!
110    spx=(-1.0)*px*L5*tand(alf)/2.0/(s1+L2)
        spy=py*s2/(s2+s1)
        spz=pz*s2*tand(alf)/2.0/(s1+s2)
        smx=(-1.0)*mx/2.0/L5
        smy=my*tand(alf)/2.0/(s1+L2)
        smz=(-1.0)*4.0*mz/(L1+L2)**2
        if (mz.ge.0.0) smz=0.0    ! SB will load during -Mz and not +Mz
!
! Next, add up the 6 reaction contributions by superposition...
!
        rlfsy(i)=spx+spy+spz+smx+smy+smz
!
! ...and find the component of the y-axis reactions along the swaybrace axis. It is
! noticed that a positive y-direction reaction (not load) of RLFSY will have a
! compressive component along the swaybrace rod and therefore is multiplied by
! a negative one to match correct, final sign convention.
!
        rlfsy(i)=(-1.0)*(rlfsy(i))*sind(alf)
!

```



```

!Continue by finding reaction at left, forward swaybrace along the z-axis (Sflz):
!
    spx=px*L5/2.0/(L2+s1)
    spy=(-1.0)*py*s2/(s2+s1)/tand(alf)
    spz=(-1.0)*pz*s2/2.0/(s1+s2)
    smx=mx/2.0/L5/tand(alf)
    smy=(-1.0)*my/2.0/(s1+L2)
    smz=4.0*mz/(L1+L2)**2/tand(alf)
    if (mz.ge.0.0) smz=0.0      ! SB will load during -Mz and not +Mz
!
! Add up the 6 reaction contributions by superposition...
!
    rlfsz(i)=spx+spy+spz+smx+smy+smz
!
! ...and find the component of the z-axis reactions along the swaybrace axis. It is
! noticed that a negative z-direction reaction (not load) of RLFSZ will have a
! compressive component along the swaybrace rod and therefore does not require a
! sign change to match the correct, final sign convention.
!
    rlfsz(i)=(rlfsz(i))*cosd(alf)
!
! NOW add the two components together to form the reaction along the sb axis. The 0.5 term
! accounts for a split of the total reaction (before preload) between loading and unloading:
!
    rlfs(i)=0.5*(rlfsy(i)+rlfsz(i))
!
! Add in the preload component (all sign conventions are now identical).
!
    rlfs(i)=rlfs(i)+sfp(lcase)
!
! Write all of the individual Sfp components to a file for review and graphing
!
    if (i.eq.1) then
        sfpcheck='sfpcheck.dat'
        open(unit=12, file=sfpcheck)
!
        write (12,*) ' (SFPCHECK was created on ', today, ')'
        write (12,200)
        write (12,*) '   Loads Contributing to Sfp           Preload = ', sfp(lcase)
        write (12,200)
        write (12,270) 'Dtime ', Spx, ' ', Spy, ' ', Spz, ' ', Smx, ' ', Smy, ' ', Smz, ' ', SFP, '
        write (12,270) '(sec) ',(lb) ',(lb) ',(lb) ',(lb) ',(lb) ',(lb) ',(lb) ',(lb) '
        endif
!
        write (12,280) dtime(i),spx, spy, spz, smx, smy, smz, rlfs(i)
!
!Swaybrace reactions are now changed to zero if fully unloaded with regard to load and preload.
! If the total swaybrace reaction is negative, it is reacting and therefore in compression.
! If the total swaybrace reaction is positive, the swaybrace has completely unloaded and
! the resultant must be set to zero.
!
    if (rlfs(i).gt.0.0) rlfs(i)=0.0
!
!

```

```

!B. FIND the overall reaction at right, fwd swaybrace along the y-axis (Sfry):
!
    spx=px*L5*tand(alf)/2.0/(s1+L2)
    spy=(-1.0)*py*s2/(s2+s1)
    spz=(-1.0)*pz*s2*tand(alf)/2.0/(s1+s2)
    smx=(-1.0)*mx/2.0/L5
    smy=(-1.0)*my*tand(alf)/2.0/(s1+L2)
    smz=(-1.0)*4.0*mz/(L1+L2)**2
        if (mz.le.0.0) smz=0.0      ! SB will load during +Mz and not -Mz
!
! Add up the 6 reaction contributions by superposition...
!
    rrfsy(i)=spx+spy+spz+smx+smy+smz
!
! ...and find the component of the y-axis reactions along the swaybrace axis. It is
! noticed that a positive y-direction reaction (not load) of RRFSY will have a
! tensile component along the swaybrace rod and therefore does not require a
! sign change to match the correct, final sign convention.
!
    rrfsy(i)=(rrfsy(i))*sind(alf)
!
! Continue by finding reaction at right, forward swaybrace along the z-axis (Sfrz):
!
    spx=px*L5/2.0/(L2+s1)
    spy=(-1.0)*py*s2/(s2+s1)/tand(alf)
    spz=(-1.0)*pz*s2/2.0/(s1+s2)
    smx=(-1.0)*mx/2.0/L5/tand(alf)
    smy=(-1.0)*my/2.0/(s1+L2)
    smz=(-1.0)*4.0*mz/(L1+L2)**2/tand(alf)
        if (mz.le.0.0) smz=0.0      ! SB will load during +Mz and not -Mz
!
! Add up the 6 reaction contributions by superposition...
!
    rrfsz(i)=spx+spy+spz+smx+smy+smz
!
! ...and find the component of the z-axis reactions along the swaybrace axis. It is
! noticed that a positive z-direction reaction (not load) of RRFSZ will have a
! tensile component along the swaybrace rod and therefore does not require a
! sign change to match the correct, final sign convention.
!
    rrfsz(i)=(rrfsz(i))*cosd(alf)
!
! NOW add the two components together to form the reaction along the sb axis. The 0.5 term
! accounts for a split of the total reaction (before preload) between loading and unloading:
!
    rrf(i)=0.5*(rrfsy(i)+rrfsz(i))
!
! And add in the preload component (all sign conventions are now identical):
!
    rrf(i)=rrf(i)+sfs(lcase)
!
! Write all of the individual Sfs components to a file for review and graphing
!
    if (i.eq.1) then
        sfscheck='sfscheck.dat'
        open(unit=11, file=sfscheck)

```

```

!
    write (11,*) ' (SfSCHECK was created on ', today, ' )'
    write (11,200)
    write (11,*) '   Loads Contributing to Sfs           Preload = ', sfs(lcase)
    write (11,200)
    write (11,270) 'Dtime ', Spx, ' ', Spy, ' ', Spz, ' ', Smx, ' ', Smy, ' ', Smz, ' ', Sfs, '
    write (11,270) '(sec) ',(lb), ' ',(lb), ' ',(lb), ' ', (lb), ' ', (lb), ' ', (lb), ' ', (lb), '
endif
!
    write (11,280) dtime(i),spx, spy, spz, smx, smy, smz, rrfs(i)
!
!Swaybrace reactions are now changed to zero if fully unloaded with regard to load and preload.
! If the total swaybrace reaction is negative, it is reacting and therefore in compression.
! If the total swaybrace reaction is positive, the swaybrace has completely unloaded and
! the resultant must be set to zero.
!
    if (rrfs(i).gt.0.0) rrfs(i)=0.0
!
!
!C. Find the overall reaction at left, aft swaybrace along the y-axis (Saly):
!
    spx=px*L5*tand(alf)/2.0/(L1+s2)
    spy=(-1.0)*py*s1/(s2+s1)
    spz=pz*s1*tand(alf)/2.0/(s1+s2)
    smx=(-1.0)*mx/2.0/L5
    smy=(-1.0)*my*tand(alf)/2.0/(s2+L1)
    smz=4.0*mz/(L1+L2)**2
    if (mz.le.0.0) smz=0.0      ! SB will load during +Mz and not -Mz
!
! Add up the 6 reaction contributions by superposition...
!
    rlasy(i)=spx+spy+spz+smx+smy+smz
!
! ...and find the component of the y-axis reactions along the swaybrace axis. It is
! noticed that a positive y-direction reaction (not load) of RLASY will have a
! compressive component along the swaybrace rod and therefore is multiplied by
! a negative one to match correct, final sign convention.
!
    rlasy(i)=(-1.0)*(rlasy(i))*sind(alf)
!
! Continue by finding reaction at left, aft swaybrace along the z-axis (Salz):
!
    spx=(-1.0)*px*L5/2.0/(L1+s2)
    spy=py*s1/(s2+s1)/tand(alf)
    spz=(-1.0)*pz*s1/2.0/(s1+s2)
    smx=mx/2.0/L5/tand(alf)
    smy=my/2.0/(s2+L1)
    smz=(-1.0)*4.0*mz/(L1+L2)**2/tand(alf)
    if (mz.le.0.0) smz=0.0      ! SB will load during +Mz and not -Mz
!
! Add up the 6 reaction contributions by superposition...
!
    rlasz(i)=spx+spy+spz+smx+smy+smz
!
! ...and find the component of the z-axis reactions along the swaybrace axis. It is
! noticed that a negative z-direction reaction (not load) of RLASZ will have a

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```

! compressive component along the swaybrace rod and therefore does not require a
! sign change to match the correct, final sign convention.
!
      rlasz(i)=(rlasz(i))*cosd(alf)
!
! NOW add the two components together to form the reaction along the sb axis. The 0.5 term
! accounts for a split of the total reaction (before preload) between loading and unloading:
!
      rlas(i)=0.5*(rlasy(i)+rlasz(i))
!
! Add in the preload component (all sign conventions are now identical):
!
      rlas(i)=rlas(i)+sap(lcase)
!
! Write all of the individual Sap components to a file for review and graphing
!
      if (i.eq.1) then
        sapcheck='sapcheck.dat'
        open(unit=13, file=sapcheck)
!
        write (13,*) ' (SAPCHECK was created on ', today, ')'
        write (13,200)
        write (13,*) '   Loads Contributing to Sap           Preload = ', sap(lcase)
        write (13,200)
        write (13,270) 'Dtime ', Spx, ' ', Spy, ' ', Spz, ' ', Smx, ' ', Smy, ' ', Smz, ' ', SAP, ' '
        write (13,270) '(sec) ',(lb), ' ',(lb), ' ',(lb), ' ', (lb), ' ', (lb), ' ', (lb), ' ', (lb), ' '
        endif
!
        write (13,280) dtime(i),spx, spy, spz, smx, smy, smz, rlas(i)
!
! Swaybrace reactions are now changed to zero if fully unloaded with regard to load and preload.
! If the total swaybrace reaction is negative, it is reacting and therefore in compression.
! If the total swaybrace reaction is positive, the swaybrace has completely unloaded and
! the resultant must be set to zero.
!
      if (rlas(i).gt.0.0) rlas(i)=0.0
!
!
! D. Find the overall reaction at right, aft swaybrace along the y-axis (Sary):
!
      spx=(-1.0)*px*L5*tand(alf)/2.0/(L1+s2)
      spy=(-1.0)*py*s1/(s2+s1)
      spz=(-1.0)*pz*s1*tand(alf)/2.0/(s1+s2)
      smx=(-1.0)*mx/2.0/L5
      smy=my*tand(alf)/2.0/(s2+L1)
      smz=4.0*mz/(L1+L2)**2
      if (mz.ge.0.0) smz=0.0 ! SB will load during -Mz and not +Mz
!
! Add up the 6 reaction contributions by superposition...
!
      rrasy(i)=spx+spy+spz+smx+smy+smz
!
! ...and find the component of the y-axis reactions along the swaybrace axis. It is
! noticed that a positive y-direction reaction (not load) of RRASY will have a
! tensile component along the swaybrace rod and therefore does not require a
! sign change to match the correct, final sign convention.

```

```

!
      rras(i)=(rrasy(i))*sind(alf)
!
! Continue by finding reaction at right, aft swaybrace along the z-axis (Sarz):
!
      spx=(-1.0)*px*L5/2.0/(L1+s2)
      spy=(-1.0)*py*s1/(s2+s1)/tand(alf)
      spz=(-1.0)*pz*s1/2.0/(s1+s2)
      smx=(-1.0)*mx/2.0/L5/tand(alf)
      smy=my/2.0/(s2+L1)
      smz=4.0*mz/(L1+L2)**2/tand(alf)
      if (mz.ge.0.0) smz=0.0      ! SB will load during -Mz and not +Mz
!
! Add up the 6 reaction contributions by superposition...
!
      rrasz(i)=spx+spy+spz+smx+smy+smz
!
! ...and find the component of the z-axis reactions along the swaybrace axis. It is
! noticed that a positive z-direction reaction (not load) of RRASZ will have a
! tensile component along the swaybrace rod and therefore does not require a
! sign change to match the correct, final sign convention.
!
      rrasz(i)=(rrasz(i))*cosd(alf)
!
! NOW add the two components together to form the reaction along the sb axis. The 0.5 term
! accounts for a split of the total reaction (before preload) between loading and unloading:
!
      rras(i)=0.5*(rrasy(i)+rrasz(i))
!
! Add in the preload component (all sign conventions are now identical):
!
      rras(i)=rras(i)+sas(lcase)
!
! Write all of the individual Sas components to a file for review and graphing
!
      if (i.eq.1) then
        sascheck='sascheck.dat'
        open(unit=4, file=sascheck)
!
        write (4,*) ' (SASCHECK was created on ', today, ' )'
        write (4,200)
        write (4,*) '   Loads Contributing to Sas           Preload = ', sas(lcase)
        write (4,200)
        write (4,270) 'Dtime ', Spx, ' ', Spy, ' ', Spz, ' ', Smx, ' ', Smy, ' ', Smz, ' ', Sas, ' '
        write (4,270) '(sec) ',(lb), ' ',(lb), ' ',(lb), ' ', (lb), ' ', (lb), ' ', (lb), ' ', (lb), ' '
      endif
!
      write (4,280) dtime(i),spx, spy, spz, smx, smy, smz, rras(i)
!
!Swaybrace reactions are now changed to zero if fully unloaded with regard to load and preload.
! If the total swaybrace reaction is negative, it is reacting and therefore in compression.
! If the total swaybrace reaction is positive, the swaybrace has completely unloaded and
! the resultant must be set to zero.
!
      if (rras(i).gt.0.0) rras(i)=0.0
!

```

```

!
!E. Find the overall reaction at the FORWARD LUG along the x-, y-, and z-axes
!
! Since lug longitudinal and lateral loads may be in either direction and still
! react in tension, the sign attached to the final reaction result will denote
! global direction (positive aft and right).
!
! Lfx (Reaction in x-direction due to a contribution from Px only)
!
! From experimental data, the forward lug reacts 38.5% of the longitudinal load, the
! aft lug reacts 60.6% of the longitudinal load and 0.9% is attributed to unrecorded
! friction in the swaybraces. No lug preload data was available in the x-direction.
!
      rflx(i)=(-1.0)*px*0.385
!
!
! Lfy (Reaction in y-direction due to a contribution from Mx and Mz only)
!
      lmx=mx/2.0/L5
      lmz=mz/(L1+L2)
!
! Since both y-reactions and the preload have the same sign convention, the final
! lug reaction in the lateral direction is found as:
!
      rfly(i)=lmx+lmz+lfl(lcase)
!
!
! Lfz (Reaction in z-direction due to all contributions)
!
      lpx=px*L5/(s2+L1)
      lpy=(abs(py))*L2/tand(alf)/(L1+L2)
      lpz=(-1.0)*(pz)*L2/(L1+L2)
      lmx=(-1.0)*mx/2.0/L5/tand(alf)/2.0
      lmy=(-1.0)*my/(s2+L1)
      lmz=abs(mz)/(L1+L2)/tand(alf)
!
! The following three reaction components will be equally shared in loading and unloading:
!
      lpx=0.5*lpx
      lpz=0.5*lpz
      lmy=0.5*lmy
!
! Add up the 6 reaction contributions by superposition. It is noticed that a
! positive z-direction reaction (not load) of RFLZ will have a tensile reaction
! along the lug and therefore does not require a sign change to match the correct,
! final sign convention (positive tension).
!
      rflz(i)=lpx+lpy+lpz+lmx+lmy+lmz
!
! Add in the preload component (RFLZ and lug preload sign conventions are identical):
!
      rflz(i)=rflz(i)+lfw(lcase)
!
! Write all of the individual Lfz components to a file for review and graphing
!
      if (i.eq.1) then

```

```

lfzcheck='lfzcheck.dat'
open(unit=5, file=lfzcheck)
!
write (5,*) ' (LFZCHECK was created on ', today, ' )'
write (5,200)
write (5,*) '   Loads Contributing to Lfz           Preload = ', lfw(lcase)
write (5,200)
write (5,270) 'Dtime ', Lpx ', ' Lpy ', ' Lpz ', ' Lmx ', ' Lmy ', ' Lmz ', ' Lfz '
write (5,270) '(sec) ', (lb) ', (lb) ', (lb) ', ' (lb) ', ' (lb) ', ' (lb) ', ' (lb) '
endif
!
write (5,280) dtime(i), lpx, lpy, lpz, lmx, lmy, lmz, rflz(i)
!
! Now check if total vertical lug reaction is still positive and therefore in
! tension. If the total reaction is negative, then the lug has completely
! unloaded and the resultant must be set to zero.
!
if (rflz(i).lt.0.0) rflz(i)=0.0
!
!
!F. Find the overall reaction at the AFT LUG along the x-, y-, and z-axes
!
! Since lug longitudinal and lateral loads may be in either direction and still
! react in tension, the sign attached to the final reaction result will denote
! global direction (positive aft and right).
!
! Lax   (Reaction in x-direction due to a contribution from Px only)
!
! From experimental data, the forward lug reacts 38.5% of the longitudinal load, the
! aft lug reacts 60.6% of the longitudinal load and 0.9% is attributed to unrecorded
! friction in the swaybraces. No lug preload data was available in the x-direction.
!
ralx(i)=(-1.0)*px*0.606
!
!
! Lay   (Reaction in y-direction due to a contribution from Mx and Mz only)
!
lmx=mx/2.0/L5
lmz=(-1.0)*mz/(L1+L2)
!
! Since both y-reactions and the preload have the same sign convention, the final
! lug reaction in the lateral direction is found as:
!
raly(i)=lmx+lmz+lal(lcase)
!
!
! Laz   (Reaction in z-direction due to all contributions)
!
lpx=(-1.0)*px*L5/(s1+L2)
lpy=(abs(py))*L1/tand(alf)/(L1+L2)
lpz=(-1.0)*(pz)*L1/(L1+L2)
lmx=(-1.0)*mx/2.0/L5/tand(alf)
lmy=my/(s1+L2)
lmz=abs(mz)/(L1+L2)/tand(alf)
!
! The following three reaction components will be equally shared in loading and unloading:

```

```

!
    lpx=.5*lpx
    lpz=.5*lpz
    lmy=.5*lmy
!
! Add up the 6 reaction contributions by superposition. It is noticed that a
! positive z-direction reaction (not load) of RALZ will have a tensile reaction
! along the lug and therefore does not require a sign change to match the correct,
! final sign convention (positive tension).
!
    ralz(i)=lpx+lpy+lpz+lmx+lmy+lmz
!
! Add in the preload component (RALZ and lug preload sign conventions are identical):
!
    ralz(i)=ralz(i)+law(lcase)
!
! Write all of the individual Laz components to a file for review and graphing
!
    if (i.eq.1) then
        lazcheck='lazcheck.dat'
        open(unit=10, file=lazcheck)
!
        write (10,*) ' (LAZCHECK was created on ', today, ')'
        write (10,200)
        write (10,*) '   Loads Contributing to Laz           Preload = ', law(lcase)
        write (10,200)
        write (10,270) 'Dtime ', Lpx, ', Lpy ', Lpz, ', Lmx ', Lmy, ', Lmz ', Laz, '
        write (10,270) '(sec) ',(lb), ',(lb) ',(lb), ', (lb) ', (lb), ', (lb) ', (lb) '
    endif
!
    write (10,280) dtime(i),lpx, lpy, lpz, lmx, lmy, lmz, ralz(i)
!
! Now check if total vertical lug reaction is still positive and therefore in
! tension. If the total reaction is negative, then the lug has completely
! unloaded and the resultant must be set to zero.
!
    if (ralz(i).lt.0.0) ralz(i)=0.0
!
!
!-----
!
!All reaction calculations are now finished for the current data slice. Proceed to the
!next data slice and redo all reaction calculations
!
    if (k.eq.i) goto 120
    if (testtype.eq.1) then
        j=j+1
        goto 100
    else
        i=i+1
        goto 60
    endif
!
!-----
!
!Reaction calculations are finished for all time slices; results need written to an output file.
!
120    open(unit=3, file=react)    ! opens output file for all calculated reaction loads

```



```

!
! The following code writes all reactions for each time slice in tabular form to
! named output file #3. The first line prints the file name and todays date in the file.
!
      i=1
      j=1
      write (3,200)
      write (3,290)
      write (3,*) '          REACT: These data were calculated on ', today
      write (3,200)
      write (3,*) ' Swaybrace rods can only react in compression (negative values) along'
      write (3,*) ' the axis of the swaybrace rod. Lug hooks can only react in tension'
      write (3,*) ' vertically (positive values), but in either direction laterally or'
      write (3,*) ' longitudinally.'
      write (3,200)
!
!Begin new output trial to only show overall sb and all 3 lugs.
!Also add loadcase designation similar to grnddata.
!
      if (testtype.eq.1) then
         write (3,*) ' Load Test Forward Forward Aft Aft '
         write (3,*) ' Case Point Port SB Stbd SB Port SB Stbd SB'
         write (3,*) ' (LB.) (LB.) (LB.) (LB.) '
      else
         write (3,*) ' Delta Forward Forward Aft Aft '
         write (3,*) ' Time Port SB Stbd SB Port SB Stbd SB'
         write (3,*) ' (sec) (LB.) (LB.) (LB.) (LB.) '
      endif
!
! This DO statement allows the program to write the results of the ground test data
! with reference to the testpoint, or flight test data reference to the Delta Time
!
      ii=0
      do i=1,k
         if (testtype.eq.1) then
            if (point(i).eq.1) then
               ii=ii+1
               write (3,200)
               ! Updates loadcase counter
               ! Separates loadcases by 2 blank lines
            endif
            write (3,300) ii, point(i), rlfs(i), rrfs(i), rlas(i), rras(i)
         else
            if (i.eq.1) write (3,200)
            write (3,310) dtime(i), rlfs(i), rrfs(i), rlas(i), rras(i)
         endif
      end do
!
!The next set of code prints the lug loads with lateral components.
!
      write (3,200)
      if (testtype.eq.1) then
         write (3,*) 'Loadcase/ Forward Lug Aft Lug'
         write (3,*) 'Testpoint Long. Lateral Vertical Long. Lateral Vertical'
         write (3,*) ' (LB.) (LB.) (LB.) (LB.) (LB.) (LB.) '
      else
         write (3,*) ' Delta Forward Lug Aft Lug'
         write (3,*) ' Time Long. Lateral Vertical Long. Lateral Vertical'

```

```

        write (3,*) ' (sec)      (LB.)  (LB.)  (LB.)  (LB.)  (LB.)  (LB.)'
    endif
    ii=0

    do i=1,k
        if (testtype.eq.1) then
            if (point(i).eq.1) then
                ii=ii+1                ! Updates loadcase counter
                write (3,200)          ! Separates loadcases by a blank line
            endif
            write (3,320) ii, point(i), rflx(i), rfly(i), rflz(i), ralx(i), raly(i), ralz(i)
        else
            if (i.eq.1) write (3,200)
            write (3,330) dttime(i), rflx(i), rfly(i), rflz(i), ralx(i), raly(i), ralz(i)
        endif
    end do
    write (3,200)
    write (3,*) 'End of Data'

!
! Format statements for the output file
!
200    format (/)
210    format (x,a6,4x,a7,a7,a7,a7,a7,a7,a7,a7,/)
220    format (x,f6.3,x,f7.3,f7.3,f7.3,f7.3,f7.3,f7.3,f7.3,f7.3,/)
230    format (2x,a7,3x,a6,4x,a6,4x,a6,4x,a8,5x,a8,5x,a8,x,/)
240    format (x,f6.3,2x,f8.0,2x,f8.0,2x,f8.0,4x,f8.0,4x,f9.0,4x,f9.0)
250    format (x,a10,3x,a7,5x,a7,2x,a7,2x,a7,2x,a7,2x,a7,2x,a7,/)
260    format (5x,i2,8x,i2,4x,f9.0,f9.0,f9.0,f9.0,f9.0,f9.0)
270    format (2x,a7,3x,a6,4x,a6,4x,a6,4x,a8,5x,a8,5x,a8,5x,a8,x,/)
280    format (x,f6.3,3x,f7.0,3x,f7.0,3x,f7.0,4x,f7.0,6x,f7.0,6x,f7.0,6x,f7.0)
290    format (24x, 'CALCULATED INTERFACE REACTIONS')
300    format (5x, i2, 5x, i2, 6x, f9.1, 6x, f9.1, 6x, f9.1, 6x, f9.1)
310    format (5x, f7.4, 6x, f9.1, 6x, f9.1, 6x, f9.1, 6x, f9.1)
320    format (2x, i2, 2x, i2, 3x, f9.1, 2x, f9.1, 2x, f9.1, 3x, f9.1, 2x, f9.1, 2x, f9.1)
330    format (f7.4, 3x, f9.1, x, f9.1, 2x, f9.1, 3x, f9.1, x, f9.1, 2x, f9.1)

!
    rewind (unit=3)
    close (unit=3)
    close (unit=4)
    close (unit=5)
    close (unit=9)
    close (unit=10)
    close (unit=11)
    close (unit=12)
    close (unit=13)

!
end

```

APPENDIX B: *Instrumentation Specifications*

LOW PROFILE™ LOAD CELLS

Model 1100 Ultra Precision Series Universal (U.S. & Metric)

Why INTERFACE 1100 series load cells are the best in class:

- Proprietary Interface temperature compensated strain gages
- Accuracy to .02%
- High output – to 4mV/V
- Eccentric load compensated
- Low deflection
- .0008%/°F (.0015%/°C) temp effect on output
- Shunt calibration
- High precision base included
- Barometric compensation
- Tension and compression

DIMENSIONS

See Drawing	MODEL							
	1110		1120		1132		1140	
	CAPACITY							
	U.S. (lbf)	Metric (kN)	U.S. (lbf)	Metric (kN)	U.S. (lbf)	Metric (kN)	U.S. (lbf)	Metric (kN)
	300, 500, 1K, 2K, 3K, 5K, 10K	1.5, 2.5 5, 10, 25, 50	25K, 50K	100, 250	100K	450	200K	900
	inch	mm	inch	mm	inch	mm	inch	mm
①	4.13	104.8	6.06	153.9	8.00	203.2	11.0	279
②	1.38	34.9	1.75	44.5	2.50	63.5	3.50	88.9
③	1.25	31.7	1.63	41.4	2.25	57.2	3.00	76.2
④	1.34	34.0	2.65	67.3	3.76	95.2	4.81	122.2
⑤	3.50	88.9	5.13	130.3	130.3	165.1	900	229
⑥	22.5°	22.5°	15.0°	15.0°	11.25°	11.25°	11.25°	11.25°
⑦	0.28	7.10	0.41	10.4	0.53	13.5	0.65	16.8
⑧	5/8-18 UNF-3B	M-16 X 2-4H	1 1/4-12 UNF-3B	M33 X 2-4H	1 3/4-12 UNF-3B	M42 X 2-4H	2 3/4-8 UNF-3B	M72 X 2-4H
	1.12 in. deep	28.4 mm deep	1.40 in. deep	35.6 mm deep	2.15 in. deep	54.6 mm deep	3.25 in. deep	82.6 mm deep
⑨	0.20	5.10	0.30	7.60	0.40	10.2	0.50	12.7
⑩	1.13	28.6	1.75	44.5	2.00	50.8	3.00	76.2
⑪	0.03	0.80	0.03	0.80	0.03	0.80	0.03	0.80
⑫	1.25	31.8	2.25	57.2	3.00	76.2	4.50	114
⑬	5/8-18 UNF-3B	M-16 X 2-4H	1 1/4-12 UNF-3B	M33 X 2-4H	1 3/4-12 UNF-3B	M42 X 2-4H	2 3/4-8 UNF-3B	M72 X 2-4H
	.87 in. deep	22.1 mm deep	1.40 in. deep	35.6 mm deep	1.75 in. deep	44.5 mm deep	2.75 in. deep	69.8 mm deep

SPECIFICATIONS

PARAMETERS	MODEL				
	1110	1110	1120	1132	1140
	CAPACITY				
U.S. Models (lbf)	300, 500, 1K, 2K	5K, 10K	25K, 50K	100K	200K
Metric Models (kN)	1.5, 2.5, 5, 10	25, 50	100, 250	450	900
ACCURACY – (MAX ERROR)					
Static Error Band-% FS	± 0.02	± 0.03	± 0.04	± 0.05	± 0.06
Nonlinearity-% FS	± 0.03	± 0.04	± 0.05	± 0.05	± 0.06
Hysteresis-% FS	± 0.02	± 0.04	± 0.05	± 0.05	± 0.06
Nonrepeatability-% RO	± 0.01	± 0.01	± 0.01	± 0.01	± 0.01
Creep, in 20 min.-%	± 0.025	± 0.025	± 0.025	± 0.025	± 0.025
Side Load Sensitivity-%	± 0.1	± 0.1	± 0.1	± 0.1	± 0.1
Eccentric Load Sensitivity-%/in	± 0.1	± 0.1	± 0.1	± 0.1	± 0.1
TEMPERATURE					
Compensated Range-°F	15 to 115	15 to 115	15 to 115	15 to 115	15 to 115
Compensated Range-°C	-10 to 45	-10 to 45	-10 to 45	-10 to 45	-10 to 45
Operating Range-°F	-65 to 200	-65 to 200	-65 to 200	-65 to 200	-65 to 200
Operating Range-°C	-55 to 90	-55 to 90	-55 to 90	-55 to 90	-55 to 90
Effect on Zero-%RO/°F – MAX	± 0.0004	± 0.0004	± 0.0004	± 0.0004	± 0.0004
Effect on Zero-%RO/°C – MAX	± 0.0007	± 0.0007	± 0.0007	± 0.0007	± 0.0007
Effect on Output-%/°F – MAX	± 0.0008	± 0.0008	± 0.0008	± 0.0008	± 0.0008
Effect on Output-%/°C – MAX	± 0.0015	± 0.0015	± 0.0015	± 0.0015	± 0.0015
ELECTRICAL					
Rated Output-mV/V (Nominal)	2.0	4.0	4.0	4.0	4.0
Excitation Voltage-VDC MAX	10	10	10	10	10
Bridge Resistance-Ohm (Nominal)	350	350	350	350	350
Zero Balance-% RO	± 1.0	± 1.0	± 1.0	± 1.0	± 1.0
Insulation Resistance-Megohm	5000	5000	5000	5000	5000
MECHANICAL					
Safe Overload-% CAP	± 150	± 150	± 150	± 150	± 150
Deflection @ RO-inch	0.002	0.004	0.004	0.006	0.012
Deflection @ RO-mm	0.05	0.10	0.10	0.15	0.20
Base Part Number (Ref) (Metric)	B101 (m)	B102 (m)	B103 (m)	B112 (m)	B105 (m)
Natural Frequency-kHz	2.7, 3.5,	4.7, 6.6	4.6, 5.0	4.0	3.5
	4.9, 7.0				
Weight-lb	3.3	7.3	21.5	52	146
Weight-kg	1.5	3.3	9.8	24	66
Connector	PC04E-10-6P	PC04E-10-6P	PC04E-10-6P	PC04E-10-6P	PC04E-10-6P
Calibration	T & C	T & C	T & C	T & C	T & C

OPTIONS*

Compression overload protection
 Integral 10 ft cable
 Bayonet Connector
 Multiple bridge
 Standardized output
 Connector Protection

ACCESSORIES*

Mating connector
 Instrumentation
 Loading hardware

STANDARD CONFIGURATIONS

- 10 ft Integral Cable (11xxAJ-nn)
- <or> PC04E-10-6P Connector (11xxAF-nn)
- <or> PTO2E-10-6P Bayonet Connector (11xxACK-nn)

Micro-Measurements
Division
Made in USA

MEASUREMENTS GROUP, INC.
RALEIGH, NORTH CAROLINA

PRECISION STRAIN GAGES

F007

054011-2243
CODE

(+0.6 ±0.2)%
K₁

2.095 ±0.5%
GAGE FACTOR AT 24°C

350.0 ±0.4%
RESISTANCE IN OHMS AT 24°C

R-A56AD109
LOT NUMBER

QUANTITY

5

OPTION

E

TYPE

EA-06-125TR-350

EA-06-125TR-350

GENERAL INFORMATION: EA-SERIES STRAIN GAGES

GENERAL DESCRIPTION: EA-Series gages are a general purpose family of constantan strain gages widely used in experimental stress analysis. These gages are of open-faced construction with a 1 mil [0.001 in (0.03 mm)] tough, flexible polyimide film backing.

TEMPERATURE RANGE: -100° to +350° F (-75° to +175° C) for continuous use in static measurements; -320° to +400° F (-195° to +205° C) for special or short-term exposure.

SELF-TEMPERATURE COMPENSATION: See data curve below.

STRAIN LIMITS: Approximately 5% for gage lengths 1/8 in. (3.2 mm) and larger and approximately 3% for gage lengths under 1/8 in. (3.2 mm).

FATIGUE LIFE: 10⁶ cycles at ±1200µin/in (µm/m); 10⁶ cycles at ±1500µin/in (µm/m); 10⁶ cycles at ±1800µin/in (µm/m). 10⁶ cycles at 2800µin/in (µm/m) for unidirectional tension or compression loading. Longer gage lengths and lower resistances result in greater endurance and less scatter in fatigue life.

CEMENTS: Compatible with M-M Certified M-Bond 200 but it will normally not provide the greatest fatigue life. Micro-Measurements M-Bond AE-10/15, M-Bond GA-2, M-Bond 600, and M-Bond 610 are excellent. M-Bond 610 is the best choice over the entire operating range. Refer to M-M Catalog A-110 for information on bonding agents, and Bulletins B-127, B-130, and B-137 for installation procedures.

SOLDER: If operating temperature will not exceed +300° F (+150° C), M-Line 361 (63-37) tin-lead solder may be used for lead attachment. M-Line 450 (95-5) tin-antimony is satisfactory to +400° F (+205° C). When solder turrets (Option S) are supplied on these gages, they are formed with +570° F (+300° C) lead-tin silver solder alloy. Refer to M-M Catalog A-110 for further information on solder, and Tech Tip TT-609 for lead attachment techniques.

PROTECTIVE COATINGS: These EA open-faced gages should always be protected with a suitable coating that is applied as soon as possible after gage installation. Refer to M-M Catalog A-110 for information on Strain Gage Protective Coatings.

NOTE: The backing of EA-Series gages has been specially treated for optimum bond formation with all appropriate strain gage adhesives. No further cleaning is necessary if contamination of the prepared surface is avoided during handling.

G023

Micro-Measurements
Division
Made in USA

MEASUREMENTS GROUP, INC.
RALEIGH, NORTH CAROLINA

PRECISION STRAIN GAGES

F007

072816-3204
CODE

TRANVERSE SENSITIVITY AT 24°C
(+0.1 ± 0.2)%

GAGE FACTOR AT 24°C
2.080 ± 0.5%

RESISTANCE IN OHMS AT 24°C
350.0 ± 0.3%

LOT NUMBER
R-A58AD21

QUANTITY
5

OPTION

CEA-06-250UN-350
TYPE

CEA-06-250UN-350

GENERAL INFORMATION: CEA-SERIES STRAIN GAGES

GENERAL DESCRIPTION: CEA gages are a general-purpose family of constantan strain gages widely used in experimental stress analysis. The gages are supplied with a fully encapsulated grid and exposed copper-coated integral solder tabs.

TEMPERATURE RANGE: -100° to +400° F (-75° to +205° C) for continuous use in static measurements.

SELF-TEMPERATURE COMPENSATION: See data curve below.

STRAIN LIMITS: Approximately 5% for gage lengths 1/8 in. (3.2 mm) and larger; approximately 3% for gage lengths under 1/8 in. (3.2 mm).

FATIGUE LIFE: Fatigue life is a marked function of solder joint formation. With 30-AWG leads directly attached to gage tabs, fatigue life will be 10⁶ cycles at ±1500 μin/in (μm/m) using M-Line 361A solder.

CEMENTS: Compatible with M-M Certified M-Bond 200, but it will normally not provide the greatest strain limit. Micro-Measurements M-Bond AE-10/15, M-Bond GA-2, M-Bond 600, and M-Bond 610 are excellent. M-Bond 610 is the best choice over the entire operating range. Refer to M-M Catalog A-110 for information on bonding agents, and Bulletins B-127, B-130, and B-137 for installation procedures.

SOLDER: If operating temperature will not exceed +300° F (+150° C), M-Line solder 361A (63-37) tin-lead solder may be used for lead attachment. M-Line solder (95-5) tin-antimony is satisfactory to +400° F (+205° C). Refer to M-m Catalog A-110 for further information on solders, and Tech Tip TT-609 for lead attachment techniques.

BACKING: The backing of CEA-Series gages has been specially treated for optimum bond formation with all appropriate strain gage adhesives. No further cleaning is necessary if contamination of the prepared surface is avoided during handling.

G045

Division
Made in USA

MEASUREMENTS GROUP, INC.
RALEIGH, NORTH CAROLINA

**PRECISION
STRAIN GAGES**

F015

061720-3672
CODE

SECTION 3
NOMINAL (All Sections)
0.9±1.0%

SECTION 2
0.95±0.5% (+0.7±0.2)%

SECTION 1
0.80±0.5% (+1.4±0.2)%

24°C
GAGE FACTOR
RESISTANCE IN OHMS AT 24°C
350.0±0.4%

TRANSVERSE
SENSITIVITY 24°C

R-A50BD61
LOT NUMBER

QUANTITY
5

OPTION

CEA-06-062UT-350
TYPE

CEA-06-062UT-350

GENERAL INFORMATION: CEA-SERIES STRAIN GAGES

GENERAL DESCRIPTION: CEA gages are a general-purpose family of constantan strain gages widely used in experimental stress analysis. The gages are supplied with a fully encapsulated grid and exposed copper-coated integral solder tabs.

TEMPERATURE RANGE: -100° to +400° F (-75° to +205° C) for continuous use in static measurements.

SELF-TEMPERATURE COMPENSATION: See data curve below.

STRAIN LIMITS: Approximately 5% for gage lengths 1/8 in. (3.2 mm) and larger; approximately 3% for gage lengths under 1/8 in. (3.2 mm).

FATIGUE LIFE: Fatigue life is a marked function of solder joint formation. With 30-AWG leads directly attached to gage tabs, fatigue life will be 10⁵ cycles at ±1500µin/in (µm/m) using M-Line 361A solder.

CEMENTS: Compatible with M-M Certified M-Bond 200, but it will normally not provide the greatest strain limit. Micro-Measurements M-Bond AE-10/15, M-Bond GA-2, M-Bond 600, and M-Bond 610 are excellent. M-Bond 610 is the best choice over the entire operating range. Refer to M-M Catalog A-110 for information on bonding agents, and Bulletins B-127, B-130, and B-137 for installation procedures.

SOLDER: If operating temperature will not exceed +300° F (+150° C), M-Line solder 361A (63-37) tin-lead solder may be used for lead attachment. M-Line solder (95-5) tin-antimony is satisfactory to +400° F (+205° C). Refer to M-m Catalog A-110 for further information on solders, and Tech Tip TT-609 for lead attachment techniques.

BACKING: The backing of CEA-Series gages has been specially treated for optimum bond formation with all appropriate strain gage adhesives. No further cleaning is necessary if contamination of the prepared surface is avoided during handling.

G045

Variable Capacitance Accelerometer

Model 7290A

- Rugged
- 2 to 100 g Full Scale
- Overrange Stops
- Gas Damping
- ± 2 V Full Scale Output

DESCRIPTION

The ENDEVCO® Model 7290A MICROTRON® accelerometer family utilizes unique variable capacitance microsensors. The accelerometers are designed for measurement of relatively low level accelerations in aerospace and automotive environments. Typical applications require measurement of whole body motion immediately after the accelerometer is subjected to a shock motion, and in the presence of severe vibrational inputs.

Gas damping and internal overrange stops enable the anisotropically-etched silicon microsensors to withstand high shock and acceleration loads.

The Model 7290A can operate from 9.5 V to 18.0 V and provide a high level, low impedance output. The ± 2 volt differential output is dc coupled at a dc bias of approximately 3.6 V. Frequency response is controlled by the near-critically damped sensors. The use of gas damping results in very small thermally-induced changes of frequency response.

ENDEVCO Model 106/109 Dual Channel System, Model 4430A Signal Conditioner or Model 68207 BCAS™ Computer Controlled System are recommended as signal conditioner and power supply.

U.S. Patents 4,574,327, 4,609,968 and 4,999,735

Actual size

SPECIFICATIONS

PERFORMANCE CHARACTERISTICS: All values are typical at +75°F (+24°C) and 15 Vdc excitation unless otherwise stated. Calibration data, traceable to the National Institute of Standards, (NIST), is supplied.

	Units	Model 7290A-2	-10	-30	-100
RANGE [1]	g pk	± 2	± 10	± 30	± 100
SENSITIVITY (at 100 Hz) [2] [3]	mV/g	1000 $\pm$ 50	200 $\pm$ 10	66 $\pm$ 4	20 $\pm$ 1.0
FREQUENCY RESPONSE ($\pm$ 5%) [4]	Hz	0 to 35	0 to 500	0 to 800	0 to 1000
MOUNTED RESONANCE FREQUENCY	Hz	1300	3000	5500	5500
NON-LINEARITY AND HYSTERESIS [5]	% FSO Typ	± 0.20	± 0.20	± 0.20	± 1
	% FSO (Max)	± 0.50	± 0.50	± 0.50	± 2
TRANSVERSE SENSITIVITY [6]	% Max	2	2	2	2
ZERO MEASURAND OUTPUT [3]	mV Max	± 50	± 50	± 50	± 50
DAMPING RATIO		4.5	0.7	0.7	0.6
DAMPING RATIO CHANGE	%/°F	+0.04	+0.04	+0.04	+0.04
From -65°F to +250°F (-55°C to +121°C)	%/°C	+0.08	+0.08	+0.08	+0.08

Variable Capacitance Accelerometer

SPECIFICATIONS—continued

PERFORMANCE CHARACTERISTICS—continued

	Units	Model 7290A-2	-10	-30	-100
THERMAL ZERO SHIFT					
From 32°F to 122°F (0°C to 50°C)	% FSO Max	±1.0	±1.0	±1.0	±1.0
From -13°F to +167°F (-25°C to +75°C)	% FSO Max	±2.0	±2.0	±2.0	±2.0
THERMAL SENSITIVITY SHIFT					
From 32°F to 122°F (0°C to +50°C)	% Max	±2.0	±2.0	±2.0	±2.0
From -13°F to +167°F (-25°C to +75°C)	% Max	±3.0	±3.0	±3.0	±3.0
THERMAL TRANSIENT ERROR					
Equiv. g/°F		< 0.0006	< 0.0006	< 0.0006	< 0.0006
PER ISA RP 37.2	Equiv. g/°C	< 0.001	< 0.001	< 0.001	< 0.001
OVERRANGE (Determined by Electrical clipping or Mechanical stops, whichever is smaller.)					
Electrical clipping	g	-3.5/+3.8	-18/+19	-53/+57	-175/+190
Mechanical stops, typical/minimum	g	±4/±3	±30/±15	±90/±45	±170/±150
Recovery Time	μs	< 10	< 10	< 10	< 10
THRESHOLD (RESOLUTION) [7]	Equiv. g's	0.0005	0.0025	0.008	0.025
BASE STRAIN SENSITIVITY, MAX [8]	Equiv. g	0.01	0.01	0.01	0.01
MAGNETIC SUSCEPTIBILITY [9]	Equiv. g	< 0.1	< 0.1	< 0.1	< 0.1
WARM-UP TIME (to within 1%)	ms	1	1	1	1

ELECTRICAL

EXCITATION [3]	9.5 to 18.0 Vdc, 20 Vdc maximum without damage; excitation voltage can be applied to any lead without damage
CURRENT DRAIN [10]	7.5 mA Typ, 10 mA Max at 15 Vdc
OUTPUT IMPEDANCE/LOAD	500 ohms max/10K ohms resistance minimum, 0.1 μF capacitance maximum
RESIDUAL NOISE	100 μV rms typ, 500 μVrms max; 0.5 to 100 Hz. 500 μV rms typ, 1mV max; 0.5 Hz to 10 KHz

PHYSICAL

CASE, MATERIAL	Anodized aluminum alloy
ELECTRICAL, CONNECTIONS	Integral cable, four conductor No. 32 AWG, Teflon® insulated leads, braided shield, silicone jacket
IDENTIFICATION	Manufacturer's logo, model number and serial number
MOUNTING/TORQUE	Holes for two 4-40 or M3 mounting screws/6 lbf-in (0.7 Nm)
WEIGHT	10 grams (cable weighs 9 grams/meter)

ENVIRONMENTAL

ACCELERATION LIMITS (in any direction)	
Static	20 000 g
Sinusoidal/Random Vibration	100 g pk, 20 - 2000 Hz/40 g rms, 20 - 2000 Hz
Shock (half-sine pulse)	5000 g, 150 μsec or longer for the -2 and -10; 10 000 g, 80 μsec or longer for the -30 and -100
Zero Shift	0.1% FSO typical at 5000 g
TEMPERATURE	
Operating	-65°F to +250°F (-55°C to +121°C)
Storage	-100°F to +300°F (-73°C to +150°C)
HUMIDITY/ALTITUDE	Unaffected. Unit is epoxy sealed. Hybrid and sensor are hermetically sealed/Unaffected
ESD SENSITIVITY	Unit meets Class 3 requirements of MIL-STD-883

CALIBRATION DATA SUPPLIED

SENSITIVITY (at 100 Hz and 10 g pk, 7290A-2 at 1 g)	mV/g with 15 Vdc excitation
FREQUENCY RESPONSE	20 Hz to 2000 Hz for 7290A-2, to 5000 Hz for all other ranges, % deviation reference 100 Hz
ZERO MEASURAND OUTPUT	mV
MAXIMUM TRANSVERSE SENSITIVITY	% of sensitivity

ACCESSORIES

EHW265	(2) Size 4, Flat Washers
EH409	(2) 4-40 x 3/8 inch Cap Screws
EHM464	(1) Hex Wrench

OPTIONAL ACCESSORIES

24328	4 Conductor Shielded Cable
7990	Triaxial Mounting Block

NOTES

- Customized range, 7290A-XX, available on special order. FSO is nominally 4 volts. Combined non-linearity and hysteresis is typically ±1% FSO and ±2% FSO, maximum.
- Reference frequency is 20 Hz on the 2 g range.
- Over the excitation range 9.5 to 18.0 Vdc. Sensitivity changes +0.1%/V typical and zero measurand output changes -0.5 mV/V typical.

- Extended frequency response available on special order to extend to 0-900 Hz for 7290A-10, 0-1500 Hz for 7290A-30, and 0-2000 Hz for 7290A-100.
- Full scale output (FSO) is nominally 4 volts.
- 1% is typical. 1% maximum available on special order.
- THRESHOLD = MAX. RESIDUAL NOISE; 0.5 TO 100 Hz SENSITIVITY
- Per ISA 37.2 at 250 Microstrain.
- At 100 Gauss, 60 Hz.
- Current drain increases slightly with increasing excitation; typical change is +.06 mA per volt from 9.5 to 18.0 Vdc.

NOTE: Tighter specifications available on special order.

Continued product improvement necessitates that Endevco reserve the right to modify these specifications without notice. Endevco maintains a program of constant surveillance over all products to ensure a high level of reliability. This program includes attention to reliability factors during product design, the support of stringent Quality Control requirements, and compulsory corrective action procedures. These measures, together with conservative specifications have made the name Endevco synonymous with reliability.

ENDEVCO CORPORATION, 30700 RANCHO VIEJO ROAD, SAN JUAN CAPISTRANO, CA 92675 USA (714) 493-8181 fax (714) 661-7231

0195

APPENDIX C: *Reduced External Loads for Ground Test*

TABLE C1: EXTERNALLY APPLIED ACTUATOR LOADS DURING LOAD CASES 1 AND 2 WITH RESULTANTS AT STORE CG

	Testpoint Counter	APPLIED ACTUATOR LOADS (lbs.)						LOADS AT STORE CG (including weight of store)					
		Welded Lug 2 (Port, Middle)			Welded Lug 5 (Sbd, Middle)			Forces (lbs.)			Moments (in-lbs.)		
		x-direction	y-direction	z-direction	x-direction	y-direction	z-direction	x-direction	y-direction	z-direction	Roll	Pitch	Yaw
Load Case 1 (Long. Aft)	1-1	0	0	0	0	0	0	0	0	-1,975	0	0	0
	1-2	508	0	0	534	0	0	1,042	0	-1,975	0	0	-286
	1-3	1,007	0	0	1,032	0	0	2,039	0	-1,975	0	0	-275
	1-4	1,506	0	0	1,529	0	0	3,035	0	-1,975	0	0	-253
	1-5	2,005	0	0	2,052	0	0	4,057	0	-1,975	0	0	-517
	1-6	2,515	0	0	2,528	0	0	5,043	0	-1,975	0	0	-143
	1-7	3,003	0	0	3,041	0	0	6,044	0	-1,975	0	0	-418
	1-8	3,511	0	0	3,542	0	0	7,053	0	-1,975	0	0	-341
	1-9	4,006	0	0	4,046	0	0	8,052	0	-1,975	0	0	-440
	1-10	4,502	0	0	4,552	0	0	9,054	0	-1,975	0	0	-550
	1-11	4,945	0	0	5,001	0	0	9,946	0	-1,975	0	0	-616
	1-12	4,513	0	0	4,457	0	0	8,970	0	-1,975	0	0	616
	1-13	4,006	0	0	3,968	0	0	7,974	0	-1,975	0	0	418
	1-14	3,514	0	0	3,483	0	0	6,997	0	-1,975	0	0	341
	1-15	3,015	0	0	2,983	0	0	5,998	0	-1,975	0	0	352
	1-16	2,507	0	0	2,479	0	0	4,986	0	-1,975	0	0	308
	1-17	2,001	0	0	1,984	0	0	3,985	0	-1,975	0	0	187
	1-18	1,502	0	0	1,493	0	0	2,995	0	-1,975	0	0	99
	1-19	1,003	0	0	995	0	0	1,998	0	-1,975	0	0	88
	1-20	500	0	0	494	0	0	994	0	-1,975	0	0	66
	1-21	12	0	0	9	0	0	21	0	-1,975	0	0	33
Load Case 2 (Lateral Sbd)	Testpoint Counter	APPLIED ACTUATOR LOAD (lbs.)						LOADS AT STORE CG (including weight of store)					
		Welded Lug 5 (Sbd, Mid)			N/A (Only loaded Welded Lug 5)			Forces (lbs.)			Moments (in-lbs.)		
	x-direction	y-direction	z-direction	x-direction	y-direction	z-direction	x-direction	y-direction	z-direction	Roll	Pitch	Yaw	
	2-1	0	0	0	0	0	0	0	0	-1,975	0	0	0
	2-2	0	1,004	0	0	0	0	0	1,004	-1,975	0	0	0
	2-3	0	2,006	0	0	0	0	0	2,006	-1,975	0	0	0
	2-4	0	3,000	0	0	0	0	0	3,000	-1,975	0	0	0
	2-5	0	4,004	0	0	0	0	0	4,004	-1,975	0	0	0
	2-6	0	5,029	0	0	0	0	0	5,029	-1,975	0	0	0
	2-7	0	6,003	0	0	0	0	0	6,003	-1,975	0	0	0
	2-8	0	7,004	0	0	0	0	0	7,004	-1,975	0	0	0
	2-9	0	8,001	0	0	0	0	0	8,001	-1,975	0	0	0
	2-10	0	9,003	0	0	0	0	0	9,003	-1,975	0	0	0
	2-11	0	10,007	0	0	0	0	0	10,007	-1,975	0	0	0
	2-12	0	9,003	0	0	0	0	0	9,003	-1,975	0	0	0
	2-13	0	8,001	0	0	0	0	0	8,001	-1,975	0	0	0
	2-14	0	7,004	0	0	0	0	0	7,004	-1,975	0	0	0
	2-15	0	6,003	0	0	0	0	0	6,003	-1,975	0	0	0
	2-16	0	5,008	0	0	0	0	0	5,008	-1,975	0	0	0
	2-17	0	4,004	0	0	0	0	0	4,004	-1,975	0	0	0
	2-18	0	3,000	0	0	0	0	0	3,000	-1,975	0	0	0
	2-19	0	2,006	0	0	0	0	0	2,006	-1,975	0	0	0
	2-20	0	1,004	0	0	0	0	0	1,004	-1,975	0	0	0
	2-21	0	14	0	0	0	0	0	14	-1,975	0	0	0

Note: POSITIVE sign convention is aft, starboard, up, port down roll, nose up pitch, nose left yaw

TABLE C2: EXTERNALLY APPLIED ACTUATOR LOADS DURING LOAD CASES 3 AND 4 WITH RESULTANTS AT STORE CG

	Testpoint Counter	APPLIED ACTUATOR LOADS (lbs.)						LOADS AT STORE CG (including weight of store)					
		Welded Lug 2 (Port, Mid)			Welded Lug 5 (Stbd, Mid)			Forces (lbs.)			Moments (in-lbs.)		
		x-direction	y-direction	z-direction	x-direction	y-direction	z-direction	x-direction	y-direction	z-direction	Roll	Pitch	Yaw
Load Case 3 (Vertical Up)	3-1	0	0	0	0	0	0	0	0	-1,975	0	0	0
	3-2	0	0	502	0	0	502	0	0	-971	0	0	0
	3-3	0	0	1,003	0	0	1,003	0	0	31	0	0	0
	3-4	0	0	1,501	0	0	1,501	0	0	1,028	0	0	0
	3-5	0	0	2,002	0	0	2,002	0	0	2,029	0	0	0
	3-6	0	0	2,504	0	0	2,504	0	0	3,033	0	0	0
	3-7	0	0	3,001	0	0	3,001	0	0	4,028	0	0	0
	3-8	0	0	3,503	0	0	3,503	0	0	5,032	0	0	0
	3-9	0	0	4,001	0	0	4,001	0	0	6,026	0	0	0
	3-10	0	0	4,503	0	0	4,503	0	0	7,030	0	0	0
	3-11	0	0	5,000	0	0	5,000	0	0	8,025	0	0	0
	3-12	0	0	4,506	0	0	4,506	0	0	7,037	0	0	0
	3-13	0	0	4,008	0	0	4,008	0	0	6,040	0	0	0
	3-14	0	0	3,507	0	0	3,507	0	0	5,039	0	0	0
	3-15	0	0	3,001	0	0	3,001	0	0	4,028	0	0	0
	3-16	0	0	2,501	0	0	2,501	0	0	3,026	0	0	0
	3-17	0	0	2,002	0	0	2,002	0	0	2,029	0	0	0
	3-18	0	0	1,501	0	0	1,501	0	0	1,028	0	0	0
	3-19	0	0	1,003	0	0	1,003	0	0	31	0	0	0
	3-20	0	0	502	0	0	502	0	0	-971	0	0	0
	3-21	0	0	7	0	0	7	0	0	-1,961	0	0	0
Load Case 4 (Vertical Dn)	Testpoint Counter	APPLIED ACTUATOR LOADS (lbs.)						LOADS AT STORE CG (including weight of store)					
		Welded Lug 2 (Port, Mid)			Welded Lug 5 (Stbd, Mid)			Forces (lbs.)			Moments (in-lbs.)		
	x-direction	y-direction	z-direction	x-direction	y-direction	z-direction	x-direction	y-direction	z-direction	Roll	Pitch	Yaw	
	4-1	0	0	0	0	0	0	0	-1,975	0	0	0	
	4-2	0	0	-502	0	0	-502	0	0	-2,979	0	0	0
	4-3	0	0	-1,003	0	0	-1,003	0	0	-3,981	0	0	0
	4-4	0	0	-1,501	0	0	-1,501	0	0	-4,978	0	0	0
	4-5	0	0	-2,002	0	0	-2,002	0	0	-5,979	0	0	0
	4-6	0	0	-2,504	0	0	-2,504	0	0	-6,983	0	0	0
	4-7	0	0	-3,001	0	0	-3,001	0	0	-7,978	0	0	0
	4-8	0	0	-3,503	0	0	-3,503	0	0	-8,982	0	0	0
	4-9	0	0	-4,001	0	0	-4,001	0	0	-9,976	0	0	0
	4-10	0	0	-4,503	0	0	-4,503	0	0	-10,980	0	0	0
	4-11	0	0	-5,000	0	0	-5,000	0	0	-11,975	0	0	0
	4-12	0	0	-4,503	0	0	-4,503	0	0	-10,980	0	0	0
	4-13	0	0	-4,001	0	0	-4,001	0	0	-9,976	0	0	0
	4-14	0	0	-3,507	0	0	-3,507	0	0	-8,989	0	0	0
	4-15	0	0	-3,005	0	0	-3,005	0	0	-7,985	0	0	0
	4-16	0	0	-2,504	0	0	-2,504	0	0	-6,983	0	0	0
	4-17	0	0	-2,002	0	0	-2,002	0	0	-5,979	0	0	0
	4-18	0	0	-1,501	0	0	-1,501	0	0	-4,978	0	0	0
	4-19	0	0	-1,003	0	0	-1,003	0	0	-3,981	0	0	0
	4-20	0	0	-502	0	0	-502	0	0	-2,979	0	0	0
4-21	0	0	-7	0	0	-7	0	0	-1,989	0	0	0	

Note: POSITIVE sign convention is aft, starboard, up, port down roll, nose up pitch, nose left yaw

TABLE C3: EXTERNALLY APPLIED ACTUATOR LOADS DURING LOAD CASES 5 AND 6 WITH RESULTANTS AT STORE CG

	Testpoint Counter	APPLIED ACTUATOR LOADS (lbs.)						LOADS AT STORE CG (including weight of store)					
		Welded Lug 2 (Port, Mid)			Welded Lug 5 (Sbd, Mid)			Forces (lbs.)			Moments (in-lbs.)		
		x-direction	y-direction	z-direction	x-direction	y-direction	z-direction	x-direction	y-direction	z-direction	Roll	Pitch	Yaw
Load Case 5 (Positive Roll)	5-1	0	0	0	0	0	0	0	0	-1,975	0	0	0
	5-2	0	0	-607	0	0	500	0	0	-2,082	12,182	0	0
	5-3	0	0	-1,098	0	0	1,000	0	0	-2,073	23,086	0	0
	5-4	0	0	-1,587	0	0	1,500	0	0	-2,062	33,962	0	0
	5-5	0	0	-2,083	0	0	2,000	0	0	-2,058	44,921	0	0
	5-6	0	0	-2,576	0	0	2,501	0	0	-2,050	55,838	0	0
	5-7	0	0	-3,072	0	0	3,003	0	0	-2,043	66,825	0	0
	5-8	0	0	-3,555	0	0	3,503	0	0	-2,027	77,646	0	0
	5-9	0	0	-4,051	0	0	4,003	0	0	-2,023	88,605	0	0
	5-10	0	0	-4,544	0	0	4,504	0	0	-2,015	99,522	0	0
	5-11	0	0	-5,001	0	0	4,877	0	0	-2,099	108,666	0	0
	5-12	0	0	-4,665	0	0	4,507	0	0	-2,133	100,897	0	0
	5-13	0	0	-4,146	0	0	4,003	0	0	-2,118	89,649	0	0
	5-14	0	0	-3,655	0	0	3,503	0	0	-2,127	78,746	0	0
	5-15	0	0	-3,163	0	0	3,003	0	0	-2,135	67,828	0	0
	5-16	0	0	-2,648	0	0	2,501	0	0	-2,122	56,636	0	0
	5-17	0	0	-2,137	0	0	2,000	0	0	-2,111	45,512	0	0
	5-18	0	0	-1,630	0	0	1,500	0	0	-2,104	34,430	0	0
	5-19	0	0	-1,130	0	0	1,000	0	0	-2,104	23,430	0	0
	5-20	0	0	-622	0	0	500	0	0	-2,097	12,347	0	0
	5-21	0	0	-57	0	0	-34	0	0	-2,066	261	0	0
Load Case 6 (Nose Up and Lateral Port)													
	Testpoint Counter	APPLIED ACTUATOR LOADS (lbs.)						LOADS AT STORE CG (including weight of store)					
		Welded Lugs 1 & 4 (Port & Sbd, Fwd)			Welded Lug 2 (Port, Mid)			Forces (lbs.)			Moments (in-lbs.)		
		x-direction	y-direction	z-direction	x-direction	y-direction	z-direction	x-direction	y-direction	z-direction	Roll	Pitch	Yaw
	6-1	0	0	0	0	0	0	0	0	-1,975	0	0	0
	6-2	0	0	519	0	-507	0	0	-507	-1,456	0	18,680	0
	6-3	0	0	1,015	0	-1,003	0	0	-1,003	-960	0	36,549	0
	6-4	0	0	1,512	0	-1,503	0	0	-1,503	-463	0	54,418	0
	6-5	0	0	2,015	0	-2,003	0	0	-2,003	40	0	72,558	0
	6-6	0	0	2,527	0	-2,503	0	0	-2,503	552	0	90,967	0
	6-7	0	0	3,038	0	-3,003	0	0	-3,003	1,063	0	109,377	0
	6-8	0	0	3,546	0	-3,502	0	0	-3,502	1,571	0	127,651	0
	6-9	0	0	4,050	0	-4,002	0	0	-4,002	2,075	0	145,791	0
	6-10	0	0	4,565	0	-4,501	0	0	-4,501	2,590	0	164,335	0
	6-11	0	0	4,977	0	-4,883	0	0	-4,883	3,002	0	179,189	0
	6-12	0	0	4,431	0	-4,501	0	0	-4,501	2,456	0	159,519	0
	6-13	0	0	3,927	0	-4,002	0	0	-4,002	1,952	0	141,380	0
	6-14	0	0	3,438	0	-3,502	0	0	-3,502	1,463	0	123,780	0
	6-15	0	0	2,939	0	-3,003	0	0	-3,003	964	0	105,821	0
	6-16	0	0	2,443	0	-2,503	0	0	-2,503	468	0	87,952	0
	6-17	0	0	1,969	0	-2,003	0	0	-2,003	-6	0	70,892	0
	6-18	0	0	1,480	0	-1,503	0	0	-1,503	-495	0	53,293	0
	6-19	0	0	985	0	-1,003	0	0	-1,003	-990	0	35,469	0
	6-20	0	0	493	0	-504	0	0	-504	-1,482	0	17,734	0
	6-21	0	0	4	0	-7	0	0	-7	-1,971	0	135	0

Note: POSITIVE sign convention is aft, starboard, up, port down roll, nose up pitch, nose left yaw

TABLE C4: EXTERNALLY APPLIED ACTUATOR LOADS DURING LOAD CASES 7 AND 8 WITH RESULTANTS AT STORE CG

	Testpoint Counter	APPLIED ACTUATOR LOADS (lbs.)						LOADS AT STORE CG (including weight of store)					
		Welded Lugs 1 & 4 (Port & Sbd, Fwd)			Welded Lugs 3 & 6 (Port & Sbd, Aft)			Forces (lbs.)			Moments (in-lbs.)		
		x-direction	y-direction	z-direction	x-direction	y-direction	z-direction	x-direction	y-direction	z-direction	Roll	Pitch	Yaw
Load Case 7 (Positive Pitch)	7-1	0	0	0	0	0	0	0	0	-1,975	0	0	0
	7-2	0	0	405	0	0	-504	0	0	-2,074	0	32,714	0
	7-3	0	0	913	0	0	-1,011	0	0	-2,073	0	69,254	0
	7-4	0	0	1,420	0	0	-1,503	0	0	-2,058	0	105,254	0
	7-5	0	0	1,919	0	0	-2,011	0	0	-2,067	0	141,479	0
	7-6	0	0	2,436	0	0	-2,503	0	0	-2,043	0	177,794	0
	7-7	0	0	2,947	0	0	-3,005	0	0	-2,034	0	214,289	0
	7-8	0	0	3,458	0	0	-3,502	0	0	-2,018	0	250,559	0
	7-9	0	0	3,970	0	0	-4,005	0	0	-2,011	0	287,099	0
	7-10	0	0	4,481	0	0	-4,513	0	0	-2,007	0	323,774	0
	7-11	0	0	4,972	0	0	-4,983	0	0	-1,985	0	358,379	0
	7-12	0	0	4,336	0	0	-4,501	0	0	-2,140	0	318,148	0
	7-13	0	0	3,840	0	0	-4,002	0	0	-2,137	0	282,283	0
	7-14	0	0	3,340	0	0	-3,502	0	0	-2,137	0	246,283	0
	7-15	0	0	2,836	0	0	-3,002	0	0	-2,141	0	210,148	0
	7-16	0	0	2,343	0	0	-2,503	0	0	-2,135	0	174,463	0
	7-17	0	0	1,855	0	0	-2,003	0	0	-2,123	0	138,913	0
	7-18	0	0	1,374	0	0	-1,503	0	0	-2,104	0	103,589	0
	7-19	0	0	893	0	0	-1,003	0	0	-2,086	0	68,264	0
	7-20	0	0	385	0	0	-504	0	0	-2,094	0	31,994	0
	7-21	0	0	-46	0	0	-7	0	0	-2,029	0	-1,395	0
Load Case 8 (Negative Yaw)	Testpoint Counter	APPLIED ACTUATOR LOADS (lbs.)						LOADS AT STORE CG (including weight of store)					
		Welded Lug 3 (Port, Aft)			Welded Lug 4 (Sbd, Fwd)			Forces (lbs.)			Moments (in-lbs.)		
	x-direction	y-direction	z-direction	x-direction	y-direction	z-direction	x-direction	y-direction	z-direction	Roll	Pitch	Yaw	
	8-1	0	0	0	0	0	0	0	-1,975	0	0	0	
	8-2	0	-507	0	0	531	0	24	-1,975	-390	0	-37,395	
	8-3	0	-1,003	0	0	1,050	0	47	-1,975	-770	0	-73,935	
	8-4	0	-1,503	0	0	1,554	0	51	-1,975	-1,147	0	-110,070	
	8-5	0	-2,003	0	0	2,053	0	50	-1,975	-1,521	0	-146,025	
	8-6	0	-2,503	0	0	2,553	0	50	-1,975	-1,896	0	-182,025	
	8-7	0	-3,002	0	0	3,065	0	63	-1,975	-2,275	0	-218,385	
	8-8	0	-3,502	0	0	3,568	0	67	-1,975	-2,651	0	-254,520	
	8-9	0	-4,002	0	0	4,084	0	82	-1,975	-3,032	0	-291,060	
	8-10	0	-4,501	0	0	4,595	0	94	-1,975	-3,411	0	-327,465	
	8-11	0	-4,914	0	0	5,007	0	94	-1,975	-3,720	0	-357,165	
	8-12	0	-4,505	0	0	4,477	0	-28	-1,975	-3,368	0	-323,369	
	8-13	0	-4,005	0	0	4,007	0	2	-1,975	-3,005	0	-288,450	
	8-14	0	-3,505	0	0	3,512	0	7	-1,975	-2,632	0	-252,630	
	8-15	0	-3,002	0	0	3,008	0	6	-1,975	-2,254	0	-216,360	
	8-16	0	-2,503	0	0	2,512	0	9	-1,975	-1,881	0	-180,540	
	8-17	0	-2,003	0	0	2,012	0	8	-1,975	-1,506	0	-144,540	
	8-18	0	-1,503	0	0	1,508	0	4	-1,975	-1,129	0	-108,405	
	8-19	0	-1,003	0	0	1,008	0	4	-1,975	-754	0	-72,405	
	8-20	0	-504	0	0	515	0	12	-1,975	-382	0	-36,675	
	8-21	0	-4	0	0	39	0	35	-1,975	-16	0	-1,530	

Note: POSITIVE sign convention is aft, starboard, up, port down roll, nose up pitch, nose left yaw

APPENDIX D: *Reduced Lug Millivolt Data*

TABLE D1: INSTRUMENTED LUG STRAIN GAGE DATA. *Load Case 1: Longitudinal Load*

Total External	FORWARD LUG STRAIN GAGES (mv)					AFT LUG STRAIN GAGES (mv)				
Load (lb.)	<i>Vertical (interior)</i>	<i>Bending (side)</i>	<i>Shear (fore/aft)</i>	<i>Shear (side)</i>	<i>Shear (fore/aft)</i>	<i>Vertical (interior)</i>	<i>Bending (side)</i>	<i>Shear (fore/aft)</i>	<i>Shear (side)</i>	<i>Shear (fore/aft)</i>
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1,041	0.06	0.00	0.12	-0.12	-0.24	-0.07	-0.09	-0.30	0.61	0.00
2,038	0.18	-0.03	0.28	-0.27	-0.52	-0.10	-0.12	-0.64	1.25	0.00
3,035	0.34	-0.03	0.43	-0.55	-0.79	-0.07	-0.15	-0.94	1.98	-0.03
4,057	0.49	-0.03	0.52	-0.46	-1.04	0.00	-0.18	-1.31	2.90	-0.10
5,043	0.73	-0.06	0.58	-0.49	-1.19	0.12	-0.18	-1.74	3.90	-0.16
6,044	0.89	-0.06	0.67	-0.49	-1.37	0.21	-0.24	-2.10	4.88	-0.22
7,053	1.10	-0.06	0.73	-0.52	-1.52	0.33	-0.30	-2.44	5.25	-0.28
8,052	1.28	-0.09	0.82	-0.55	-1.65	0.48	-0.39	-2.78	5.28	-0.31
9,054	1.50	-0.09	0.95	-0.58	-1.80	0.64	-0.48	-3.05	5.31	-0.37
9,947	1.68	-0.09	1.04	-0.64	-2.01	0.73	-0.58	-3.33	5.34	-0.43
8,970	1.50	-0.06	0.82	-0.58	-1.83	0.73	-0.58	-3.08	5.28	-0.46
7,975	1.31	-0.06	0.76	-0.55	-1.59	0.67	-0.39	-2.81	5.28	-0.43
6,998	1.16	-0.03	0.58	-0.46	-1.37	0.58	-0.30	-2.53	5.22	-0.43
5,998	0.98	-0.03	0.46	-0.36	-1.16	0.55	-0.18	-2.26	5.19	-0.43
4,987	0.80	0.03	0.34	-0.27	-0.91	0.45	-0.09	-2.01	5.09	-0.40
3,986	0.61	0.03	0.18	-0.18	-0.70	0.39	-0.06	-1.77	4.67	-0.34
2,995	0.46	0.00	0.03	-0.06	-0.39	0.33	-0.03	-1.40	3.75	-0.28
1,998	0.31	0.00	-0.06	0.00	-0.15	0.24	0.03	-1.01	2.68	-0.22
994	0.12	-0.06	0.00	0.00	-0.03	0.09	0.03	-0.49	1.28	-0.13
21	-0.03	-0.06	0.00	-0.06	0.03	0.03	0.03	0.03	0.03	-0.03

TABLE D2: INSTRUMENTED LUG STRAIN GAGE DATA. *Load Case 2: Lateral Load*

Total External	FORWARD LUG STRAIN GAGES (mv)					AFT LUG STRAIN GAGES (mv)				
Load (lb.)	<i>Vertical (interior)</i>	<i>Bending (side)</i>	<i>Shear (fore/aft)</i>	<i>Shear (side)</i>	<i>Shear (fore/aft)</i>	<i>Vertical (interior)</i>	<i>Bending (side)</i>	<i>Shear (fore/aft)</i>	<i>Shear (side)</i>	<i>Shear (fore/aft)</i>
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1,004	0.97	-0.15	-0.03	0.18	0.15	0.25	0.22	-0.19	0.06	0.09
2,006	1.64	-0.06	-0.24	0.33	0.24	0.80	0.52	-0.19	0.15	0.12
3,000	2.29	0.03	-0.30	0.36	0.06	1.32	0.77	-0.19	0.25	0.12
4,004	2.83	0.16	-0.33	0.42	-0.13	1.84	0.95	-0.22	0.34	0.09
5,029	3.38	0.25	-0.45	0.49	-0.37	2.29	1.16	-0.25	0.40	0.06
6,003	3.90	0.34	-0.52	0.58	-0.55	2.75	1.32	-0.22	0.46	-0.03
7,004	4.45	0.52	-0.61	0.70	-0.83	3.30	1.59	-0.13	0.52	-0.06
8,001	4.88	0.61	-0.70	0.76	-1.04	3.79	1.87	-0.10	0.61	-0.03
9,003	5.37	0.77	-0.85	0.85	-1.29	4.28	2.11	0.00	0.64	-0.03
10,007	5.86	0.92	-0.91	0.91	-1.47	4.70	2.29	0.00	0.67	-0.06
9,003	5.34	0.83	-0.64	0.94	-1.68	4.31	1.87	0.03	0.40	-0.34
8,001	4.85	0.70	-0.36	0.91	-1.83	3.85	1.62	0.18	0.22	-0.49
7,004	4.30	0.64	-0.09	0.88	-1.96	3.33	1.50	0.36	0.03	-0.58
6,003	3.75	0.55	0.25	0.79	-2.08	2.84	1.35	0.58	-0.15	-0.67
5,008	3.20	0.40	0.37	0.64	-1.90	2.35	1.16	0.64	-0.24	-0.67
4,004	2.65	0.25	0.43	0.45	-1.53	1.87	0.95	0.54	-0.21	-0.58
3,000	2.04	0.12	0.40	0.27	-1.19	1.38	0.68	0.39	-0.15	-0.46
2,006	1.46	0.06	0.34	0.12	-0.86	0.89	0.46	0.24	-0.09	-0.28
1,004	0.85	0.03	0.19	-0.03	-0.61	0.37	0.16	0.03	-0.06	-0.19
14	0.06	0.00	-0.06	-0.03	0.00	-0.03	0.00	0.03	0.03	0.06

TABLE D3: INSTRUMENTED LUG STRAIN GAGE DATA. *Load Case 3: Vertical Load (up)*

Total External	FORWARD LUG STRAIN GAGES (mv)					AFT LUG STRAIN GAGES (mv)				
Load (lb.)	<i>Vertical (interior)</i>	<i>Bending (side)</i>	<i>Shear (fore/aft)</i>	<i>Shear (side)</i>	<i>Shear (fore/aft)</i>	<i>Vertical (interior)</i>	<i>Bending (side)</i>	<i>Shear (fore/aft)</i>	<i>Shear (side)</i>	<i>Shear (fore/aft)</i>
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1,004	-0.10	0.00	-0.03	0.00	0.00	-0.16	-0.09	-0.09	-0.03	-0.03
2,006	-0.19	0.03	-0.06	0.07	0.03	-0.37	-0.12	-0.12	-0.06	-0.03
3,003	-0.19	0.03	-0.12	0.07	0.00	-0.43	-0.15	-0.15	-0.06	-0.03
4,004	-0.22	0.06	-0.09	0.07	-0.03	-0.43	-0.18	-0.15	-0.06	0.00
5,008	-0.28	0.06	-0.09	0.03	-0.03	-0.43	-0.15	-0.12	-0.06	-0.03
6,003	-0.34	0.09	-0.09	0.03	-0.03	-0.43	-0.12	-0.12	-0.09	-0.03
7,007	-0.40	0.12	-0.12	0.00	-0.03	-0.43	-0.15	-0.12	-0.06	-0.03
8,001	-0.40	0.09	-0.15	0.03	0.00	-0.43	-0.12	-0.18	-0.06	-0.03
9,005	-0.43	0.12	-0.15	0.07	0.03	-0.43	-0.15	-0.12	-0.06	-0.03
10,000	-0.46	0.12	-0.15	0.03	0.06	-0.46	-0.12	-0.15	-0.06	-0.03
9,012	-0.43	0.09	-0.18	0.07	0.00	-0.43	-0.12	-0.12	-0.06	-0.03
8,015	-0.37	0.12	-0.21	0.10	0.03	-0.43	-0.12	-0.15	-0.06	-0.03
7,014	-0.34	0.12	-0.21	0.10	-0.03	-0.43	-0.12	-0.15	-0.06	-0.03
6,003	-0.28	0.12	-0.25	0.13	0.00	-0.43	-0.12	-0.15	-0.06	-0.03
5,001	-0.22	0.16	-0.21	0.16	0.00	-0.40	-0.15	-0.12	-0.09	-0.03
4,004	-0.19	0.12	-0.21	0.16	-0.03	-0.43	-0.15	-0.12	-0.06	-0.06
3,003	-0.10	0.12	-0.25	0.13	0.03	-0.43	-0.15	-0.18	-0.09	-0.03
2,006	-0.07	0.06	-0.18	0.13	0.03	-0.34	-0.12	-0.15	-0.06	-0.03
1,004	0.03	0.03	-0.15	0.16	0.09	-0.19	-0.09	-0.18	-0.06	0.03
14	0.12	0.00	-0.12	0.16	0.12	0.00	-0.09	-0.22	-0.03	0.06

TABLE D4: INSTRUMENTED LUG STRAIN GAGE DATA. *Load Case 4: Vertical Load (down)*

Total External	FORWARD LUG STRAIN GAGES (mv)					AFT LUG STRAIN GAGES (mv)				
Load (lb.)	<i>Vertical (interior)</i>	<i>Bending (side)</i>	<i>Shear (fore/aft)</i>	<i>Shear (side)</i>	<i>Shear (fore/aft)</i>	<i>Vertical (interior)</i>	<i>Bending (side)</i>	<i>Shear (fore/aft)</i>	<i>Shear (side)</i>	<i>Shear (fore/aft)</i>
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1,004	0.06	-0.03	0.00	0.00	0.03	0.15	0.00	-0.12	0.00	0.06
2,006	0.15	-0.03	-0.03	0.03	0.06	0.31	0.00	-0.15	-0.03	0.12
3,003	0.27	-0.06	-0.06	0.06	0.09	0.49	0.00	-0.19	0.03	0.21
4,004	0.39	-0.09	-0.09	0.09	0.12	0.64	0.03	-0.34	0.03	0.30
5,008	0.58	-0.06	-0.12	0.15	0.19	0.85	0.03	-0.40	0.07	0.36
6,003	0.82	-0.12	-0.12	0.21	0.22	1.04	0.06	-0.46	0.10	0.39
7,007	1.03	-0.12	-0.09	0.27	0.22	1.22	0.12	-0.49	0.10	0.48
8,001	1.25	-0.18	-0.09	0.24	0.19	1.40	0.16	-0.49	0.13	0.48
9,005	1.49	-0.21	-0.06	0.30	0.15	1.59	0.19	-0.52	0.13	0.55
10,000	1.74	-0.24	-0.06	0.27	0.19	1.77	0.22	-0.55	0.16	0.58
9,005	1.46	-0.18	0.00	0.24	0.06	1.59	0.22	-0.40	0.13	0.45
8,001	1.22	-0.18	0.06	0.15	0.00	1.40	0.19	-0.31	0.13	0.33
7,014	1.03	-0.15	0.09	0.12	-0.12	1.25	0.19	-0.19	0.10	0.24
6,010	0.79	-0.09	0.12	0.03	-0.18	1.01	0.16	-0.09	0.10	0.15
5,008	0.58	-0.06	0.12	-0.04	-0.27	0.85	0.16	0.03	0.07	0.03
4,004	0.36	-0.03	0.15	-0.13	-0.30	0.64	0.12	0.12	0.07	-0.07
3,003	0.21	-0.03	0.15	-0.13	-0.27	0.46	0.09	0.09	0.07	-0.10
2,006	0.09	-0.03	0.06	-0.07	-0.18	0.31	0.06	0.09	0.03	-0.13
1,004	0.03	-0.03	0.03	-0.04	-0.09	0.15	0.00	0.06	0.03	-0.07
14	0.03	-0.03	-0.03	-0.04	0.00	0.00	-0.06	0.00	-0.03	-0.07

TABLE D5: INSTRUMENTED LUG STRAIN GAGE DATA. *Load Case 5: Rolling Moment*

Total External	FORWARD LUG STRAIN GAGES (mv)					AFT LUG STRAIN GAGES (mv)				
Load (lb.)	<i>Vertical (interior)</i>	<i>Bending (side)</i>	<i>Shear (fore/aft)</i>	<i>Shear (side)</i>	<i>Shear (fore/aft)</i>	<i>Vertical (interior)</i>	<i>Bending (side)</i>	<i>Shear (fore/aft)</i>	<i>Shear (side)</i>	<i>Shear (fore/aft)</i>
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1,107	0.79	-0.12	1.01	-0.22	1.35	0.24	0.12	0.27	0.12	0.39
2,099	1.55	-0.61	1.04	-0.10	1.44	0.82	-0.18	0.33	0.21	0.58
3,087	2.22	-0.94	1.10	0.03	1.47	1.46	-0.43	0.58	0.30	0.70
4,084	2.87	-1.28	1.10	0.18	1.35	2.07	-0.70	0.88	0.39	0.82
5,076	3.45	-1.58	1.10	0.30	1.28	2.65	-0.98	1.22	0.51	0.97
6,075	4.06	-1.89	1.16	0.36	1.22	3.20	-1.22	1.55	0.61	1.13
7,059	4.58	-2.35	1.29	0.48	1.10	3.84	-1.53	1.92	0.67	1.22
8,055	5.12	-2.71	1.35	0.58	1.01	4.33	-1.80	2.26	0.73	1.31
9,047	5.67	-3.05	1.41	0.70	0.95	4.94	-2.02	2.59	0.82	1.40
9,879	6.10	-3.54	1.59	0.82	0.83	5.37	-2.38	2.96	0.79	1.43
9,172	5.64	-3.66	1.53	0.76	0.74	4.97	-2.44	2.71	0.70	1.34
8,150	4.94	-3.72	1.22	0.64	0.43	4.33	-2.53	2.32	0.61	1.06
7,159	4.21	-3.72	1.04	0.64	-0.06	3.72	-2.60	2.01	0.27	0.61
6,166	3.57	-3.35	1.32	0.51	-0.21	3.08	-2.44	2.01	0.12	0.30
5,149	2.90	-2.93	1.68	0.30	-0.09	2.50	-2.02	2.32	0.12	0.33
4,137	2.26	-2.56	1.68	0.12	0.09	1.92	-1.59	2.22	0.18	0.45
3,130	1.61	-2.26	1.53	-0.04	0.22	1.34	-1.22	1.80	0.18	0.45
2,130	0.97	-1.89	1.22	-0.13	0.28	0.76	-0.86	1.25	0.18	0.39
1,122	0.39	-1.31	0.68	-0.16	0.25	0.24	-0.34	0.58	0.09	0.27
91	-0.03	0.03	0.03	0.06	0.09	0.06	0.06	0.06	0.00	0.09

TABLE D6: INSTRUMENTED LUG STRAIN GAGE DATA. *Load Case 6: Combined Load*

Total External	FORWARD LUG STRAIN GAGES (mv)					AFT LUG STRAIN GAGES (mv)				
Load (lb.)	<i>Vertical (interior)</i>	<i>Bending (side)</i>	<i>Shear (fore/aft)</i>	<i>Shear (side)</i>	<i>Shear (fore/aft)</i>	<i>Vertical (interior)</i>	<i>Bending (side)</i>	<i>Shear (fore/aft)</i>	<i>Shear (side)</i>	<i>Shear (fore/aft)</i>
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1,026	-0.21	-0.03	0.09	0.00	0.22	0.27	-0.06	0.09	0.03	0.18
2,019	-0.30	-0.09	0.12	-0.06	0.34	0.58	-0.13	0.15	0.09	0.40
3,015	-0.43	-0.12	0.12	-0.06	0.49	0.85	-0.22	0.12	0.12	0.52
4,019	-0.58	-0.25	0.12	-0.03	0.49	1.13	-0.43	-0.18	0.06	0.33
5,030	-0.70	-0.31	0.00	0.04	0.49	1.46	-0.61	-0.49	0.03	0.06
6,041	-0.79	-0.40	-0.16	0.07	0.40	1.77	-0.80	-0.58	0.03	0.00
7,047	-0.95	-0.49	-0.34	0.19	0.31	2.07	-0.92	-0.61	0.03	0.03
8,051	-1.07	-0.55	-0.46	0.28	0.16	2.38	-1.01	-0.55	0.06	0.06
9,066	-1.16	-0.67	-0.52	0.34	0.03	2.65	-1.13	-0.49	0.12	0.12
9,860	-1.22	-0.70	-0.49	0.37	-0.06	2.96	-1.19	-0.37	0.15	0.27
8,932	-0.95	-0.55	-0.31	0.31	0.03	2.65	-1.07	-0.31	0.19	0.43
7,929	-0.70	-0.46	-0.25	0.28	0.16	2.38	-0.95	-0.06	0.25	0.61
6,940	-0.52	-0.40	-0.16	0.22	0.25	2.10	-0.80	0.21	0.25	0.73
5,942	-0.40	-0.31	-0.06	0.16	0.34	1.80	-0.67	0.55	0.28	0.91
4,946	-0.30	-0.22	0.00	0.10	0.37	1.46	-0.52	0.85	0.34	1.10
3,972	-0.21	-0.12	0.03	0.04	0.37	1.19	-0.43	0.95	0.34	1.01
2,984	-0.21	0.00	0.00	0.04	0.22	0.88	-0.37	0.92	0.28	0.79
1,989	-0.21	0.03	-0.03	0.04	0.09	0.55	-0.25	0.73	0.25	0.49
996	-0.09	0.09	-0.06	0.04	0.00	0.27	-0.09	0.43	0.12	0.21
11	0.00	0.03	0.00	0.04	-0.03	-0.03	0.00	0.00	0.00	-0.03

TABLE D7: INSTRUMENTED LUG STRAIN GAGE DATA. *Load Case 7: Pitching Moment*

Total External	FORWARD LUG STRAIN GAGES (mv)					AFT LUG STRAIN GAGES (mv)				
Load (lb.)	Vertical (interior)	Bending (side)	Shear (fore/aft)	Shear (side)	Shear (fore/aft)	Vertical (interior)	Bending (side)	Shear (fore/aft)	Shear (side)	Shear (fore/aft)
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
909	-0.28	0.03	0.00	0.00	0.09	0.52	0.03	0.00	0.07	0.19
1,924	-0.58	0.06	-0.06	0.03	0.22	1.04	0.03	-0.07	0.10	0.34
2,924	-0.80	0.09	-0.13	0.06	0.28	1.55	0.03	-0.16	0.13	0.52
3,930	-1.01	0.15	-0.19	0.06	0.34	2.07	0.00	-0.25	0.13	0.77
4,939	-1.29	0.21	-0.25	0.12	0.34	2.62	-0.03	-0.37	0.16	0.98
5,952	-1.41	0.24	-0.28	0.09	0.34	3.17	-0.03	-0.34	0.22	1.13
6,960	-1.59	0.24	-0.28	0.06	0.34	3.69	-0.06	-0.34	0.28	1.25
7,975	-1.68	0.30	-0.31	0.06	0.31	4.21	-0.09	-0.28	0.34	1.38
8,994	-1.87	0.33	-0.37	0.06	0.28	4.76	-0.12	-0.16	0.40	1.47
9,955	-1.99	0.43	-0.40	0.03	0.16	5.28	-0.12	-0.03	0.49	1.53
8,837	-1.74	0.36	-0.37	0.06	0.16	4.70	-0.15	0.12	0.43	1.29
7,841	-1.50	0.33	-0.34	0.03	0.16	4.18	0.00	0.21	0.43	1.07
6,841	-1.29	0.27	-0.28	0.03	0.12	3.66	-0.06	0.27	0.37	0.83
5,837	-1.10	0.18	-0.22	0.00	0.09	3.14	-0.06	0.36	0.31	0.71
4,846	-0.89	0.15	-0.16	0.00	0.06	2.56	-0.03	0.39	0.31	0.52
3,859	-0.74	0.15	-0.09	0.03	0.00	2.04	0.00	0.39	0.25	0.34
2,877	-0.58	0.15	-0.06	-0.03	-0.09	1.49	0.00	0.51	0.22	0.16
1,896	-0.43	0.09	0.03	-0.06	-0.15	0.97	0.00	0.58	0.16	-0.03
889	-0.22	0.06	0.06	-0.03	-0.18	0.49	0.03	0.33	0.10	-0.03
54	0.03	-0.03	0.03	-0.03	-0.03	0.03	0.06	0.03	0.00	0.03

TABLE D8: INSTRUMENTED LUG STRAIN GAGE DATA. *Load Case 8: Rolling Moment*

Total External	FORWARD LUG STRAIN GAGES (mv)					AFT LUG STRAIN GAGES (mv)				
Load (lb.)	Vertical (interior)	Bending (side)	Shear (fore/aft)	Shear (side)	Shear (fore/aft)	Vertical (interior)	Bending (side)	Shear (fore/aft)	Shear (side)	Shear (fore/aft)
0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
1,039	0.00	1.19	-1.25	0.43	-1.19	0.12	-1.40	0.61	0.15	0.46
2,054	-0.03	2.32	-1.89	0.46	-1.86	-0.12	-3.23	1.28	0.21	0.95
3,058	-0.12	3.72	-2.47	0.46	-2.47	-0.30	-4.88	2.08	0.30	1.53
4,056	-0.24	5.40	-3.17	0.43	-3.24	-0.46	-6.44	2.81	0.36	2.14
5,056	-0.40	7.29	-3.97	0.43	-4.06	-0.64	-8.00	3.64	0.42	2.72
6,066	-0.58	9.25	-4.76	0.40	-4.86	-0.73	-9.52	4.43	0.55	3.33
7,070	-0.76	11.32	-5.56	0.49	-5.62	-0.73	-11.08	5.16	0.64	3.94
8,085	-0.95	13.40	-6.44	0.61	-6.44	-0.73	-12.64	5.99	0.73	4.52
9,096	-1.13	15.50	-7.27	0.74	-7.18	-0.76	-14.22	6.75	0.82	5.07
9,921	-1.25	17.34	-7.94	0.80	-7.79	-0.76	-15.57	7.30	0.82	5.50
8,982	-1.13	16.21	-7.23	0.37	-7.27	-0.85	-14.68	6.66	0.36	4.82
8,012	-0.95	15.08	-6.59	-0.03	-6.69	-0.88	-13.34	6.29	0.00	4.40
7,017	-0.85	13.79	-5.83	-0.39	-5.89	-0.79	-11.69	5.71	-0.06	4.09
6,010	-0.79	12.42	-5.07	-0.55	-4.89	-0.76	-9.92	4.76	-0.06	3.51
5,015	-0.64	10.71	-4.27	-0.64	-4.12	-0.67	-8.24	3.82	-0.09	2.84
4,015	-0.52	8.82	-3.48	-0.70	-3.39	-0.55	-6.65	2.90	-0.16	2.17
3,011	-0.40	6.80	-2.60	-0.70	-2.57	-0.39	-5.10	1.99	-0.16	1.47
2,011	-0.24	4.76	-1.74	-0.58	-1.68	-0.27	-3.51	1.10	-0.19	0.73
1,019	-0.18	2.62	-0.89	-0.45	-0.83	-0.06	-1.89	0.25	-0.16	0.12
43	-0.15	0.49	-0.06	-0.27	-0.12	-0.09	-0.18	-0.33	-0.12	-0.27

APPENDIX E: *Reduced Swaybrace Millivolt Data*

TABLE E1: INSTRUMENTED SWAYBRACE STRAIN DATA
Load Case 1: Longitudinal Load

Total External	SWAYBRACE STRAIN GAGE DATA (mv)			
Load (lb.)	Forward Stbd	Forward Port	Aft Stbd	Aft Port
0	-0.95	-0.70	0.09	0.03
1,041	-0.82	-0.61	0.06	0.03
2,038	-0.70	-0.49	-0.09	-0.03
3,035	-0.67	-0.49	-0.34	-0.15
4,057	-0.64	-0.49	-0.61	-0.34
5,043	-0.61	-0.52	-0.85	-0.55
6,044	-0.61	-0.49	-1.16	-0.76
7,053	-0.58	-0.49	-1.43	-0.95
8,052	-0.58	-0.49	-1.74	-1.22
9,054	-0.58	-0.49	-1.98	-1.40
9,947	-0.52	-0.49	-2.26	-1.59
8,970	-0.58	-0.49	-2.11	-1.47
7,975	-0.61	-0.49	-1.86	-1.31
6,998	-0.64	-0.49	-1.59	-1.19
5,998	-0.64	-0.49	-1.34	-1.04
4,987	-0.67	-0.49	-1.10	-0.85
3,986	-0.70	-0.52	-0.92	-0.76
2,995	-0.76	-0.52	-0.67	-0.58
1,998	-0.82	-0.58	-0.40	-0.37
994	-0.95	-0.64	-0.06	-0.15
21	-0.95	-0.70	0.00	0.00

TABLE E2: INSTRUMENTED SWAYBRACE STRAIN DATA
Load Case 2: Lateral Load

Total External	SWAYBRACE STRAIN GAGE DATA (mv)			
Load (lb.)	Forward Stbd	Forward Port	Aft Stbd	Aft Port
0	-0.61	-0.46	0.03	0.03
1,004	-3.36	-0.43	-0.43	0.09
2,006	-4.95	-0.43	-1.89	0.06
3,000	-6.35	-0.46	-3.33	0.03
4,004	-7.63	-0.46	-4.73	0.06
5,029	-8.85	-0.43	-6.11	0.09
6,003	-10.01	-0.43	-7.30	0.03
7,004	-11.14	-0.46	-8.76	0.06
8,001	-12.09	-0.46	-10.20	0.06
9,003	-13.10	-0.46	-11.60	0.06
10,007	-14.19	-0.43	-12.79	0.06
9,003	-13.10	-0.46	-11.60	0.06
8,001	-12.00	-0.43	-10.35	0.06
7,004	-10.84	-0.46	-9.13	0.03
6,003	-9.58	-0.46	-7.88	0.06
5,008	-8.36	-0.46	-6.50	0.06
4,004	-7.08	-0.43	-5.19	0.03
3,000	-5.71	-0.46	-3.82	0.03
2,006	-4.37	-0.43	-2.41	0.06
1,004	-2.90	-0.43	-1.01	0.06
14	-0.64	-0.52	0.03	0.09

TABLE E3: INSTRUMENTED SWAYBRACE STRAIN DATA
Load Case 3: Vertical Load (up)

Total External Load (lb.)	SWAYBRACE STRAIN GAGE DATA (mv)			
	<i>Forward Stbd</i>	<i>Forward Port</i>	<i>Aft Stbd</i>	<i>Aft Port</i>
0	-0.89	-0.12	-0.24	-0.37
1,004	-1.07	-0.24	-0.24	-0.34
2,006	-1.31	-0.55	-0.31	-0.37
3,003	-1.62	-0.85	-0.40	-0.46
4,004	-1.77	-1.19	-0.76	-0.64
5,008	-1.95	-1.47	-1.13	-0.82
6,003	-2.11	-1.74	-1.53	-1.04
7,007	-2.29	-2.01	-1.86	-1.25
8,001	-2.50	-2.32	-2.20	-1.47
9,005	-2.78	-2.56	-2.53	-1.71
10,000	-3.02	-2.87	-2.81	-1.95
9,012	-2.87	-2.63	-2.50	-1.71
8,015	-2.63	-2.35	-2.17	-1.53
7,014	-2.47	-2.01	-1.83	-1.28
6,003	-2.29	-1.74	-1.47	-1.10
5,001	-2.17	-1.47	-1.13	-0.85
4,004	-2.01	-1.16	-0.79	-0.67
3,003	-1.83	-0.89	-0.43	-0.49
2,006	-1.53	-0.58	-0.27	-0.40
1,004	-1.34	-0.40	-0.24	-0.37
14	-1.19	-0.21	-0.27	-0.37

TABLE E4: INSTRUMENTED SWAYBRACE STRAIN DATA
Load Case 4: Vertical Load (down)

Total External Load (lb.)	SWAYBRACE STRAIN GAGE DATA (mv)			
	<i>Forward Stbd</i>	<i>Forward Port</i>	<i>Aft Stbd</i>	<i>Aft Port</i>
0	-1.89	-0.92	-0.21	-0.40
1,004	-1.65	-0.70	-0.24	-0.43
2,006	-1.43	-0.49	-0.21	-0.43
3,003	-1.19	-0.31	-0.21	-0.46
4,004	-1.01	-0.18	-0.18	-0.43
5,008	-0.92	-0.09	-0.24	-0.43
6,003	-0.89	-0.09	-0.21	-0.43
7,007	-0.85	-0.06	-0.24	-0.43
8,001	-0.82	-0.06	-0.21	-0.40
9,005	-0.82	-0.03	-0.21	-0.40
10,000	-0.79	-0.03	-0.21	-0.43
9,005	-0.82	-0.06	-0.21	-0.40
8,001	-0.82	-0.06	-0.21	-0.43
7,014	-0.85	-0.03	-0.21	-0.43
6,010	-0.89	-0.09	-0.21	-0.43
5,008	-0.89	-0.09	-0.21	-0.43
4,004	-0.95	-0.15	-0.21	-0.43
3,003	-1.07	-0.24	-0.21	-0.43
2,006	-1.31	-0.40	-0.21	-0.46
1,004	-1.59	-0.64	-0.21	-0.43
14	-1.92	-0.95	-0.21	-0.46

TABLE E5: INSTRUMENTED SWAYBRACE STRAIN DATA
Load Case 5: Rolling Moment

Total External Load (lb.)	SWAYBRACE STRAIN GAGE DATA (mv)			
	<i>Forward Stbd</i>	<i>Forward Port</i>	<i>Aft Stbd</i>	<i>Aft Port</i>
0	-1.92	-1.31	-0.24	-0.31
1,107	-4.91	-0.15	-0.40	-0.27
2,099	-7.02	-0.18	-2.23	-0.27
3,087	-8.85	-0.15	-4.12	-0.31
4,084	-10.56	-0.15	-5.89	-0.27
5,076	-12.12	-0.18	-7.57	-0.24
6,075	-13.61	-0.15	-9.28	-0.24
7,059	-15.05	-0.15	-10.96	-0.24
8,055	-16.39	-0.15	-12.61	-0.27
9,047	-17.77	-0.15	-14.26	-0.27
9,879	-18.86	-0.18	-15.66	-0.27
9,172	-17.86	-0.15	-14.56	-0.27
8,150	-16.33	-0.18	-12.94	-0.24
7,159	-14.77	-0.18	-11.32	-0.27
6,166	-13.06	-0.18	-9.68	-0.24
5,149	-11.36	-0.15	-7.88	-0.21
4,137	-9.58	-0.15	-6.07	-0.24
3,130	-7.81	-0.18	-4.33	-0.24
2,130	-6.01	-0.18	-2.59	-0.27
1,122	-4.21	-0.18	-0.85	-0.24
91	-1.89	-1.16	-0.24	-0.27

TABLE E6: INSTRUMENTED SWAYBRACE STRAIN DATA
Load Case 6: Combined Load

Total External Load (lb.)	SWAYBRACE STRAIN GAGE DATA (mv)			
	<i>Forward Stbd</i>	<i>Forward Port</i>	<i>Aft Stbd</i>	<i>Aft Port</i>
0	-3.51	-2.44	0.00	-0.24
1,026	-3.02	-3.51	-0.03	-0.61
2,019	-2.59	-4.61	0.00	-0.95
3,015	-2.32	-5.71	-0.03	-1.28
4,019	-2.17	-6.78	-0.03	-1.68
5,030	-2.14	-7.84	-0.03	-2.11
6,041	-2.08	-8.94	-0.03	-2.53
7,047	-1.95	-10.04	0.00	-2.90
8,051	-1.86	-11.14	0.00	-3.27
9,066	-1.77	-12.24	0.03	-3.60
9,860	-1.74	-13.13	0.03	-3.88
8,932	-1.83	-12.36	0.00	-3.66
7,929	-2.08	-11.42	0.00	-3.36
6,940	-2.26	-10.50	0.00	-2.99
5,942	-2.35	-9.49	0.03	-2.56
4,946	-2.38	-8.46	-0.03	-2.17
3,972	-2.41	-7.30	0.00	-1.86
2,984	-2.50	-6.04	0.00	-1.43
1,989	-2.72	-4.79	0.00	-1.04
996	-3.02	-3.60	0.03	-0.61
11	-3.45	-2.44	0.00	-0.24

TABLE E7: INSTRUMENTED SWAYBRACE STRAIN DATA
Load Case 7: Pitching Moment

Total External Load (lb.)	SWAYBRACE STRAIN GAGE DATA (mv)			
	<i>Forward Stbd</i>	<i>Forward Port</i>	<i>Aft Stbd</i>	<i>Aft Port</i>
0	-3.48	-2.81	0.03	0.00
909	-3.75	-3.24	0.03	0.06
1,924	-4.18	-3.75	0.06	0.06
2,924	-4.61	-4.27	0.03	0.06
3,930	-5.10	-4.82	0.06	0.06
4,939	-5.59	-5.40	0.03	0.06
5,952	-6.20	-6.01	0.03	0.06
6,960	-6.75	-6.65	0.03	0.06
7,975	-7.36	-7.33	0.03	0.06
8,994	-7.94	-7.94	0.06	0.06
9,955	-8.55	-8.61	0.06	0.06
8,837	-7.97	-7.91	0.06	0.03
7,841	-7.51	-7.36	0.06	0.03
6,841	-7.05	-6.81	0.06	0.00
5,837	-6.53	-6.26	0.12	0.03
4,846	-6.04	-5.68	0.21	0.03
3,859	-5.46	-5.07	0.06	0.06
2,877	-4.91	-4.46	0.06	0.03
1,896	-4.33	-3.79	0.06	0.03
889	-3.91	-3.27	0.06	0.03
54	-3.48	-2.84	0.06	0.00

TABLE E8: INSTRUMENTED SWAYBRACE STRAIN DATA
Load Case 8: Yawing Moment

Total External Load (lb.)	SWAYBRACE STRAIN GAGE DATA (mv)			
	<i>Forward Stbd</i>	<i>Forward Port</i>	<i>Aft Stbd</i>	<i>Aft Port</i>
0	-3.45	-2.23	-0.21	-0.31
1,039	-3.63	-2.38	-0.24	-0.34
2,054	-3.60	-2.66	-0.24	-0.34
3,058	-3.48	-2.99	-0.21	-0.34
4,056	-3.54	-3.30	-0.24	-0.31
5,056	-3.57	-3.51	-0.21	-0.34
6,066	-3.57	-3.82	-0.37	-0.31
7,070	-3.42	-4.15	-0.73	-0.34
8,085	-3.27	-4.52	-1.13	-0.31
9,096	-3.17	-4.88	-1.50	-0.31
9,921	-3.14	-5.19	-1.80	-0.34
8,982	-3.48	-5.04	-1.34	-0.34
8,012	-3.94	-4.67	-1.01	-0.34
7,017	-4.27	-4.30	-0.67	-0.34
6,010	-4.46	-3.88	-0.40	-0.34
5,015	-4.49	-3.63	-0.21	-0.34
4,015	-4.43	-3.30	-0.24	-0.34
3,011	-4.37	-3.05	-0.21	-0.34
2,011	-4.18	-2.81	-0.24	-0.34
1,019	-3.91	-2.44	-0.21	-0.34
43	-3.51	-2.01	-0.21	-0.37

APPENDIX F: *Reduced Lug and Swaybrace Reaction
Forces; Measured, Ground Test*

TABLE F1: MEASURED REACTION FORCES AT INTERFACE POINTS DURING LOAD CASES 1 AND 2

	Testpoint Counter	Measured SB Rod Reactions (lbs)				Measured Lug Reactions (lbs)					
		Forward		Aft		Forward			Aft		
		Port	Stbd	Port	Stbd	Long.	Lateral	Vertical	Long.	Lateral	Vertical
Load Case 1 (Long. Aft)	1-1	-185	-382	-336	-200	0	41	1,564	0	-24	1,466
	1-2	-106	-267	-336	-212	-429	-31	1,684	-491	-44	1,468
	1-3	0	-160	-373	-274	-957	-68	1,889	-1,147	-18	1,426
	1-4	0	-133	-446	-378	-1,461	-340	2,172	-1,662	1	1,339
	1-5	0	-107	-561	-489	-1,857	-142	2,437	-2,283	24	1,342
	1-6	-27	-80	-689	-588	-2,101	-91	2,821	-2,991	20	1,122
	1-7	0	-80	-817	-716	-2,422	-19	3,095	-3,624	75	905
	1-8	0	-53	-933	-828	-2,669	-13	3,446	-4,229	17	666
	1-9	0	-53	-1,098	-956	-2,935	62	3,732	-4,872	-93	91
	1-10	0	-53	-1,208	-1,055	-3,284	124	4,099	-5,387	-170	54
	1-11	0	0	-1,323	-1,171	-3,637	112	4,408	-5,918	-247	27
	1-12	0	-53	-1,250	-1,109	-3,128	-25	4,117	-5,489	-141	27
	1-13	0	-80	-1,153	-1,006	-2,786	-31	3,789	-4,898	-107	171
	1-14	0	-107	-1,080	-894	-2,293	-94	3,542	-4,350	-31	720
	1-15	0	-107	-988	-791	-1,896	-50	3,233	-3,804	31	1,085
	1-16	0	-133	-872	-692	-1,461	-110	2,950	-3,318	85	1,471
	1-17	-27	-160	-817	-617	-1,005	-112	2,625	-2,911	100	1,418
	1-18	-27	-213	-708	-514	-456	-19	2,339	-2,287	76	1,446
	1-19	-79	-267	-580	-402	-71	-7	2,075	-1,603	18	1,677
	1-20	-132	-382	-446	-262	-27	131	1,729	-753	-15	1,871
	1-21	-185	-382	-354	-237	36	47	1,483	81	-18	1,611
Load Case 2 (Lateral Stbd)	2-1	-405	-542	-336	-200	0	27	1,867	0	-26	1,526
	2-2	-379	-2,984	-284	-608	-85	217	4,026	-47	-105	2,079
	2-3	-379	-4,396	-310	-1,901	-91	247	5,531	-36	-87	3,454
	2-4	-405	-5,639	-336	-3,177	-71	210	6,974	-24	-67	4,764
	2-5	-405	-6,775	-310	-4,418	-45	166	8,174	-22	-63	6,099
	2-6	-379	-7,859	-284	-5,641	-34	151	9,389	-23	-65	7,236
	2-7	-379	-8,889	-336	-6,695	-27	147	10,542	-8	-39	8,432
	2-8	-405	-9,892	-310	-7,989	1	107	11,762	25	16	9,842
	2-9	-405	-10,736	-310	-9,265	14	86	12,712	45	48	11,065
	2-10	-405	-11,633	-310	-10,506	42	41	13,799	77	102	12,332
	2-11	-379	-12,601	-310	-11,560	74	-16	14,890	80	108	13,411
	2-12	-405	-11,633	-310	-10,506	40	55	13,710	57	68	12,575
	2-13	-379	-10,656	-310	-9,398	8	116	12,598	78	103	11,477
	2-14	-405	-9,626	-336	-8,317	-3	135	11,360	106	151	10,170
	2-15	-405	-8,507	-310	-7,209	-10	139	10,119	147	219	8,962
	2-16	-405	-7,424	-310	-5,987	-22	145	8,895	154	230	7,720
	2-17	-379	-6,287	-336	-4,826	-25	129	7,684	129	188	6,454
	2-18	-405	-5,070	-336	-3,612	-24	106	6,338	93	129	5,168
	2-19	-379	-3,881	-310	-2,362	-9	58	5,064	58	70	3,863
	2-20	-379	-2,575	-310	-1,122	16	-8	3,720	1	-24	2,503
	2-21	-458	-568	-284	-200	7	10	2,001	12	-6	1,441

Note: POSITIVE sign convention is aft, starboard, up, port down roll, nose up pitch, nose left yaw

TABLE F2: MEASURED REACTION FORCES AT INTERFACE POINTS DURING LOAD CASES 3 AND 4

	Testpoint Counter	Measured SB Rod Reactions (lbs.)				Measured Lug Reactions (lbs)					
		Forward		Aft		Forward			Aft		
		Port	Stbd	Port	Stbd	Long.	Lateral	Vertical	Long.	Lateral	Vertical
Load Case 3 (Vertical Up)	3-1	-106	-790	-322	-213	0	161	1,826	0	7	1,517
	3-2	-185	-950	-290	-213	0	161	1,224	-26	12	956
	3-3	-389	-1,163	-322	-261	-22	214	686	-24	46	187
	3-4	-586	-1,439	-420	-323	-22	214	683	-38	31	0
	3-5	-810	-1,572	-614	-572	8	169	503	-38	31	0
	3-6	-995	-1,732	-809	-828	38	113	141	-24	46	0
	3-7	-1,173	-1,874	-1,047	-1,104	68	68	0	-8	94	0
	3-8	-1,351	-2,033	-1,273	-1,332	120	-19	0	-24	46	0
	3-9	-1,555	-2,220	-1,511	-1,567	68	68	0	-53	17	0
	3-10	-1,713	-2,469	-1,771	-1,796	68	79	0	-24	46	0
	3-11	-1,917	-2,682	-2,030	-1,989	98	23	0	-38	31	0
	3-12	-1,759	-2,549	-1,771	-1,775	38	124	0	-24	46	0
	3-13	-1,574	-2,335	-1,576	-1,547	46	121	0	-38	31	0
	3-14	-1,351	-2,193	-1,306	-1,312	46	121	0	-38	31	0
	3-15	-1,173	-2,033	-1,111	-1,063	24	163	148	-38	31	0
	3-16	-995	-1,927	-841	-828	42	145	513	-8	94	0
	3-17	-791	-1,785	-647	-593	2	205	689	-24	46	0
	3-18	-613	-1,625	-452	-344	24	163	1,235	-36	65	0
	3-19	-409	-1,359	-355	-233	-36	253	1,411	-38	31	292
	3-20	-290	-1,190	-322	-213	-88	340	2,016	-53	17	830
	3-21	-165	-1,057	-322	-233	-118	385	2,558	-88	-50	1,523
Load Case 4 (Vertical Dn)	4-1	-810	-1,678	-349	-186	0	204	3,095	0	3	1,771
	4-2	-563	-1,252	-261	-138	-30	249	3,204	-57	-33	2,125
	4-3	-378	-861	-178	-92	-7	201	3,371	-77	-33	2,529
	4-4	-220	-435	-107	-53	-14	198	3,589	-84	-8	2,958
	4-5	-105	-115	-55	-25	-22	195	3,808	-126	-48	3,295
	4-6	-26	0	-20	-5	54	54	4,161	-146	-47	3,801
	4-7	-26	0	-20	-5	40	48	4,596	-139	-59	4,248
	4-8	0	0	-8	0	85	-48	4,980	-93	-42	4,670
	4-9	0	0	-8	0	2	90	5,375	-47	-36	5,098
	4-10	27	0	0	0	18	39	5,808	-31	-26	5,557
	4-11	27	0	0	0	-35	132	6,265	-9	-24	5,984
	4-12	0	0	-8	0	2	90	5,750	56	-4	5,567
	4-13	0	0	-8	0	-66	234	5,308	69	-3	5,118
	4-14	27	0	0	0	-59	237	4,956	120	16	4,771
	4-15	-26	0	-20	-5	-67	291	4,519	137	32	4,199
	4-16	-26	0	-20	-5	-90	358	4,133	188	41	3,827
	4-17	-79	-9	-43	-18	-129	457	3,731	191	49	3,332
	4-18	-158	-222	-79	-38	-129	457	3,460	147	24	2,887
	4-19	-299	-648	-143	-73	-83	361	3,246	109	6	2,533
	4-20	-511	-1,146	-238	-125	-60	313	3,142	34	13	2,150
	4-21	-784	-1,732	-360	-193	-60	313	3,148	-66	-28	1,802

Note: POSITIVE sign convention is aft, starboard, up, port down roll, nose up pitch, nose left yaw

TABLE F3: MEASURED REACTION FORCES AT INTERFACE POINTS DURING LOAD CASES 5 AND 6

	Testpoint Counter	Measured SB Rod Reactions (lbs.)				Measured Lug Reactions (lbs)					
		Forward		Aft		Forward			Aft		
		Port	Stbd	Port	Stbd	Long.	Lateral	Vertical	Long.	Lateral	Vertical
Load Case 5 (Positive Roll)	5-1	-1,154	-1,705	0	-213	0	132	3,382	0	13	1,788
	5-2	0	-4,360	35	-369	224	1,386	5,225	20	676	2,361
	5-3	-26	-6,234	35	-2,152	206	2,160	6,885	22	1,438	3,924
	5-4	0	-7,859	0	-3,995	178	2,763	8,353	15	2,061	5,651
	5-5	0	-9,377	35	-5,720	126	3,233	9,766	8	2,703	7,321
	5-6	-26	-10,762	61	-7,358	88	3,663	11,029	-2	3,467	8,918
	5-7	0	-12,086	61	-9,025	66	3,966	12,360	-7	4,155	10,428
	5-8	0	-13,364	61	-10,662	21	4,453	13,473	-10	4,727	12,208
	5-9	0	-14,554	35	-12,271	-14	4,854	14,641	-13	5,259	13,591
	5-10	0	-15,780	35	-13,879	-51	5,326	15,835	-24	5,814	15,245
	5-11	-26	-16,747	35	-15,244	-96	5,835	16,746	-13	6,141	16,541
	5-12	0	-15,859	35	-14,171	-93	5,666	15,706	-2	5,868	15,539
	5-13	-26	-14,501	61	-12,592	-102	5,027	14,121	-16	5,386	13,922
	5-14	-26	-13,116	35	-11,013	-164	4,409	12,461	11	4,060	12,448
	5-15	-26	-11,597	61	-9,414	-151	3,625	11,055	8	3,142	10,816
	5-16	0	-10,088	87	-7,660	-85	2,949	9,604	12	2,757	9,250
	5-17	0	-8,507	61	-5,896	-18	2,459	8,220	13	2,621	7,591
	5-18	-26	-6,935	61	-4,199	38	2,007	6,805	13	2,248	5,914
	5-19	-26	-5,337	35	-2,503	67	1,585	5,413	5	1,810	4,217
	5-20	-26	-3,738	61	-807	71	1,039	4,165	12	915	2,608
	5-21	-1,022	-1,678	35	-213	-3	369	3,324	11	66	1,926
Load Case 6 (Nose Up and Lateral Port)	6-1	-2,149	-3,117	-209	0	0	233	5,279	0	30	2,065
	6-2	-3,091	-3,987	-532	-27	-24	260	5,072	9	42	2,775
	6-3	-4,059	-4,751	-828	0	-60	295	4,983	29	71	3,577
	6-4	-5,028	-5,230	-1,116	-27	2	320	4,855	35	79	4,277
	6-5	-5,970	-5,497	-1,464	-27	-151	328	4,698	-3	22	5,024
	6-6	-6,903	-5,550	-1,839	-27	-46	321	4,574	-26	-14	5,875
	6-7	-7,872	-5,656	-2,205	-27	24	303	4,476	-38	-33	6,712
	6-8	-8,841	-5,887	-2,527	0	123	269	4,307	-46	-46	7,506
	6-9	-9,809	-6,047	-2,850	0	130	216	4,178	-39	-37	8,323
	6-10	-10,778	-6,207	-3,137	27	-8	197	4,078	-22	-14	9,044
	6-11	-11,562	-6,260	-3,381	27	-146	166	4,012	-14	-2	9,859
	6-12	-10,884	-6,100	-3,190	0	-174	205	4,295	10	34	9,035
	6-13	-10,056	-5,656	-2,928	0	-71	272	4,557	43	82	8,340
	6-14	-9,246	-5,337	-2,606	0	-74	321	4,744	52	97	7,627
	6-15	-8,356	-5,177	-2,231	27	-56	346	4,873	72	128	6,876
	6-16	-7,449	-5,124	-1,891	-27	-18	348	4,979	106	179	6,003
	6-17	-6,428	-5,070	-1,621	0	56	335	5,074	112	189	5,308
	6-18	-5,318	-4,911	-1,246	0	143	250	5,073	91	159	4,516
	6-19	-4,218	-4,520	-906	0	138	200	5,070	87	153	3,614
	6-20	-3,170	-3,987	-532	27	194	181	5,191	43	92	2,826
	6-21	-2,149	-3,223	-209	0	16	213	5,279	0	30	1,990

Note: POSITIVE sign convention is aft, starboard, up, port down roll, nose up pitch, nose left yaw

TABLE F4: MEASURED REACTION FORCES AT INTERFACE POINTS DURING LOAD CASES 7 AND 8

	Testpoint Counter	Measured SB Rod Reactions (lbs.)				Measured Lug Reactions (lbs)					
		Forward		Aft		Forward			Aft		
		Port	Stbd	Port	Stbd	Long.	Lateral	Vertical	Long.	Lateral	Vertical
Load Case 7 (Positive Pitch)	7-1	-2,474	-3,090	0	0	0	150	5,461	0	30	1,835
	7-2	-2,853	-3,330	0	0	2	146	3,799	14	44	3,162
	7-3	-3,302	-3,712	0	0	-17	185	2,005	-13	45	4,498
	7-4	-3,760	-4,094	0	0	-37	223	712	-50	36	5,804
	7-5	-4,244	-4,529	0	0	-32	216	29	-93	-7	7,156
	7-6	-4,755	-4,964	0	0	-72	292	0	-144	-2	8,574
	7-7	-5,292	-5,506	0	0	-47	246	15	-118	-3	9,999
	7-8	-5,856	-5,994	0	0	-25	204	37	-106	-19	11,352
	7-9	-6,454	-6,536	0	0	-20	197	42	-65	21	12,716
	7-10	-6,992	-7,051	0	0	-17	193	44	4	90	14,169
	7-11	-7,581	-7,592	0	0	13	139	74	84	142	15,526
	7-12	-6,965	-7,077	0	0	-15	190	47	143	229	14,068
	7-13	-6,481	-6,669	0	0	5	151	66	186	244	12,668
	7-14	-5,997	-6,260	0	0	0	159	61	202	260	11,361
	7-15	-5,512	-5,799	0	0	15	128	76	233	263	10,036
	7-16	-5,001	-5,363	0	0	12	132	328	247	277	8,517
	7-17	-4,464	-4,848	0	0	-10	174	1,246	235	293	7,164
	7-18	-3,927	-4,360	0	0	34	90	2,233	286	288	5,758
	7-19	-3,337	-3,845	0	0	52	55	3,061	308	281	4,429
	7-20	-2,879	-3,472	0	0	27	101	4,285	177	179	3,135
	7-21	-2,501	-3,090	0	0	20	112	5,605	14	16	1,895
Load Case 8 (Negative Yaw)	8-1	-1,964	-3,064	-270	-186	0	264	5,106	0	33	2,113
	8-2	-2,241	-3,032	-299	-444	-163	-1,164	5,094	-8	1,137	3,044
	8-3	-2,759	-2,973	-354	-926	-127	-2,077	5,193	-67	2,556	3,276
	8-4	-3,369	-2,903	-418	-1,493	-63	-3,001	5,550	-60	3,745	3,604
	8-5	-3,942	-2,837	-478	-2,026	58	-4,150	6,038	-26	4,809	3,940
	8-6	-4,331	-2,793	-519	-2,387	115	-5,401	6,702	-6	5,906	4,244
	8-7	-4,904	-2,728	-579	-2,920	165	-6,651	7,453	33	6,963	4,734
	8-8	-5,514	-2,658	-643	-3,488	155	-7,887	8,193	67	8,068	5,464
	8-9	-6,198	-2,580	-715	-4,124	109	-9,185	8,984	87	9,211	6,212
	8-10	-6,864	-2,504	-785	-4,743	31	-10,409	9,720	91	10,387	6,880
	8-11	-7,437	-2,438	-846	-5,276	-4	-11,437	10,185	78	11,412	7,517
	8-12	-7,160	-2,470	-817	-5,018	262	-10,657	9,671	-85	10,978	6,935
	8-13	-6,476	-2,548	-745	-4,382	345	-9,808	8,869	-69	9,913	6,349
	8-14	-5,791	-2,626	-673	-3,746	301	-8,722	8,443	41	8,487	5,828
	8-15	-5,015	-2,715	-591	-3,024	-14	-7,429	8,198	52	7,141	5,028
	8-16	-4,552	-2,768	-542	-2,594	8	-6,269	7,571	10	5,977	4,423
	8-17	-3,942	-2,837	-478	-2,026	56	-5,112	7,102	-44	4,906	3,942
	8-18	-3,480	-2,890	-430	-1,596	107	-3,838	6,638	-118	3,923	3,563
	8-19	-3,036	-2,941	-383	-1,184	34	-2,485	5,981	-203	2,924	3,078
	8-20	-2,352	-3,019	-311	-547	-8	-1,165	5,808	-228	1,812	2,799
	8-21	-1,557	-3,110	-227	192	108	13	5,785	-144	385	1,929

Note: POSITIVE sign convention is aft, starboard, up, port down roll, nose up pitch, nose left yaw

APPENDIX G: *Reduced Lug and Swaybrace Reaction
Forces; Calculated, Ground Test*

TABLE G1: CALCULATED REACTION FORCES AT INTERFACE POINTS DURING LOAD CASES 1 AND 2

	Testpoint Counter	CALCULATED SB Rod Reactions (lbs)				CALCULATED Lug Reactions (lbs)					
		Forward		Aft		Forward			Aft		
		Port	Stbd	Port	Stbd	Long.	Lateral	Vertical	Long.	Lateral	Vertical
Load Case 1 (Long. Aft)	1-1	-185	-382	-336	-200	0	41	1,564	0	0	1,466
	1-2	-2	-195	-354	-222	-401	32	1,572	-632	9	1,111
	1-3	0	-15	-369	-237	-785	32	1,733	-1,236	9	768
	1-4	0	0	-384	-252	-1,169	33	2,044	-1,839	8	425
	1-5	0	0	-402	-274	-1,562	24	2,399	-2,459	17	78
	1-6	0	0	-542	-408	-1,942	37	2,733	-3,056	4	0
	1-7	0	0	-722	-592	-2,327	28	3,082	-3,663	13	0
	1-8	0	0	-904	-773	-2,715	30	3,428	-4,274	11	0
	1-9	0	0	-1,083	-954	-3,100	27	3,772	-4,880	14	0
	1-10	0	0	-1,264	-1,136	-3,486	23	4,119	-5,487	18	0
	1-11	0	0	-1,424	-1,297	-3,829	21	4,427	-6,027	20	0
	1-12	0	0	-1,257	-1,112	-3,453	61	4,091	-5,436	-20	0
	1-13	0	0	-1,075	-933	-3,070	54	3,746	-4,832	-13	0
	1-14	0	0	-899	-758	-2,694	52	3,408	-4,240	-11	0
	1-15	0	0	-719	-578	-2,309	52	3,065	-3,635	-11	0
	1-16	0	0	-536	-396	-1,920	51	2,716	-3,022	-10	0
	1-17	0	0	-401	-263	-1,534	47	2,369	-2,415	-6	98
	1-18	0	0	-384	-247	-1,153	44	2,028	-1,815	-3	437
	1-19	0	-24	-369	-231	-769	43	1,725	-1,211	-2	780
	1-20	-6	-204	-353	-216	-383	43	1,564	-602	-2	1,125
	1-21	-181	-379	-337	-200	-8	42	1,564	-13	-1	1,459
Load Case 2 (Lateral Stbd)	2-1	-405	-542	-336	-200	0	27	1,867	0	0	1,526
	2-2	-405	-1,852	-336	-1,362	0	27	3,096	0	0	2,660
	2-3	-405	-3,160	-336	-2,522	0	27	4,323	0	0	3,793
	2-4	-405	-4,458	-336	-3,672	0	27	5,540	0	0	4,917
	2-5	-405	-5,768	-336	-4,834	0	27	6,770	0	0	6,052
	2-6	-405	-7,106	-336	-6,021	0	27	8,025	0	0	7,210
	2-7	-405	-8,377	-336	-7,148	0	27	9,218	0	0	8,311
	2-8	-405	-9,684	-336	-8,307	0	27	10,444	0	0	9,443
	2-9	-405	-10,985	-336	-9,461	0	27	11,665	0	0	10,570
	2-10	-405	-12,293	-336	-10,620	0	27	12,892	0	0	11,703
	2-11	-405	-13,603	-336	-11,782	0	27	14,121	0	0	12,837
	2-12	-405	-12,293	-336	-10,620	0	27	12,892	0	0	11,703
	2-13	-405	-10,985	-336	-9,461	0	27	11,665	0	0	10,570
	2-14	-405	-9,684	-336	-8,307	0	27	10,444	0	0	9,443
	2-15	-405	-8,377	-336	-7,148	0	27	9,218	0	0	8,311
	2-16	-405	-7,078	-336	-5,996	0	27	7,999	0	0	7,187
	2-17	-405	-5,768	-336	-4,834	0	27	6,770	0	0	6,052
	2-18	-405	-4,458	-336	-3,672	0	27	5,540	0	0	4,917
	2-19	-405	-3,160	-336	-2,522	0	27	4,323	0	0	3,793
	2-20	-405	-1,852	-336	-1,362	0	27	3,096	0	0	2,660
	2-21	-405	-560	-336	-216	0	27	1,884	0	0	1,541

Note: POSITIVE sign convention is aft, starboard, up, port down roll, nose up pitch, nose left yaw

TABLE G2: CALCULATED REACTION FORCES AT INTERFACE POINTS DURING LOAD CASES 3 AND 4

	Testpoint Counter	CALCULATED SB Rod Reactions (lbs)				CALCULATED Lug Reactions (lbs)					
		Forward		Aft		Forward			Aft		
		Port	Stbd	Port	Stbd	Long.	Lateral	Vertical	Long.	Lateral	Vertical
Load Case 3 (Vertical Up)	3-1	-106	-790	-322	-213	0	161	1,826	0	7	1,517
	3-2	-135	-819	-339	-230	0	161	1,304	0	7	1,036
	3-3	-163	-847	-355	-246	0	161	783	0	7	555
	3-4	-192	-876	-371	-262	0	161	265	0	7	76
	3-5	-342	-1,026	-581	-472	0	161	0	0	7	0
	3-6	-621	-1,305	-827	-718	0	161	0	0	7	0
	3-7	-896	-1,580	-1,072	-963	0	161	0	0	7	0
	3-8	-1,175	-1,859	-1,319	-1,210	0	161	0	0	7	0
	3-9	-1,450	-2,134	-1,563	-1,454	0	161	0	0	7	0
	3-10	-1,728	-2,412	-1,810	-1,701	0	161	0	0	7	0
	3-11	-2,004	-2,688	-2,054	-1,945	0	161	0	0	7	0
	3-12	-1,730	-2,414	-1,811	-1,702	0	161	0	0	7	0
	3-13	-1,454	-2,138	-1,566	-1,457	0	161	0	0	7	0
	3-14	-1,177	-1,861	-1,320	-1,211	0	161	0	0	7	0
	3-15	-896	-1,580	-1,072	-963	0	161	0	0	7	0
	3-16	-619	-1,303	-826	-717	0	161	0	0	7	0
	3-17	-342	-1,026	-581	-472	0	161	0	0	7	0
	3-18	-192	-876	-371	-262	0	161	265	0	7	76
	3-19	-163	-847	-355	-246	0	161	783	0	7	555
	3-20	-135	-819	-339	-230	0	161	1,304	0	7	1,036
	3-21	-107	-791	-323	-214	0	161	1,819	0	7	1,511
Load Case 4 (Vertical Dn)	4-1	-810	-1,678	-349	-186	0	204	3,095	0	3	1,771
	4-2	-532	-1,400	-102	0	0	204	3,085	0	3	1,830
	4-3	-254	-1,122	0	0	0	204	3,075	0	3	2,198
	4-4	0	-846	0	0	0	204	3,050	0	3	2,677
	4-5	0	-569	0	0	0	204	3,306	0	3	3,157
	4-6	0	-290	0	0	0	204	3,562	0	3	3,639
	4-7	0	-15	0	0	0	204	3,815	0	3	4,117
	4-8	0	0	0	0	0	204	4,250	0	3	4,599
	4-9	0	0	0	0	0	204	4,767	0	3	5,076
	4-10	0	0	0	0	0	204	5,289	0	3	5,558
	4-11	0	0	0	0	0	204	5,807	0	3	6,035
	4-12	0	0	0	0	0	204	5,289	0	3	5,558
	4-13	0	0	0	0	0	204	4,767	0	3	5,076
	4-14	0	0	0	0	0	204	4,254	0	3	4,602
	4-15	0	-13	0	0	0	204	3,817	0	3	4,120
	4-16	0	-290	0	0	0	204	3,562	0	3	3,639
	4-17	0	-569	0	0	0	204	3,306	0	3	3,157
	4-18	0	-846	0	0	0	204	3,050	0	3	2,677
	4-19	-254	-1,122	0	0	0	204	3,075	0	3	2,198
	4-20	-532	-1,400	-102	0	0	204	3,085	0	3	1,830
	4-21	-806	-1,674	-346	-183	0	204	3,095	0	3	1,770

Note: POSITIVE sign convention is aft, starboard, up, port down roll, nose up pitch, nose left yaw

TABLE G3: CALCULATED REACTION FORCES AT INTERFACE POINTS DURING LOAD CASES 5 AND 6

	Testpoint Counter	CALCULATED SB Rod Reactions (lbs)				CALCULATED Lug Reactions (lbs)					
		Forward		Aft		Forward			Aft		
		Port	Stbd	Port	Stbd	Long.	Lateral	Vertical	Long.	Lateral	Vertical
Load Case 5 (Positive Roll)	5-1	-1,154	-1,705	-270	-213	0	165	3382	0	17	1,788
	5-2	0	-3,423	0	-1,934	0	803	3954	0	697	3,106
	5-3	0	-4,989	0	-3,500	0	1375	5444	0	1308	4,478
	5-4	0	-6,552	0	-5,063	0	1945	6931	0	1916	5,844
	5-5	0	-8,125	0	-6,636	0	2519	8432	0	2528	7,225
	5-6	0	-9,694	0	-8,204	0	3091	9926	0	3139	8,599
	5-7	0	-11,272	0	-9,782	0	3668	11429	0	3753	9,983
	5-8	0	-12,828	0	-11,338	0	4235	12905	0	4359	11,340
	5-9	0	-14,401	0	-12,911	0	4809	14406	0	4971	12,722
	5-10	0	-15,969	0	-14,479	0	5381	15899	0	5581	14,096
	5-11	0	-17,258	0	-15,770	0	5861	17197	0	6093	15,290
	5-12	0	-16,134	0	-14,647	0	5454	16150	0	5659	14,325
	5-13	0	-14,525	0	-13,037	0	4864	14599	0	5029	12,899
	5-14	0	-12,958	0	-11,471	0	4293	13108	0	4420	11,527
	5-15	0	-11,390	0	-9,903	0	3720	11615	0	3809	10,153
	5-16	0	-9,788	0	-8,301	0	3134	10072	0	3184	8,735
	5-17	0	-8,196	0	-6,708	0	2550	8540	0	2561	7,326
	5-18	0	-6,608	0	-5,120	0	1969	7017	0	1941	5,923
	5-19	0	-5,030	0	-3,542	0	1393	5508	0	1327	4,535
	5-20	0	-3,442	0	-1,954	0	811	3984	0	707	3,134
	5-21	-1,091	-1,717	-210	-228	0	178	3404	0	31	1,806
Load Case 6 (Nose Up and Lateral Port)	6-1	-2,149	-3,117	-209	0	0	233	5,279	0	30	2,065
	6-2	-3,256	-3,563	-533	0	0	233	5,093	0	30	3,136
	6-3	-4,336	-3,995	-855	0	0	233	4,928	0	30	4,172
	6-4	-5,423	-4,429	-1,182	0	0	233	4,766	0	30	5,215
	6-5	-6,512	-4,866	-1,505	0	0	233	4,595	0	30	6,264
	6-6	-7,604	-5,305	-1,825	0	0	233	4,411	0	30	7,320
	6-7	-8,695	-5,743	-2,144	0	0	233	4,227	0	30	8,376
	6-8	-9,784	-6,181	-2,464	0	0	233	4,048	0	30	9,427
	6-9	-10,872	-6,617	-2,787	0	0	233	3,875	0	30	10,476
	6-10	-11,963	-7,057	-3,104	0	0	233	3,685	0	30	11,534
	6-11	-12,803	-7,398	-3,336	0	0	233	3,510	0	30	12,363
	6-12	-11,925	-7,018	-3,171	0	0	233	3,892	0	30	11,406
	6-13	-10,837	-6,582	-2,849	0	0	233	4,066	0	30	10,359
	6-14	-9,753	-6,150	-2,519	0	0	233	4,216	0	30	9,324
	6-15	-8,667	-5,715	-2,194	0	0	233	4,381	0	30	8,281
	6-16	-7,579	-5,281	-1,867	0	0	233	4,541	0	30	7,240
	6-17	-6,499	-4,853	-1,529	0	0	233	4,667	0	30	6,219
	6-18	-5,414	-4,420	-1,198	0	0	233	4,816	0	30	5,185
	6-19	-4,327	-3,986	-870	0	0	233	4,974	0	30	4,144
	6-20	-3,243	-3,553	-543	0	0	233	5,130	0	30	3,107
	6-21	-2,162	-3,121	-215	0	0	233	5,282	0	30	2,076

Note: POSITIVE sign convention is aft, starboard, up, port down roll, nose up pitch, nose left yaw

TABLE G4: CALCULATED REACTION FORCES AT INTERFACE POINTS DURING LOAD CASES 7 AND 8

	Testpoint Counter	CALCULATED SB Rod Reactions (lbs)				CALCULATED Lug Reactions (lbs)					
		Forward		Aft		Long.	Forward		Long.	Aft	
		Port	Stbd	Port	Stbd		Lateral	Vertical		Lateral	Vertical
Load Case 7 (Positive Pitch)	7-1	-2,474	-3,090	0	0	0	150	5,461	0	30	1,835
	7-2	-2,705	-3,321	0	0	0	150	4,570	0	30	3,190
	7-3	-2,966	-3,582	0	0	0	150	3,517	0	30	4,652
	7-4	-3,224	-3,840	0	0	0	150	2,473	0	30	6,084
	7-5	-3,482	-4,098	0	0	0	150	1,434	0	30	7,538
	7-6	-3,742	-4,358	0	0	0	150	376	0	30	8,978
	7-7	-4,328	-4,944	0	0	0	150	0	0	30	10,434
	7-8	-5,091	-5,707	0	0	0	150	0	0	30	11,877
	7-9	-5,857	-6,473	0	0	0	150	0	0	30	13,335
	7-10	-6,625	-7,241	0	0	0	150	0	0	30	14,800
	7-11	-7,355	-7,971	0	0	0	150	0	0	30	16,174
	7-12	-6,471	-7,087	0	0	0	150	0	0	30	14,639
	7-13	-5,722	-6,338	0	0	0	150	0	0	30	13,203
	7-14	-4,969	-5,585	0	0	0	150	0	0	30	11,763
	7-15	-4,212	-4,828	0	0	0	150	0	0	30	10,319
	7-16	-3,716	-4,332	0	0	0	150	520	0	30	8,889
	7-17	-3,462	-4,078	0	0	0	150	1,537	0	30	7,462
	7-18	-3,210	-3,826	0	0	0	150	2,545	0	30	6,039
	7-19	-2,958	-3,574	0	0	0	150	3,552	0	30	4,618
	7-20	-2,699	-3,315	0	0	0	150	4,601	0	30	3,171
	7-21	-2,430	-3,046	-9	-9	0	150	5,460	0	30	1,820
Load Case 8 (Negative Yaw)	8-1	-1,964	-3,064	-270	-186	0	264	5,106	0	33	2,113
	8-2	-2,612	-3,039	-326	-704	0	-998	5,731	0	1,263	2,711
	8-3	-3,245	-3,015	-380	-1,211	0	-2,232	6,340	0	2,465	3,296
	8-4	-3,872	-2,966	-435	-1,689	0	-3,453	6,897	0	3,654	3,852
	8-5	-4,494	-2,911	-488	-2,160	0	-4,666	7,440	0	4,837	4,401
	8-6	-5,118	-2,857	-542	-2,633	0	-5,882	7,985	0	6,021	4,952
	8-7	-5,748	-2,820	-596	-3,125	0	-7,110	8,568	0	7,217	5,523
	8-8	-6,375	-2,771	-650	-3,604	0	-8,331	9,125	0	8,406	6,079
	8-9	-7,008	-2,736	-705	-4,100	0	-9,565	9,714	0	9,608	6,655
	8-10	-7,639	-2,697	-759	-4,592	0	-10,794	10,295	0	10,805	7,226
	8-11	-8,153	-2,653	-804	-4,982	0	-11,797	10,746	0	11,782	7,680
	8-12	-7,604	-2,581	-786	-4,430	0	-10,655	10,035	0	10,670	7,089
	8-13	-6,963	-2,636	-701	-3,974	0	-9,477	9,477	0	9,522	6,525
	8-14	-6,342	-2,696	-648	-3,509	0	-8,267	8,948	0	8,344	5,983
	8-15	-5,713	-2,749	-593	-3,032	0	-7,042	8,396	0	7,151	5,427
	8-16	-5,093	-2,806	-540	-2,566	0	-5,832	7,861	0	5,973	4,883
	8-17	-4,469	-2,858	-486	-2,092	0	-4,617	7,312	0	4,788	4,332
	8-18	-3,843	-2,907	-432	-1,613	0	-3,396	6,755	0	3,599	3,774
	8-19	-3,219	-2,961	-378	-1,141	0	-2,180	6,211	0	2,415	3,224
	8-20	-2,600	-3,025	-325	-681	0	-974	5,690	0	1,239	2,686
	8-21	-1,991	-3,107	-272	-247	0	213	5,173	0	84	2,175

Note: POSITIVE sign convention is aft, starboard, up, port down roll, nose up pitch, nose left yaw

APPENDIX H: *Measured and Calculated Reaction Graphs;
Ground Test*

FIGURE H1: Measured and Calculated Reactions for MK 84 Ground Test Load Case 1, Forward Swaybrace Assembly

FIGURE H2: Measured and Calculated Reactions for MK 84 Ground Test Load Case 1, Aft Swaybrace Assembly

FIGURE H3: Measured and Calculated Reactions for MK 84 Ground Test Load Case 1, Lug Vertical Reactions

FIGURE H4: Measured and Calculated Reactions for MK 84 Ground Test Load Case 1, Lug Longitudinal Reactions

FIGURE H5: Measured and Calculated Reactions for MK 84 Ground Test Load Case 2, Forward Swaybrace Assembly

FIGURE H6: Measured and Calculated Reactions for MK 84 Ground Test Load Case 2, Aft Swaybrace Assembly

FIGURE H7: Measured and Calculated Reactions for MK 84 Ground Test Load Case 2, Lug Vertical Reactions

FIGURE H8: Measured and Calculated Reactions for MK 84 Ground Test Load Case 3, Forward Swaybrace Assembly

FIGURE H9: Measured and Calculated Reactions for MK 84 Ground Test Load Case 3, Aft Swaybrace Assembly

FIGURE H10: Measured and Calculated Reactions for MK 84 Ground Test Load Case 3, Lug Vertical Reactions

FIGURE H11: Measured and Calculated Reactions for MK 84 Ground Test Load Case 4, Forward Swaybrace Assembly

FIGURE H12: Measured and Calculated Reactions for MK 84 Ground Test Load Case 4, Aft Swaybrace Assembly

FIGURE H13: Measured and Calculated Reactions for MK 84 Ground Test Load Case 4, Lug Vertical Reactions

FIGURE H14: Measured and Calculated Reactions for MK 84 Ground Test Load Case 5, Forward Swaybrace Assembly

FIGURE H15: Measured and Calculated Reactions for MK 84 Ground Test Load Case 5, Aft Swaybrace Assembly

FIGURE H16: Measured and Calculated Reactions for MK 84 Ground Test Load Case 5, Lug Vertical Reactions

FIGURE H17: Measured and Calculated Reactions for MK 84 Ground Test Load Case 5, Lug Lateral Reactions

FIGURE H18: Measured and Calculated Reactions for MK 84 Ground Test Load Case 6, Forward Swaybrace Assembly

FIGURE H19: Measured and Calculated Reactions for MK 84 Ground Test Load Case 6, Aft Swaybrace Assembly

FIGURE H20: Measured and Calculated Reactions for MK 84 Ground Test Load Case 6, Lug Vertical Reactions

FIGURE H21: Measured and Calculated Reactions for MK 84 Ground Test Load Case 7, Forward Swaybrace Assembly

FIGURE H22: Measured and Calculated Reactions for MK 84 Ground Test Load Case 7, Aft Swaybrace Assembly

FIGURE H23: Measured and Calculated Reactions for MK 84 Ground Test Load Case 7, Lug Vertical Reactions

FIGURE H24: Measured and Calculated Reactions for MK 84 Ground Test Load Case 8, Forward Swaybrace Assembly

FIGURE H25: Measured and Calculated Reactions for MK 84 Ground Test Load Case 8, Aft Swaybrace Assembly

FIGURE H26: Measured and Calculated Reactions for MK 84 Ground Test Load Case 8, Lug Vertical Reactions

FIGURE H27: Measured and Calculated Reactions for MK 84 Ground Test Load Case 8, Lug Lateral Reactions

APPENDIX I: *Swaybrace Rod and Lug Reaction Errors;
Flight Test*

TABLE I1: Swaybrace Rod and Lug Errors During FlightTest
Critical Reaction Errors only

Errors in Lbs. (Absolute Value)						Time (sec.)	Errors in % (Absolute Value)					
Fwd. Swaybrace		Aft Swaybrace		Lugs, Vertical			Fwd. Swaybrace		Aft Swaybrace		Lugs, Vertical	
Port	Stbd.	Port	Stbd.	Fwd.	Aft		Port	Stbd.	Port	Stbd.	Fwd.	Aft
327	*	125	*	117	*	43.800	13	*	4	*	1	*
*	*	193	*	349	*	43.803	*	*	6	*	6	*
*	*	296	486	161	*	43.805	*	*	10	21	3	*
*	*	463	347	*	*	43.808	*	*	16	13	*	*
*	*	231	114	*	*	43.810	*	*	9	4	*	*
*	*	13	75	*	*	43.813	*	*	1	2	*	*
*	*	*	92	*	*	43.815	*	*	*	2	*	*
*	*	*	178	*	*	43.818	*	*	*	5	*	*
*	*	*	168	*	*	43.820	*	*	*	4	*	*
*	*	*	41	*	*	43.823	*	*	*	2	*	*
*	*	*	272	*	*	43.825	*	*	*	9	*	*
*	*	*	88	*	*	43.828	*	*	*	3	*	*
*	*	*	*	*	1420	43.833	*	*	*	*	*	25
*	*	*	*	*	1216	43.835	*	*	*	*	*	19
*	*	*	*	*	665	43.838	*	*	*	*	*	10
*	*	*	*	*	2	43.841	*	*	*	*	*	*
*	*	*	*	414	297	43.843	*	*	*	*	8	3
451	*	*	*	211	40	43.845	21	*	*	*	3	*
380	*	*	*	30	461	43.848	14	*	*	*	*	6
305	*	11	*	387	89	43.850	11	*	1	*	4	2
359	*	133	*	554	413	43.853	14	*	6	*	5	5
206	*	95	*	396	784	43.855	8	*	4	*	3	10
67	*	80	*	78	856	43.858	4	*	3	*	*	16
*	*	22	*	656	*	43.860	*	*	1	*	9	*
*	*	17	698	88	*	43.863	*	*	*	26	2	*
*	*	64	563	*	*	43.868	*	*	3	18	*	*
*	*	*	186	*	*	43.870	*	*	*	6	*	*
*	666	*	25	*	*	43.873	*	32	*	*	*	*
*	499	*	58	*	*	43.875	*	20	*	1	*	*
*	271	*	34	*	*	43.878	*	10	*	*	*	*
*	138	*	12	*	*	43.880	*	5	*	*	*	*
*	122	*	1	*	*	43.883	*	5	*	*	*	*
499	144	*	269	*	*	43.885	24	5	*	9	*	*
384	272	*	409	*	*	43.887	16	10	*	15	*	*
415	1	*	297	*	*	43.890	15	*	*	15	*	*
362	*	*	*	*	889	43.892	12	*	*	*	*	17
423	*	*	*	*	402	43.895	13	*	*	*	*	8
8	*	*	*	*	337	43.897	1	*	*	*	*	6
20	*	*	*	*	279	43.902	*	*	*	*	*	4
187	*	66	*	*	16	43.905	5	*	3	*	*	*
205	*	71	*	1161	189	43.907	6	*	4	*	20	2
143	*	5	*	261	837	43.910	5	*	1	*	3	12
503	*	64	*	354	933	43.912	18	*	2	*	3	15
888	*	216	*	350	706	43.915	38	*	9	*	3	12
*	*	260	*	73	*	43.918	*	*	11	*	*	*
*	*	215	400	357	*	43.920	*	*	9	18	4	*
*	*	179	281	963	*	43.922	*	*	8	11	11	*
*	*	*	173	700	*	43.925	*	*	*	6	9	*
*	*	*	8	167	*	43.927	*	*	*	1	3	*
*	*	*	1	58	*	43.930	*	*	*	*	*	*
*	*	*	61	294	*	43.932	*	*	*	1	5	*
*	*	*	30	*	*	43.935	*	*	*	*	*	*
*	*	*	240	*	*	43.940	*	*	*	8	*	*
*	307	*	514	*	*	43.942	*	15	*	17	*	*
*	22	*	436	*	*	43.945	*	*	*	17	*	*
259	361	*	375	*	*	43.948	10	14	*	17	*	*
462	*	*	*	*	275	43.950	15	*	*	*	*	6
498	*	*	*	*	130	43.952	14	*	*	*	*	3
329	*	*	*	*	38	43.955	9	*	*	*	*	1
74	*	*	*	*	76	43.957	2	*	*	*	*	1
9	*	*	*	*	277	43.960	1	*	*	*	*	5
229	*	164	*	*	506	43.962	6	*	7	*	*	9
64	*	101	*	*	443	43.965	3	*	4	*	*	9
368	*	15	*	*	148	43.967	14	*	*	*	*	2
490	*	48	*	*	*	43.970	22	*	2	*	*	*
*	*	30	*	540	*	43.975	*	*	1	*	9	*
*	*	98	*	839	*	43.977	*	*	5	*	12	*
*	*	165	119	1060	*	43.980	*	*	9	5	15	*

TABLE I1: Swaybrace Rod and Lug Errors During FlightTest
Critical Reaction Errors only

Continued

Errors in Lbs. (Absolute Value)						Time	Errors in % (Absolute Value)					
Fwd. Swaybrace		Aft Swaybrace		Lugs, Vertical			Fwd. Swaybrace		Aft Swaybrace		Lugs, Vertical	
Port	Stbd.	Port	Stbd.	Fwd.	Aft	(sec.)	Port	Stbd.	Port	Stbd.	Fwd.	Aft
*	*	*	162	864	*	43.982	*	*	*	7	12	*
*	*	*	156	611	*	43.985	*	*	*	6	8	*
*	*	*	58	188	*	43.987	*	*	*	2	2	*
*	*	*	185	532	*	43.990	*	*	*	7	7	*
*	*	*	219	401	*	43.992	*	*	*	9	6	*
*	*	*	*	106	*	43.995	*	*	*	*	1	*
*	*	*	*	*	*	43.997	*	*	*	*	*	*
*	*	*	*	*	885	44.000	*	*	*	*	*	17
852	*	*	*	*	1168	44.002	34	*	*	*	*	21
574	*	*	*	*	1010	44.005	20	*	*	*	*	17
634	*	*	*	*	846	44.010	18	*	*	*	*	14
544	*	*	*	*	646	44.012	15	*	*	*	*	11
325	*	*	*	*	42	44.015	9	*	*	*	*	1
120	*	674	*	*	381	44.017	3	*	30	*	*	6
220	*	458	*	*	114	44.020	6	*	18	*	*	2
392	*	136	*	*	*	44.022	11	*	4	*	*	*
524	*	83	*	*	*	44.025	16	*	2	*	*	*
434	*	83	*	*	*	44.027	16	*	3	*	*	*
81	*	64	407	*	*	44.030	4	*	2	19	*	*
*	*	29	392	*	*	44.032	*	*	2	16	*	*
*	*	3	360	*	*	44.035	*	*	*	14	*	*
*	*	79	283	*	*	44.037	*	*	4	10	*	*
*	*	71	271	*	*	44.040	*	*	4	9	*	*
*	*	*	54	*	*	44.042	*	*	*	2	*	*
*	*	*	152	*	*	44.047	*	*	*	5	*	*
*	*	*	318	*	*	44.050	*	*	*	12	*	*
*	*	*	*	*	*	44.052	*	*	*	*	*	*
*	*	*	*	*	*	44.055	*	*	*	*	*	*
*	*	*	*	*	*	44.057	*	*	*	*	*	*
*	*	*	*	*	*	44.060	*	*	*	*	*	*
288	*	*	*	*	*	44.062	14	*	*	*	*	*
160	*	*	*	*	281	44.065	8	*	*	*	*	5
254	*	*	*	117	186	44.067	11	*	*	*	2	4
178	*	*	*	312	343	44.070	8	*	*	*	6	6
43	*	197	*	340	296	44.072	2	*	9	*	6	5
29	*	49	*	*	417	44.075	1	*	2	*	*	8
210	*	62	*	*	665	44.077	10	*	3	*	*	12
309	*	155	*	*	783	44.082	15	*	8	*	*	15
391	*	180	*	*	*	44.085	19	*	9	*	*	*
512	*	21	*	*	*	44.087	25	*	1	*	*	*
*	*	*	*	*	*	44.090	*	*	*	*	*	*
*	*	*	359	*	*	44.092	*	*	*	16	*	*
*	*	*	342	*	*	44.095	*	*	*	14	*	*
*	*	*	257	*	*	44.098	*	*	*	10	*	*
*	*	*	177	*	*	44.100	*	*	*	7	*	*
320	280	131	224	403	483	AVERAGE	12	12	5	8	5	8

NOTES: 1. Critical reactions occur when a swaybrace rod is experiencing more than 2,000 lbs. of compression or a lug has over 5,000 lbs. of tension.
2. All non-critical points are not used in the error calculations and are marked with an asterisk '*'.
3. Average swaybrace rod reaction error (all four rods): 239 lbs., 9%
All rod reaction errors are < 900 lbs. Errors are > 600 lbs. or > 20% in only 6 and 10 out of the 154 total critical calculations, respectively.
4. Average lug reaction error (both lugs): 443 lbs., 7%
All lug reaction errors are < 1,500 lbs. Errors are > 1,000 lbs. or > 15% in only 6 and 8 out of the 78 total critical calculations, respectively.