Dynamic Model of Store/Rack Interface Reactions

Tim C. Schoppert, Ph.D., P.E.
Naval Air Systems Command
Patuxent River, MD 20653
301-342-4393
tim.schoppert@navy.mil

Ken H. Means, Ph.D., P.E.
West Virginia University
Morgantown, WV 26506
304-293-4111 x2308
kmeans@mail.wvu.edu

Abstract—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 relying only on store mass properties, accelerometer data and geometry. Once theoretical equations were developed, a full-scale static ground test was conducted to provide data for model verification and refinement. Flight test data for final validation were accumulated during a carrier suitability flight test program conducted at the Naval Air Warfare Center, Patuxent River, Maryland on an F-14 aircraft with instrumented BRU-32/A bomb ejector rack and a GBU-24/B/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, agreement was found in form and magnitude for the calculated interface reactions. Critical lug and swaybrace rod reactions averaged less than 9% absolute error.

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1. 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 cost reductions and downsizing environments, the desire to make rapid production decisions 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 flight time 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 (USN's) 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 approximately the same as originally designed in 1976. The BRU-32/A Bomb Ejector Rack (BRU-32), figure 1-1, was created for the USN 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 carriage of single, external ordnance on the F/A-18 Hornet and F-14 Tomcat.

FIGURE 1-1: BRU-32/A Bomb Ejector Rack

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1 U.S. Government work not protected by U.S. copyright.
2 IEEEAC paper #1041, Updated October 14, 2002
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.

Without accurate and readily available prediction models, all ordnance with the possibility of creating large reactions in the BRU-32 must go through time-consuming and expensive structural flight test programs with fully instrumented store and rack combinations. 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 impact of critical program milestones.

Although an aircraft’s envelope of flight operations contains a plethora of combinations of airspeed, altitude, etc., many of the largest reactions experienced at the SRI are 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 typically begin with carrier suitability flight tests.

**Objective**

The objective of this research was to demonstrate the ability to accurately predict the reaction loads at the SRI via a BRU-32 on an aircraft during an arrested landing. The reaction forces were found without employing specialized SRI instrumentation, thereby avoiding the time and expense of installing and calibrating the delicate strain gages as well as installation of strain gage signal conditioning. Preloads accumulated at the interface during ordnance loading and handling were also examined. The final equations are based only on the combination of external loads that subsequently result in the maximum forces generated at each swaybrace and hook and are generalized for multiple aircraft and rack combinations. The final objectives of this research are summarized in figure 1-2.

![FIGURE 1-2: Research Summary Flowchart](image_url)

The 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.

**Approach**

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 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. 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 inertial predictions for arrested landings are also adequate for inertial-only predictions during normal flight. Full aerodynamic considerations were beyond the scope of this research.

The carrier suitability 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, geometry and flight test conditions. Further work may address real-time data collection, lighter stores, additional aircraft types, or various bomb ejector racks carrying single or multiple stores.

**BRU-32/A Bomb Ejector Rack**

In the 1970s, the USN created a design specification for a bomb ejector rack for the F/A-18 aircraft that 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 (figure 1-3) in 1976 to meet those demands.[2]

The BRU-32 combines two sets of hooks (including 14-inch and 30-inch spacings) designed for carriage of stores with two suspension lugs.[3] Stores with 10-inch to 28-inch diameters are automatically swaybraced when the hooks become latched and secondary adjustments are not required.[2] The rack assembly weighs approximately 76-lbs. and has a pitching moment of 1.52 $\text{deg}$. The static ejection acceleration for the 2,370-lb. GBU-24 from the BRU-32 is approximately 11 Gs.[5]

### 2. ANALYTICAL MODELING

This paper 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 developed, 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’s center of gravity (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. The most accurate analytical tool to determine store carriage loads for all conditions is a solution to the full Navier-Stokes equations.[6] Solutions to the complete Euler equations have been solved for various shapes by generating a grid to fit the configuration then extending the grid into the flowfield.[7,8] Both processes, however, are too difficult and time consuming for most configurations. A simpler method was required to predict real-time SRI reactions during a flight-test program.

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

To verify the structural integrity of a store and rack combination, the first consideration was how to interpret the test data. Failure can be defined many ways, from almost imperceptible yielding to complete separation.[9,10] The USN definition of a failure 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; yield and ultimate loads are defined as 115% and 150% of the limit loads, respectively.[3]

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.[11] A variety of procedures have also been utilized to obtain the substructure mass matrices, including lumped mass formulations in which a displacement method (considering geometric compatibility along each substructure boundary) is employed in the final substructure coupling.[12,13] Substructure methods relying on the displacement method have been employed in analysis of both static[11,14] and dynamic[15,16] behavior of structures. Dynamic behavior generally requires a Rayleigh-Ritz procedure to reduce the order of system matrices. Additionally, Gladwell introduced the Branch-Modes technique with the advantage of a diagonal system stiffness matrix that is formed along with the normal-mode analysis of the substructure.[12] All of these methods, however, are very time-intensive and require many input parameters. It is also difficult, if not impossible, to solve a parallel set of equations.

To more quickly solve for the store's translational and rotational accelerations, accelerations were calculated using the individual linear accelerometer data and their location on the store. First principles were incorporated to derive the equations of acceleration from raw accelerometer data.

Accelerations

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. The angular velocity and angular acceleration of a rigid body at a given instant are therefore independent of the choice of the reference point.[17] From 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 $A$, it can be shown that

$$\vec{v}_B = \vec{v}_A + \vec{\omega}_A \times \vec{r}_{B/A}$$  (1)

$$\vec{a}_B = \vec{a}_A + \vec{\alpha}_A \times \vec{r}_{B/A} + \vec{\omega}_A \times (\vec{\omega}_A \times \vec{r}_{B/A})$$  (2)

Considering a 2,000-lb. bomb as a rigid body, the acceleration 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, $\vec{a}_{rel}$. 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.

$$\vec{a}_M = \vec{a}_{CG} + \vec{a}_{rel}$$  (3)

To find the acceleration at the store CG, equation (3) is rearranged to

$$\vec{a}_{CG} = \vec{a}_M - \vec{a}_{rel}$$  (4)

The measured accelerations at each accelerometer $\vec{a}_M$ are known while the relative accelerations require calculation. Allowing $\vec{a}_M$ to coincide with another point on the surface and point $A$ to represent the CG, equations (2) and (4) were combined to find the equation of acceleration about the CG based on the measured accelerometer data.

$$\vec{a}_{CG} = \vec{a}_M - \vec{\omega} \times \vec{r}_{rel} - \vec{\omega} \times (\vec{\omega} \times \vec{r}_{rel})$$  (5)

From equations (4) and (5), the acceleration of a store accelerometer relative to the store CG $\vec{a}_{rel}$ is defined as

$$\vec{a}_{rel} = \vec{a}_M - \vec{\omega} \times \vec{r}_{rel}$$  (6)

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

$$\vec{\omega} = \omega_i \hat{i} + \omega_j \hat{j} + \omega_k \hat{k}$$

$$\vec{\alpha} = \alpha_i \hat{i} + \alpha_j \hat{j} + \alpha_k \hat{k}$$

$$\vec{a} = \alpha_i \hat{i} + \alpha_j \hat{j} + \alpha_k \hat{k}$$

By expanding equations (6) through (9), 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.

$$a_{rel,x} = r_x(\omega_x \omega_x - \alpha_x) + r_y(\omega_x \omega_y + \alpha_x) + r_z(\omega_x \omega_z + \alpha_z) - r_y(\omega_y \omega_z + \alpha_z)$$  (10)

$$a_{rel,y} = r_x(\omega_y \omega_y - \alpha_y) + r_y(\omega_y \omega_y + \alpha_y) + r_z(\omega_y \omega_z + \alpha_z) - r_z(\omega_z \omega_z + \alpha_z)$$  (11)

$$a_{rel,z} = r_x(\omega_z \omega_z - \alpha_z) + r_y(\omega_z \omega_z + \alpha_z) + r_z(\omega_z \omega_z + \alpha_z) - r_y(\omega_z \omega_z + \alpha_y)$$  (12)

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 (5) with equations (10), (11) and (12):

$$a_{CG,x} = a_{rel,x} - r_x(\omega_x \omega_x - \alpha_x) - r_y(\omega_x \omega_y + \alpha_x) + r_z(\omega_x \omega_z + \alpha_z)$$  (13)

$$a_{CG,y} = a_{rel,y} - r_x(\omega_y \omega_y - \alpha_y) + r_y(\omega_y \omega_y + \alpha_y) - r_z(\omega_z \omega_z + \alpha_z)$$  (14)

$$a_{CG,z} = a_{rel,z} - r_x(\omega_z \omega_z - \alpha_z) - r_y(\omega_z \omega_z + \alpha_z) + r_z(\omega_z \omega_z + \alpha_z)$$  (15)
The translational accelerations calculated in equations (13) through (15) are functions of the rotational velocities \((\omega_x, \omega_y, \omega_z)\) and rotational accelerations \((\ddot{\omega}_x, \ddot{\omega}_y, \ddot{\omega}_z)\). For accelerometer data, the measured accelerations were all tangential allowing the calculation of the angular accelerations when combined with the store and instrumentation geometry. Accurate 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. Additionally, these equations contain scalars instead of 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 must follow global sign conventions vice 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 measured accelerations were labeled and defined as shown in table 2-1.

<table>
<thead>
<tr>
<th>Accelerometer</th>
<th>Specific Information</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a_x)</td>
<td>X-axis accelerometer for longitudinal acceleration. Located anywhere on store, but prefer at the store longitudinal CG.</td>
</tr>
<tr>
<td>(a_{y,\text{yaw}})</td>
<td>Y-axis accelerometer used for yaw measurement. Located at or forward of longitudinal store CG and forward of (a_{z,\text{pitch}}).</td>
</tr>
<tr>
<td>(a_{y,\text{yaw}})</td>
<td>Y-axis accelerometer used for yaw measurement. Located at or aft of longitudinal store CG and aft of (a_{z,\text{pitch}}).</td>
</tr>
<tr>
<td>(a_{z,\text{pitch}})</td>
<td>Z-axis accelerometer used for roll measurement. Located on starboard side of store, preferably at store CG across from (a_{z,\text{pitch}}).</td>
</tr>
<tr>
<td>(a_{z,\text{pitch}})</td>
<td>Z-axis accelerometer used for roll measurement. Located on port side of store, preferably at store CG across from (a_{z,\text{pitch}}).</td>
</tr>
<tr>
<td>(a_{y,\text{pitch}})</td>
<td>Z-axis accelerometer used for pitch measurement. Located forward of longitudinal store CG and forward of (a_{z,\text{pitch}}).</td>
</tr>
<tr>
<td>(a_{y,\text{pitch}})</td>
<td>Z-axis accelerometer used for pitch measurement. Located aft of longitudinal store CG and aft of (a_{z,\text{pitch}}).</td>
</tr>
</tbody>
</table>

Redundant use of accelerometer data allows the necessary calculations to be completed with a minimum of six accelerometers (i.e. sharing a z-accelerometer for pitch, roll and vertical acceleration calculations, etc.). All coupled accelerometers (i.e. \(a_{x,\text{pitch}}\) and \(a_{y,\text{yaw}}\), 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.).

The magnitude of the store roll acceleration \(\alpha_x\) 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 (16) provides the average reading of roll acceleration of the store CG. The second term in equation (16) 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 affect this parameter and translational acceleration along the z-axis is canceled out via subtraction within both terms in equation (16). The value of \(L_{y,\text{roll}}\) 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. \(L_{x,\text{roll}}\) and \(L_{x,\text{pitch}}\) 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.

\[
\alpha_x = \frac{a_{z,\text{pitch}} - a_{z,\text{pitch}}}{|L_{y,\text{roll}}|} - \frac{a_{z,\text{pitch}} - a_{z,\text{pitch}}}{|L_{x,\text{pitch}}|} \left( \frac{|L_{y,\text{roll}}|}{|L_{x,\text{pitch}}|} \right) \]  \(16\)

The magnitude of the store pitch acceleration \(\alpha_y\) 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 (17) provides the average reading of pitch acceleration about the store CG, with the second term removing an effective pitch acceleration component due to roll acceleration when the two accelerometers are at different lateral locations. Yaw acceleration does not affect this parameter and translational acceleration along the z-axis is canceled out in equation (17). \(L_{y,\text{pitch}}\) and \(L_{x,\text{pitch}}\) denote 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.

\[
\alpha_y = \frac{a_{z,\text{pitch}} - a_{z,\text{pitch}}}{|L_{y,\text{pitch}}|} - \frac{a_{z,\text{pitch}} - a_{z,\text{pitch}}}{|L_{x,\text{pitch}}|} \left( \frac{|L_{y,\text{pitch}}|}{|L_{x,\text{pitch}}|} \right) \]  \(17\)

The magnitude of the store yaw acceleration \(\alpha_z\) 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 (18) provides the average reading of yaw acceleration of the store CG. The second term in equation (18) 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 (18). The values of $L_{x,ym}$ and $L_{z,ym}$ 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.

$$\alpha_z = \frac{a_{x,ym} - a_{z,ym}}{L_{x,ym}} - \frac{a_{x,ym} - a_{z,ym}}{L_{z,ym}} \left( \frac{L_{x,ym}}{L_{z,ym}} \right)$$  \hspace{1cm} (18)

Forces and moments at the store CG require accurate acceleration data. Data for equations (16) through (18) are from accelerometers placed on the store in such a way to eliminate interference from other accelerometers. Translational accelerations (equations 13 through 15) are already corrected for interference effects.

**Inertial Loads**

If coordinate axes are selected such that they are the principal axes with an origin at the body mass center or at a point fixed in inertial space, and if the angular velocity $\omega$ of the coordinate system is the same as that of the body, the rotational motion of a rigid body can be described as:

$$M_1 = I_1\dot{\omega}_1 + \omega_2\omega_3(l_2 - l_z)$$
$$M_2 = I_2\dot{\omega}_2 + \omega_3\omega_1(l_3 - l_z)$$
$$M_3 = I_3\dot{\omega}_3 + \omega_1\omega_2(l_3 - l_z)$$  \hspace{1cm} (19)

Equations (54) are known as Euler’s equations of motion for body-fixed principal axes, where $I_1$, $I_2$ and $I_3$ are the principal moments of inertia; $\omega_1$, $\omega_2$ and $\omega_3$ 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. Additionally recalling Newton’s Second Law of Motion, if the resultant force acting on a particle is not zero and mass is constant, the particle will have acceleration proportional to and in the direction of the resultant force. Replacing the time derivatives of the linear velocities with translational accelerations summarized in equations (13) through (15) yields forces than can be calculated with known parameters:

$$F_x = m(a_{x,x} + v_x\omega_x - v_y\omega_y)$$
$$F_y = m(a_{y,y} + v_y\omega_y - v_x\omega_x)$$
$$F_z = m(a_{z,z} + v_z\omega_z - v_y\omega_y)$$  \hspace{1cm} (20)

The principal axes of the bomb body correspond to the XYZ body axes and the time derivatives of angular velocity can be replaced with the angular accelerations shown in equations (16) through (18). The simplified Euler’s equations (20) can then be shown as

$$M_x = I_x\alpha_x + \omega_y\omega_z(l_x - l_y)$$
$$M_y = I_y\alpha_y + \omega_z\omega_x(l_x - l_y)$$
$$M_z = I_z\alpha_z + \omega_x\omega_y(l_x - l_z)$$  \hspace{1cm} (21)

Although the mass moments of inertia are found from mass property measurements, the translational velocities ($v_x$, $v_y$ and $v_z$) and angular velocities ($\omega_x$, $\omega_y$ and $\omega_z$) cannot be found directly and must be approximated numerically by integrating over any time step ($t_f - t_i$) as

$$v_z = v_i + a_{avg}(t_f - t_i)$$  \hspace{1cm} (22)
$$\omega_z = \omega_i + a_{avg}(t_f - t_i)$$  \hspace{1cm} (23)

where

\[ a_{avg} = \frac{a_i + a_f}{2} \]

$$a_{avg} = \frac{a_z}{2} \hspace{1cm} a_{avg} = \frac{a_z}{2}$$  \hspace{1cm} (24)

The forces resisting the inertial loads, as calculated with equations (20) and (21), are equal in magnitude but opposite in direction to the inertial forces as found with the accelerations experienced by the store during any particular maneuver. 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 (20) and (21) 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 2-1.

**FIGURE 2-1:** Three-Dimensional Flight Envelope and Sign Convention
Reactions at SRI

The accurate distribution of the three forces \( F_x, F_v, F_z \) and three moments \( M_x, M_v, M_z \) from the store CG to the SRI was critical in calculating the reactions in the BRU-32. Once the loads at the store CG were dynamically calculated for each time step as described in equations (20) and (21), the resulting reactions at the individual interface points were found through an assumption of quasi-static force and moment equilibrium. Using the principle of superposition, the six load cases were considered independently and the calculated interface reactions were combined to form the overall interface reactions at each 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 due to 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; separation between the hook and lug is possible.

The BRU-32 is a steel bomb rack and is assumed to have rigid body characteristics. Figure 2-2 shows the sign convention and layout geometry of a typical SRI assuming the requisite 30-inch lug spacing of a larger store (versus smaller stores requiring 14-inch lug spacing).

The lateral distance between two swaybrace contact points within a single assembly 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 are likely to change or redistribute during taxing and flight maneuvers but will generally return to the original values in steady state flight. These loads can be predicted based on historical averages and consistent loading techniques, but must be accounted for in the reaction equations.

Although the swaybrace rods cannot react in tension (nor can the 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 unload 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 only be reacted by the interface point that is increasing in magnitude.

The reactions at the interface points due to each load type represent the total magnitude of each reaction expected in the SRI during a state of zero preload. However, some amount of 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 \( M_z \) 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. 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 \( P_z \). The loads of \( P_x, M_x, M_y, M_z \) 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 the derived reaction equations via superposition and considering equilibrium modifications, 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. The model was modified and verified with ground and flight test data. Once all of the necessary data was entered into the program, the translational and rotational accelerations at the store CG were found with equations (13) through (18). Inertial forces and moments at the store CG were then calculated with equations (20) and (21), respectively. The reactions at the SRI were found using superposition and saved to data files for review.

3. GROUND TEST AND ANALYSIS

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, 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.

For the static ground test, a rigid test cell was assembled and a MK 84 bomb body with a conical tail fin was mounted on a BRU-32. The rack was affixed to large steel beams, ensuring that limited flexibility was present in the testing apparatus. Additional lugs were welded to the MK 84 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, 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. 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 actuators. Spreader bars were used to symmetrically load two lugs simultaneously with one actuator. Figure 3-1 shows a typical welded lug on the MK 84.

Program to Calculate Reactions at the SRI

A FORTRAN program was created to calculate the SRI reactions at each time step for ground or flight-testing, as all necessary data must be entered for each test, and requires
The BRU-32 used in the ground test was fully instrumented with strain gages 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 3-2 shows the MK 84 and the instrumented SRI attached to the test cell.

Multiple load cells were required to apply the loads from the hydraulic actuators. Loads were recorded and tracked with the voltmeters. A typical load cell is shown in figure 3-3, including the assembly attaching the load cell to a welded lug and the necessary wiring to record loads data.

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 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. After attaching the instrumented BRU-32 to the I-beams, the MK 84 was attached to the rack via standard USN loading procedures. Swaybrace rods were set in the extended position and not additionally tightened. Real-time loads data were captured at all test points at 100 samples per second (sps) as well as voltage and reaction data from the four instrumented swaybrace rods and two instrumented lugs. Calibrations were conducted before and after each load case. Figure 3-4 shows the completed test cell and MK 84.

Before each test point, a settling load of 2,500 lb. was applied to remove any slack in the instrumentation, cables and rack. A load matrix of eight test points was prepared for the test and is shown in table 3-1; test point 6 shows a combined load point whereas all other load cases represented pure force conditions through the store CG.

<table>
<thead>
<tr>
<th>Test Point</th>
<th>Load Case</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>+F_x</td>
</tr>
<tr>
<td>2</td>
<td>+F_y</td>
</tr>
<tr>
<td>3</td>
<td>+F_z</td>
</tr>
<tr>
<td>4</td>
<td>-F_y</td>
</tr>
<tr>
<td>5</td>
<td>-M_x</td>
</tr>
<tr>
<td>6</td>
<td>-F_x + M_y + M_z</td>
</tr>
<tr>
<td>7</td>
<td>+M_z</td>
</tr>
<tr>
<td>8</td>
<td>+M_x</td>
</tr>
</tbody>
</table>

During each test, a load was applied to the store from 0 lbs. to the maximum of 10,000 lbs. (approximately 5 Gs of translational acceleration) and back to 0 lbs. For the load cases requiring the use of two hydraulic actuators, 5,000 lbs.
of force were applied from each actuator and the outputs monitored using separate voltmeters to allow consistent and symmetric buildup of load on the welded lugs.

Load case 1 simulated a longitudinal force at the store CG and was loaded along the x-axis. Two hydraulic actuators each applied 5,000 lbs. of force simultaneously to the two, middle welded lugs located symmetrically on both sides of the store. Figure 3-5 shows the setup for this load case.

FIGURE 3-5: MK 84 Load Case 1—Longitudinal Pull

Load case 2 consisted of a pure lateral pull of 10,000 lbs. through the store CG via one of the middle, welded lugs. Load cases 3 and 4 consisted of a pure vertical pulls upward and downward, respectively, of 10,000 lbs. through the store CG using the center welded lugs and a spreader bar with one hydraulic actuator. Load case 5 modeled a pure moment about the longitudinal axis \( (M_L) \) by simultaneously pulling up with 5,000 lbs. on the two forward, welded lugs via a spreader bar while pulling down on the two aft, welded lugs via a second spreader bar. Load case 8 (figure 3-7) models a pure moment about the vertical axis \( (M_V) \) by simultaneously pulling laterally with 5,000 lbs. of force on the port, aft welded lug while pulling in the opposite direction with an equal load on the starboard, forward welded lug.

FIGURE 3-7: MK 84 Load Case 8 — Yaw Moment

Instrumented Interface Points—Two modified lugs were instrumented with 5 strain gage circuits (figure 3-8). Each lug contained one internal, proprietary circuit from StrainSert, Inc. measuring vertical reaction as well as 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 resistance of 350 ohms.

FIGURE 3-8: MK 3 Mod 0 Lug with Strain Gages

The four swaybrace rods were also instrumented with Vishay strain gage circuits (model number CEA-06-062UT-350) as shown in figure 3-9; these gages were STC for steel with 350 ohms resistance. The gages on each rod were connected in standard, four-circuit bridges to cancel the bending load and friction measurements.
Although the swaybrace rod is threaded into the swaybrace assembly, the rod is either engaged in a fully extended or fully retracted position. For stores with 30-inch lug spacing as in this test, the swaybrace rods are typically set in the fully extended position and not additionally tightened or torqued further after the store is loaded in the rack. Each rod includes a ball-and-socket pad that was in contact with the store; as with all ball-and-socket joints, moments could not be reacted in the swaybrace rods. For each load case listed in table 3-1, the buildup to the maximum external load was accomplished in two to three minutes while unloading took an average of less than 30 seconds.

The swaybrace gage data were combined in the bridge 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 3-10 provides an example of the strain output for Ground Test Load Case 1 showing data from the five strain gages on the 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. Swaybrace rod preloads for each load case were recorded; lug preloads were calculated using the recorded swaybrace preload data and weapon weight. Using equations (25) through (33), 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. This program incorporates the equations outlined in the previous chapter for converting store accelerations into forces and moments and then distributing the forces and moments from the store CG to the SRI.

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 equation (29). Using the measured data, it was calculated that an average of 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 that was not recorded due to the circuit design. The longitudinal lug reactions due to a longitudinal force $P_x$ (equation 29) were therefore corrected to

$$L_{x,a} = 0.606(P_x)$$  \hspace{1cm} (35)$$

$$L_{x,f} = 0.385(P_x)$$  \hspace{1cm} (34)$$

During the buildup of the external load, the interface points either react to the loading force or the unloading force 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 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 more rigid 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 developed 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 observed lug reaction. The positive yawing moment contributions to the interface reactions shown in equations (25) through (33) were therefore revised based on this data; the new reaction components due to $M_z$ are shown as
For a negative yawing moment (nose right), equations were similarly corrected to

\[ S_{f,r} = S_{a,r} = 0 \]  
\[ S_{f,l} = S_{a,l} = \frac{4M_c}{(L_1 + L_2)^2} \sin \alpha \]  
\[ L_{f,z} = L_{a,z} = \frac{M_c}{(L_1 + L_2)} \tan \alpha \]  
\[ L_{f,y} = L_{a,y} = \frac{M_c}{(L_1 + L_2)} \]  

The SRI reactions to the externally applied load during buildup, while all interface points still contained preload, was reduced in magnitude 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 (25) through (33) was only necessary until all of the unloading reactions went to zero and the reactions to the applied load were fully carried by the interface points already increasing in load.

Graphs of the measured and calculated reactions for all eight load cases were created. Three graphs showing the reactions in the forward and aft swaybrace assemblies and the vertical lug were created to describe each load case. Load case 1 shows the only occasion that the lugs reacted longitudinally; it is the only test case with an external longitudinal load. The distribution of approximately 38.5% and 60.6% of the external load to the forward and aft lug reactions, respectively, can be seen in figure 3-11 as well as the comparisons between the calculated and measured data. The total applied force for load case 1 was approximately 10,000 lb. in the aft direction.

Figure 3-12 shows the comparison of lateral lug reactions to an applied moment \( M_c \) in load case 5. Figure 3-13 compares the lateral lug reactions in response to a 360,000 in-lb. yawing moment in load case 8. The lugs are shown to react symmetrically and linearly as predicted, reaching a much larger reaction than shown in figure 3-12 due primarily to a doubling of the applied moment.

The lug reactions were shown to be primarily linear in response, especially in the critical high load areas. These results match previous flight testing which showed linearity in the response of the hook/lug reaction and proposed that a longitudinal load would be unevenly reacted between the lugs[18].

**Ground Test 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 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, including 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 cannot react in tension and the lugs cannot react in compression, yet both can unload and reduce a current load state. The corrections to the reaction equations to allow concurrent loading and unloading (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 developed equations 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 attributed to a twisting of the bomb rack. Most of these variations in reaction were shown to be possible in [18], which also stated deflections in the pylon would not noticeably effect lug reactions. Although not predicting a twisting in the rack as proposed in this research, it shows that structural problems might occur regardless of rigidity.

Unlike flight-testing where multiple load combinations on a 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 carried the entire load. During the ground test, this was seen in the initial swaybrace rod and vertical lug reactions as predicted; calculated and measured data showed high correlation as reaction slopes increased early into the 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 typical of 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.

4. Flight Test and Analysis

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 2 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 present at this same time. Assuming typical arrestment airspeed of 150 knots (approximately 250 fps), the dynamic pressure at sea level is approximately ½ psi. Assuming a reference area of 165 in² 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 aerodynamic forces for a 2,000 lb. class store is approximately ½% and 2%, respectively.

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 general class of store, with 30-inch lug spacing. Smaller stores have inherent problems due to radius and were not examined here.[3,19] 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 steel 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.[20]

For the required equations of motion as derived in section 2 and corrected in section 3, data collection was dependent on the accelerometer data and their 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 100 G amplitude. The store/rack/pylon assembly natural frequency is typically in the 20Hz – 40Hz range and
generally less than 60%.

Being much stiffer, the store has natural frequencies of vibration much higher than that of the assembly.

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. 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 the only ones used for the calculations and predictions in this research. A triaxial accelerometer group located longitudinally at the store CG also allowed ease in the calculation of translational accelerations with minimal coupling effects from other motions or accelerations along or about other axes. The physical characteristics and lug spacing of the GBU-24 with a BLU-109 bomb body are shown in figure 4-1, as well as the accelerometer placement used for flight-testing.

To keep the inertial loads at least 95% of the total load on the store and consequently neglect aerodynamic loads while capturing 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 4-3 and 4-4 show acceleration data from the six accelerometers on the BLU-109 bomb body during that time span. The instrumentation (from figure 4-1) includes: x-, y- and z-axis 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 of the store CG but on the vertical axis of the store CG; and a z-accelerometer on the port side of the store and 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 4-3:** X- and Y-Accelerations During Arrestment

The six accelerations shown in figures 4-3 and 4-4 were used to find the forces and moments at the store CG. The FORTRAN program used for ground test data calculations was modified to accept the accelerometer flight-test data and calculate the forces and moments at the store CG prior to calculating the SRI reactions. Translational and angular rates used in these equations to calculate accelerations were integrated between each pair of timesteps. The F-14 flight test team used USN accepted programs for 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 4-5 through 4-7 show the post-flight calculations of forces at the GBU-24 CG compared to predicted values of this research.

**FIGURE 4-4:** Z-Accelerations During Arrestment

**FIGURE 4-5:** $P_x$ Comparisons at Store CG

**FIGURE 4-6:** $P_y$ Comparisons at Store CG

**FIGURE 4-7:** $P_z$ Comparisons at Store CG

**FIGURE 4-8:** $M_x$ Comparisons at Store CG

**FIGURE 4-9:** $M_y$ Comparisons at Store CG

**FIGURE 4-10:** $M_z$ Comparisons at Store CG

Figures 4-8 through 4-10 show the post-flight calculations of moments at the CG of the GBU-24 compared to the predicted values of this research. The moment magnitudes are much higher and therefore more sensitive to geometry, accelerometer placement, etc., than the force values.
Figures 4-3 through 4-10 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 inertial load calculations were completed at the store CG, the FORTRAN program used the information to predict the reactions at the SRI. As with the ground test data, preload values must be incorporated 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 as the aircraft settled in for the arrestment approach were generally near steady state 1 G flight, the total load state was still approximately 0.2 Gs in the x- and z-directions, respectively. This imbalance increased or decreased the reaction at some SRI points due to an initial non-zero load state. Figure 4-2 showed the ambient accelerations prior to the arrestment.

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 lower 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 each flight given the same store weight. Flight maneuvers, however, affect preload due to redistribution until the reactions have a chance to settle and return to steady state conditions within the dynamic environment.

When preload estimation is necessary, specialized swaybrace rods may be used that allow use of a torque wrench. These swaybrace rods may be additionally torqued after store loading 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 the swaybrace and lug preloads will typically redistribute to values near their original settings once normal, steady state flight is resumed. Using an average preload from empirical data, any errors will generally be less than an order of magnitude smaller than the peak reactions.

**Model Verification with Flight Test Data**

The FORTRAN program calculated the six interface reactions at each time step and compared the results to the reactions directly measured by the instrumented rack. Unlike the ground test points involving loads along a single axis, the interactions between the various directions of flight test loads required examination. Constant preload values were known from the measured data for this test and were entered directly into the analysis. The FORTRAN program was modified to divide each reaction into the contributing components before they were subsequently combined by superposition, allowing the interaction of loads along various axes to be seen and allow for better data prediction. Figures 4-11 through 4-14 show interface reactions for the four swaybrace rods, comparing measured and calculated data points. Figures 4-15 and 4-16 compare the measured and calculated lug vertical reactions.
The predictions of the swaybrace rod and lug reactions generally matched well with the measured critical reactions. Critical reactions were defined conservatively as those reactions above 10% of the 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 release of reaction loads within the SRI; this area was not of primary concern due to its very nature. The higher compressive reactions in the swaybrace rods were predicted more accurately in all cases, including good correlation in overall shape, general response and magnitude between the measured and predicted data. Similar agreement was found in the vertical lug reactions between measured and predicted data.

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

Figure 4-17 provides a scatter plot of the absolute errors for the critical reactions of the swaybrace rods and the vertical lug reactions between the calculated and measured data during the 300-millisecond post-arrestment interval used for the reaction plots in figures 4-11 through 4-16. The average and maximum error values can both be seen; most errors in the critical lug and swaybrace reactions are shown to be less than 400 lbs. Figure 4-18 provides a scatter plot of percentage errors. An absolute error band of approximately 10% including most of the critical error results can be seen.

In calculating the reactions, preloads were combined with the new reactions at each time step and the total load state examined. If lug or swaybrace rod fully unloaded, the reaction was defined as zero and could not be reduced...
moments at the store CG were distributed to each of the six interface points. Comparing the calculated reactions to efforts in military standards similar to planning resulted in very conservative predictions; ongoing gages or instrumented suspension equipment. Previous effects were considered negligible for this analysis. A FORTRAN program was written to calculate the inertial loads and their distribution to the SRI using only measured accelerometer data, known mass properties and geometry; strain gage data were not required. Translational and rotational accelerations were found at the store CG using accelerometer data recorded on the store. Using the calculated accelerations and rates, equations required for the inertial forces and moments at the store CG were derived with Newton’s Laws, kinetics of rigid bodies 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 at each interface. Elastic effects were considered negligible for this analysis. A FORTRAN program was written to calculate the inertial dynamic loads and their distribution to the SRI.

The principal outcome of this research was the development of the first real-time, fully dynamic analysis of store reactions in an aircraft bomb rack without reliance on strain gages or instrumented suspension equipment. Previous attempts at similar programs to assist in structural flight test planning resulted in very conservative predictions; ongoing efforts in military standards similar to [3] qualify the active interest in reaction prediction methodology. Calculating the SRI reactions within a confident error band during the planning stages or actual flight-testing will save critical time and money. This research documents the first usable, accurate and repeatable version of those interests.

Flight Test Summary

Flight tests were conducted incorporating a 2,000 lb. GBU-24 on an F-14 Tomcat aircraft. Immediately after aircraft arrestment, the dynamic inertial loads were shown to be dominant while the aerodynamic loads were negligible. The GBU-24 was instrumented with accelerometers; the BRU-32 included instrumented lugs and swaybrace rods. Accelerometer readings ranged from -1.8 Gs to +1.1 Gs along the x-axis, -0.8 to +0.8 Gs along the y-axis, and -4.5 Gs to +8.7 Gs along the z-axis. After modifying the FORTRAN program to accept flight test data, the forces and moments at the store CG were calculated from basic equations while linear and angular rates were integrated across consecutive time intervals. The FORTRAN program also accepted variations in the number and placement of accelerometers to provide flexibility for various stores and test requirements.

In the 300 milliseconds immediately 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 each of the six the interface points. Comparing the calculated reactions to the measured data, good agreement in form was found for all interface points; critical lug and swaybrace rod reactions averaged less than 7% and 9% error, respectively.

5. Conclusions

A classical analysis was used to calculate the reactions at the SRI using only measured accelerometer data, known mass properties and geometry; strain gage data were not required. Translational and rotational accelerations were found at the store CG using accelerometer data recorded on the store. Using the calculated accelerations and rates, equations required for the inertial forces and moments at the store CG were derived with Newton’s Laws, kinetics of rigid bodies 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 at each interface. Elastic effects were considered negligible for this analysis. A FORTRAN program was written to calculate the inertial dynamic loads and their distribution to the SRI.

The successful completion of this research also provides numerous benefits for many 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. Further savings are obtained by minimizing: pre-flight instrumentation (including store and rack); post-flight data reduction; and repeated and cancelled test flights due to instrumentation failures in strain gages and specialized racks. Relieving the dependency on strain gages for reaction measurements is another advantage of this research; gages are costly in application and require specialized suspension equipment. The gages are also very fragile and easily damaged during the typical installation procedures for larger stores, resulting in poor data collection, wasted effort in the delay or repetition of test flights and added costs.

Additional applications of this research include: incorporating the prediction routines as secondary reaction calculations in case of primary instrumentation failure; using the program to compute the critical reaction points prior to actual flight-testing, thus allowing the test team to target a specific flight envelope instead of wasting test resources on irrelevant test points or repeated flights; and implementation of this research into a store’s development phase to provide the design engineers with unique and critical SRI loading conditions prior to store fabrication.

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, including the addition of aerodynamic load calculations, incorporating the program into a real-time telemetry system for flight-testing, gathering a larger database of flight data to refine the reaction equations, and improving preload estimation. Enhancements in any of these areas would increase the model’s usefulness and reliability as a reaction prediction tool for flight-testing as well as design and analysis.

REFERENCES


BIographies

Tim C. Schoppert has worked at the Naval Air Warfare Center in Patuxent River, Maryland since 1991 and is currently a flight test and evaluation structural engineer. He earned a Ph.D. in Aerospace Engineering through West Virginia University specializing in solid mechanics and structures and is licensed as a Professional Engineer in Mechanical Engineering. He holds an MSAE from Florida Institute of Technology and a BSAE from West Virginia University. Dr. Schoppert has also been employed by Embry-Riddle Aeronautical University as an adjunct assistant professor since 1994, teaching courses in engineering and mathematics for the undergraduate and graduate degree programs. Additionally, he has authored and instructed internet-based courses in mathematics for the Embry-Riddle Department of Distance Learning since 2000.

Kenneth H. Means is a Professor of Mechanical and Aerospace Engineering at West Virginia University in Morgantown, West Virginia. He is a licensed Professional Engineer in West Virginia. He received a PhD at West Virginia University, an MSME from Drexel University, and a BSME from West Virginia University. He specializes in dynamics and machine design. Dr. Means has worked in the aerospace industry at the Martin Marietta Corporation and Westinghouse Aerospace Division as well as a private consultant in the engineering field. Since 1981 he has been performing research and teaching at West Virginia University.