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Synthesis of Structural Responses Using Experimentally-Measured Frequency Response Functions and Field Test Data*

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This paper will present an analysis technique used to generate the structural response at locations not measured during the ejection of a captive-carried store. The ejection shock event is complicated by the fact that forces may be imparted to the store at eight distinct locations. The technique derives forcing functions by combining the initial field test data for a limited number of measurement locations with Frequency Response Functions (FRFs) measured using a traditional modal-type impact (tap) test at the same locations. The derived forcing functions were then used with tap test FRFs measured at additional locations of interest to produce the desired response data.

INTRODUCTION

Over the years, Sandia has been asked to certify the compatibility of its captive-carried stores with new and/or modified ejection rack designs. Historically this was accomplished by subjecting an instrumented store to a series of static ejection events (i.e., the store is ejected from a statically-mounted rack, rather than from a rack on a flying aircraft) using several combinations of cartridges and orifices for the rack in question. If a given combination produced shock levels that were lower than those for which the store was already qualified, then that rack configuration was approved for use with the store. Conversely, if a rack configuration produced shock levels in excess of the requirements, then it was recommended that it not be used with the store.

However, contrary to past practices, Sandia was recently asked to determine whether or not one of its stores could survive the shock levels measured for a set of rack configurations currently used for other stores, regardless of the relative shock levels.

In order to accommodate this request, Sandia measured component response data for the entire suite of proposed ejection racks, cartridges, and orifices (both the current baseline inventory and the alternative configurations). Eleven channels of accelerometer data were recorded for this test series in order to establish the component response. The response levels measured for the alternative rack configurations exceeded both the current requirements and the baseline levels over some portion of the frequency range of interest (10 Hz to 4,000 Hz).

The use of a relatively small number of accelerometers (8 to 12 is typical) has always been adequate to confirm whether or not the shock levels produced by a new rack configuration were less than the current requirements. However, once it is decided that a store must be certified to higher levels, it becomes necessary to have a more complete set of component response data from which to make decisions regarding the potential impact on component reliability.

The project group did not consider repeating the ejection shock tests with additional instrumentation a viable option. An alternative was proposed by the authors of this paper to use experimentally-measured Frequency Response Functions (FRFs) for the store to extrapolate the response data from the eleven known locations to the other points of interest.

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DISCLAIMER

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For the remainder of this paper, data and predictions based on the FRFs obtained by modal-type tap testing will be identified by the word "TAP", and the measured ejection data are identified by the acronym "DTB" (since the series of ejection tests were conducted by the rack manufacturer, Dayton T. Brown).

DATA ANALYSIS PROCEDURE

An acceleration response, A, at any point of interest in or on the store can be defined in terms of the input forces, F, and the FRFs, H, for the store. This relationship is shown in Equation {1}.

$$\{A\} = [H]\{F\} \qquad \{1\}$$

It is relatively straightforward to measure the FRFs experimentally. However, the broadband input forces were not measured during the ejection tests (although the low-frequency, or rigid body, forces are sometimes derived from piston pressure data). Therefore, the key to success for any attempt to generate acceleration responses for points not instrumented during the ejection tests relies on our ability to obtain accurate estimates of the input forces.

With this fact in mind, Equation {1} can be rearranged to derive forcing functions as shown in Equation {2}.

$$\{F_{DTB}\} = [H_{DTB}]^{1}\{A_{DTB}\} \qquad \{2\}$$

H_{DTB} is the FRF matrix for the tap-test points where we also had response data, A_{DTB}, from the ejection tests. Once we had a reasonable estimate of the ejection test input forces (F_{DTB}), then Equation {3} was used to compute an estimate of the ejection test accelerations for all of the points, A_{TAP}.

$$\{A_{TAP}\} = [H_{TAP}]\{F_{DTB}\} \qquad \{3\}$$

H_{TAP} is the FRF matrix for all of the tap-test points. Note that H_{DTB} is a subset of H_{TAP}. The predicted acceleration responses for those points where we had data from DTB were used to validate the process.

CHOICE OF DATA ANALYSIS TECHNIQUES

The H_{TAP} and H_{DTB} FRFs were measured using a modal-type tap test (hence the use of the term TAP to refer to the results from this test). However, prior to measuring this data, there were two main decisions to make; namely 1) how many force inputs should be accounted for and 2) how many response points should be used to derive the forcing functions.

At first glance we were tempted to include all of the input force points in the analysis. However, there are eight points where the rack assembly contacts the store (two lugs, two piston contact points or pads, and four sway braces) and tracking so many input forces was considered untenable. Therefore, it was decided that the effects of the sway braces could be combined with those of the pistons since they both exert compressive loads on the store at approximately the same axial location (station number). The result was that tap forces were applied at the lugs and the contact pads where the pistons strike the store (four points total) and the resulting FRFs were generated for all of the accelerometer locations. The FRFs have units of acceleration/force (in/s^2 / lbf).

The number of response channels used to reconstruct the input forces was considered important because it was feared that the inversion of H_{DTB} might not be stable. Several techniques were tried for solving Equation {2} for the input forces. Each technique was evaluated for its ability to reproduce the measured ejection test accelerations. The first technique attempted to formulate a theoretical shape for the input forces and iterate to an optimum solution by trial and error. This technique produced plausible estimations of the ejection test accelerations and provided the authors with valuable insight into the dynamic response of the store. However, it was apparent that we would not reach an optimum solution using this technique and it was abandoned for a more direct mathematical approach.

The second technique used four of the 11 ejection test response points to derive H_{DTB}. The advantage of this approach was that H_{DTB} would be a square (4×4) matrix so the inversion process would be straightforward. This technique produced results that were clearly better than the empirical approach, but still failed to accurately reproduce the ejection test accelerations.

The third and final technique used eight of the 11 ejection test response points to derive the input forces (these channels are listed in Table 1; only 8 of the 11 ejection test accelerometers were used because a triaxial accelerometer no longer worked when the tap tests were performed). In this case H_{DTB} is a rectangular (8×4) matrix. Therefore, its inversion for use in Equation {2} was done using the Moore-Penrose pseudo-inverse technique (the pinv() function in MATLAB™). This technique proved highly successful and forms the basis for the results presented in this paper.

Table 1: Accelerometers Used to Derive Input Forces

Internal Location	Store Axes
Fwd Component	Lateral (Y) & Vertical (Z)
Mid Component	Axial (X) & Lateral (Y)
Aft Lug	Axial (X) & Vertical (Z)
Aft Component	Lateral (Y) & Vertical (Z)

TEST SETUP AND DATA ACQUISITION TECHNIQUES

The tap testing was conducted at Sandia National Laboratories in Albuquerque, NM. The store was suspended using bungee cords to support its static weight while still nominally representing a free-free boundary condition as shown in Figure 1.

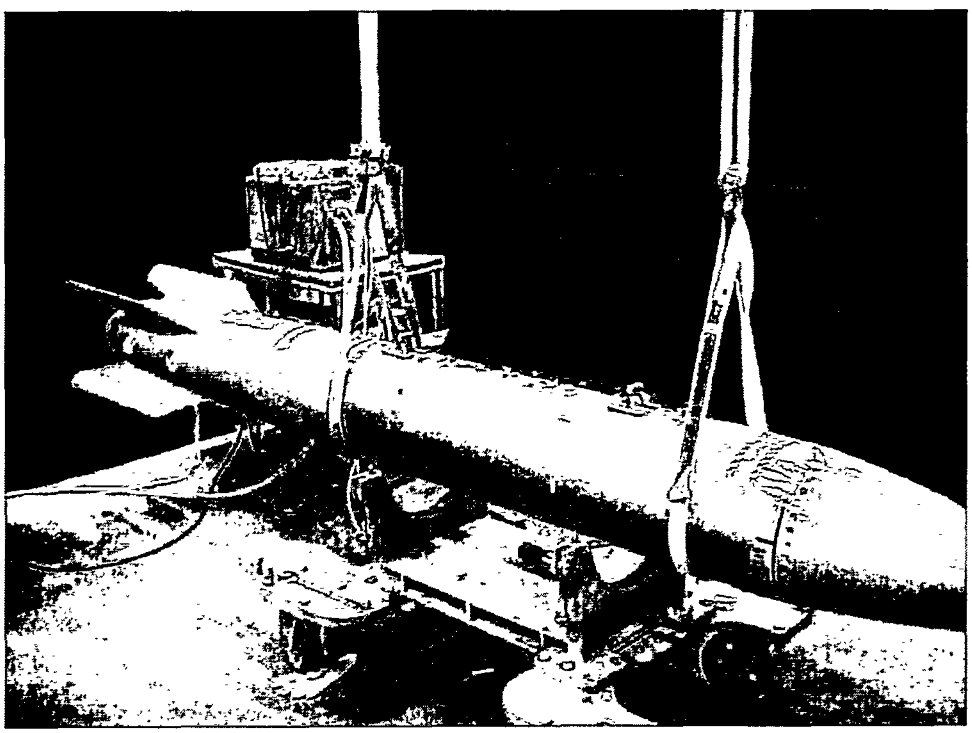

Figure 1: Hammer Tap Test Setup

A total of 32 acceleration signals and 1 force signal were recorded for each tap test. Acceleration was measured using piezoelectric accelerometers with a nominal sensitivity of 10 mV/g. Force input was produced and measured by a 1-lb modal impact hammer (PCB Piezotronics 086C05 which incorporates a piezoelectric force sensor with nominal sensitivity of 1 mV/lbf) using a 1-inch diameter, hard black plastic tip.

It was desired that the hammer impacts produce a peak acceleration of 200 g (77,300 in/s^2) at the Aft Lug-Internal vertical accelerometer to be comparable to the levels measured during the ejection tests. It was also desired that FRF data be acquired for frequencies up to 4 kHz. Three different hammers were tried to see which one would produce the best results. A 3-lb modal impact hammer (PCB 086C20) using a 2-inch diameter brass tip produced high-frequency responses, but rang excessively at approximately 3.6 kHz. The same hammer with a hard black plastic tip was also tried, but exhibited too much roll-off at high frequency. The 1-lb modal impact hammer with hard black plastic tip produced the best results and all data presented in this paper were obtained with this hammer. The autospectrum of the impact force was flat out to a cut-off of approximately 1 kHz (down 50% at 1 kHz), and then rolls off quickly until it is down by a factor of 100 by 2.5 kHz. FRF data above 2.5 kHz quickly becomes dominated by noise because of the very small amount of input energy imparted to the store by the hammer at these high frequencies. A comparison of the autospectra for the three hammer inputs at the aft lug is presented in Figure 2. The differences in magnitude at low frequency for the different hammers reflect the relative amount of force required to produce the desired acceleration level at the Aft Lug-Internal accelerometer.

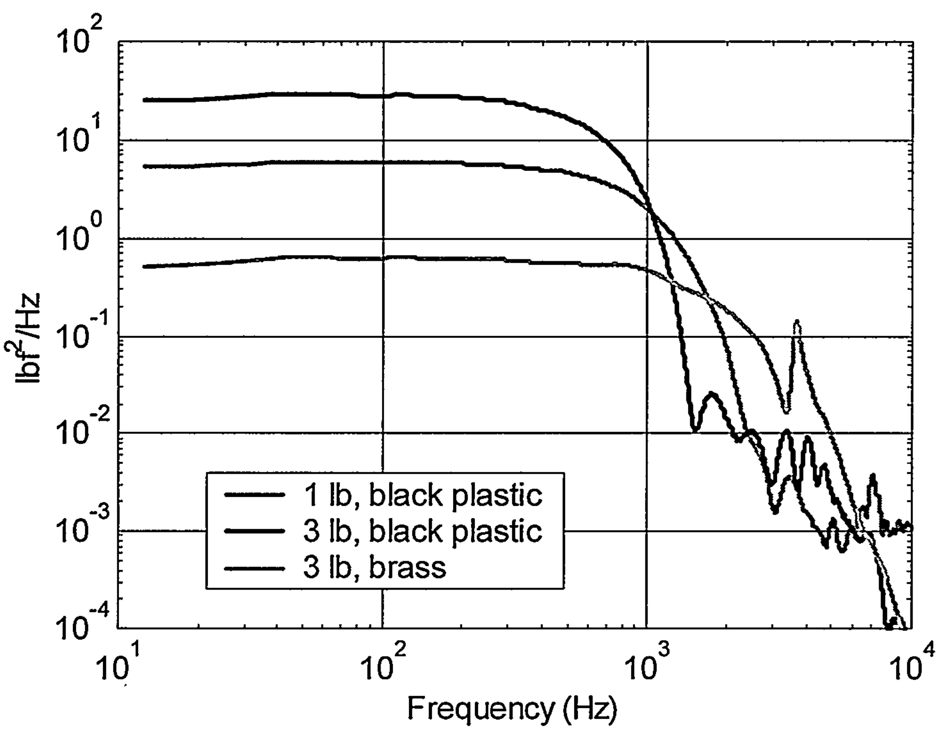

Figure 2: Hammer Input Force Autospectra
Aft Lug-External — Vertical (Z) Axis

Data acquisition was performed using a VXI system (VXI is a standard architecture for instrumentation that is based on the VME computer architecture). Data from the impact hammer and accelerometers were acquired using 3 Hewlett-Packard E1432A 16-channel digitizers installed in a Tektronix VX1410 VXI mainframe. A National Instruments VXI-MXI-2 VXI bus extender was used to interface the mainframe to a computer running I-DEAS Master Series 7 Test software (Integrated Design Engineering Analysis Software from Structural Dynamics Research Corporation) to control the data acquisition, processing, and storage. All of the sensors were directly connected to the HP E1432A digitizers; no external filtering or amplifiers were used.

The tap test series consisted of a set of hammer impacts at each of the four selected points where the rack assembly contacts the store (the forward and aft lugs, and the forward and aft piston-impact points). The saved data are the average of 20 hammer impacts, where each hammer impact was digitized using 4096 samples acquired at 25.6 kHz (sampling period of 0.16 sec) for each of the force and accelerometer channels. Before sampling, the data were high-pass filtered above 10 kHz by the HP E1432A digitizers to ensure that there was no frequency aliasing. Windowing was used on all the acquired force data (impact window) and accelerometer data (exponential decay window) to reduce noise. The data were saved as acceleration/force FRFs for frequencies from 12.5 Hz to 10,000 Hz. The DC (0 Hz) and 6.25 Hz data were not saved because the sensors do not have any DC response and the presence of low-frequency noise due to DC voltage offsets in the HP E1432A digitizers.

Figure 3 presents the hammer impact (tap) FRFs for the response of the forward component in the lateral (Y) direction. The figure consists of four subplots, one for each of the four hammer tap input locations.

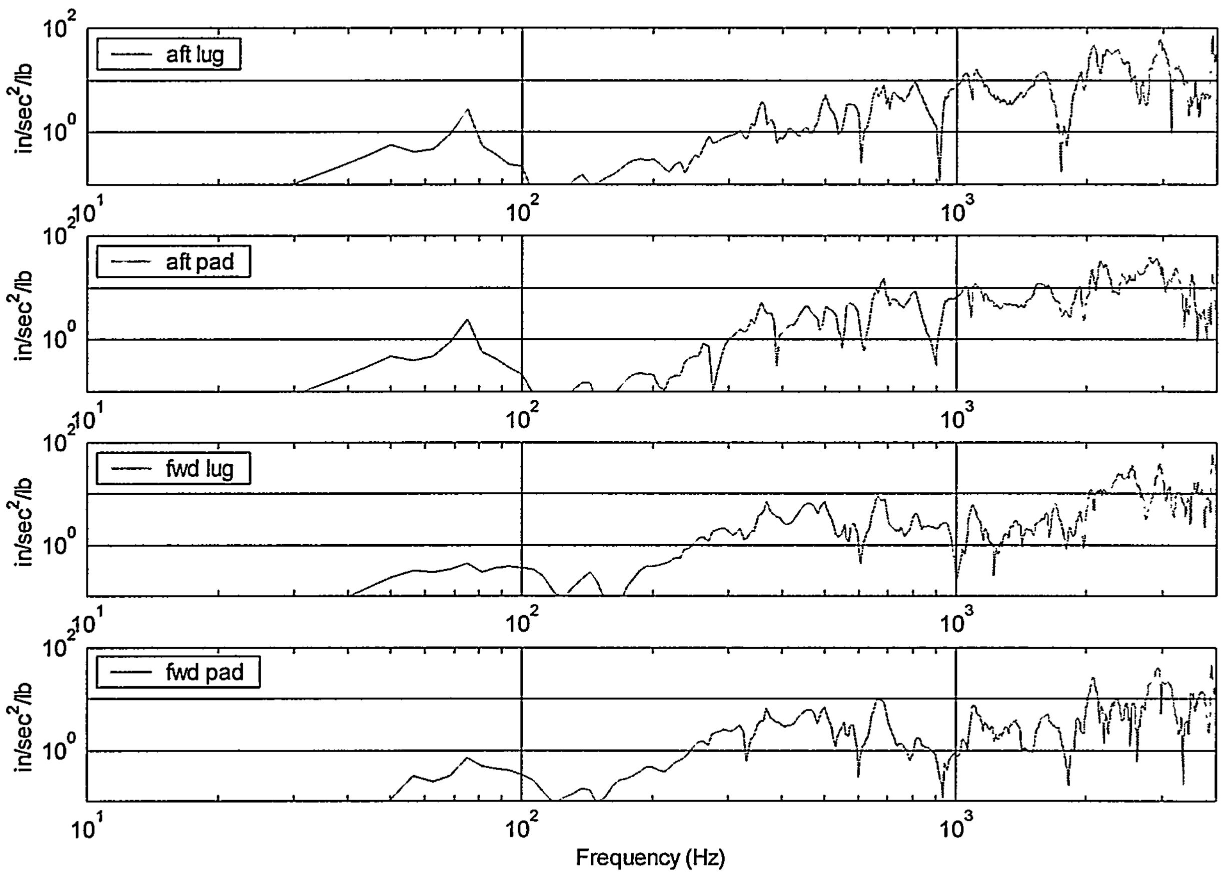

Figure 3: Measured Tap Test Frequency Response Functions
Forward Component — Lateral (Y) Axis

SUMMARY OF ANALYTICAL SIMULATIONS OF THE EJECTION TESTS

Figure 4 presents time histories of the four estimated ejection test forcing functions (F_{DTB}) derived using Equation {2} for one typical DTB ejection test. The forcing functions are probably not a true representation of the input forces. Instead, they are more likely a combination of actual input forces and the low-frequency dynamic response of the store to the step relaxation associated with the ejection event (i.e., after contacting the store, the pistons gradually increase the compressive load on the store until it is ejected from the rack and the compressive force instantly goes to zero).

For the same typical DTB ejection test as Figure 4, the comparison of the estimated (A_{TAP}) and measured (A_{DTB}) acceleration time histories and Shock Response Spectra (SRS) are presented in Figures 5, 6, and 7 for three of the eight channels used to estimate the forcing functions. The SRS were computed using a Maxi-Max Absolute Acceleration (MMAA) algorithm with 3% critical damping ratio. Both the tap test results and the ejection test data have been high-pass filtered at 50 Hz in order to remove residual effects associated with the inability of piezoelectric accelerometers to accurately measure DC response.

The acceleration time histories for the Aft Component (Figure 7) have virtually identical characteristics, and the corresponding SRS are almost indistinguishable. On the other hand, the acceleration time histories for the Mid Component (Figure 6) are comparable in amplitude but have distinctly different waveforms. A comparison of the SRS for this location confirms that the spectral content is also slightly different. The degree of agreement for the Forward Component response (Figure 5) falls in between the results for the Aft and Mid Components.

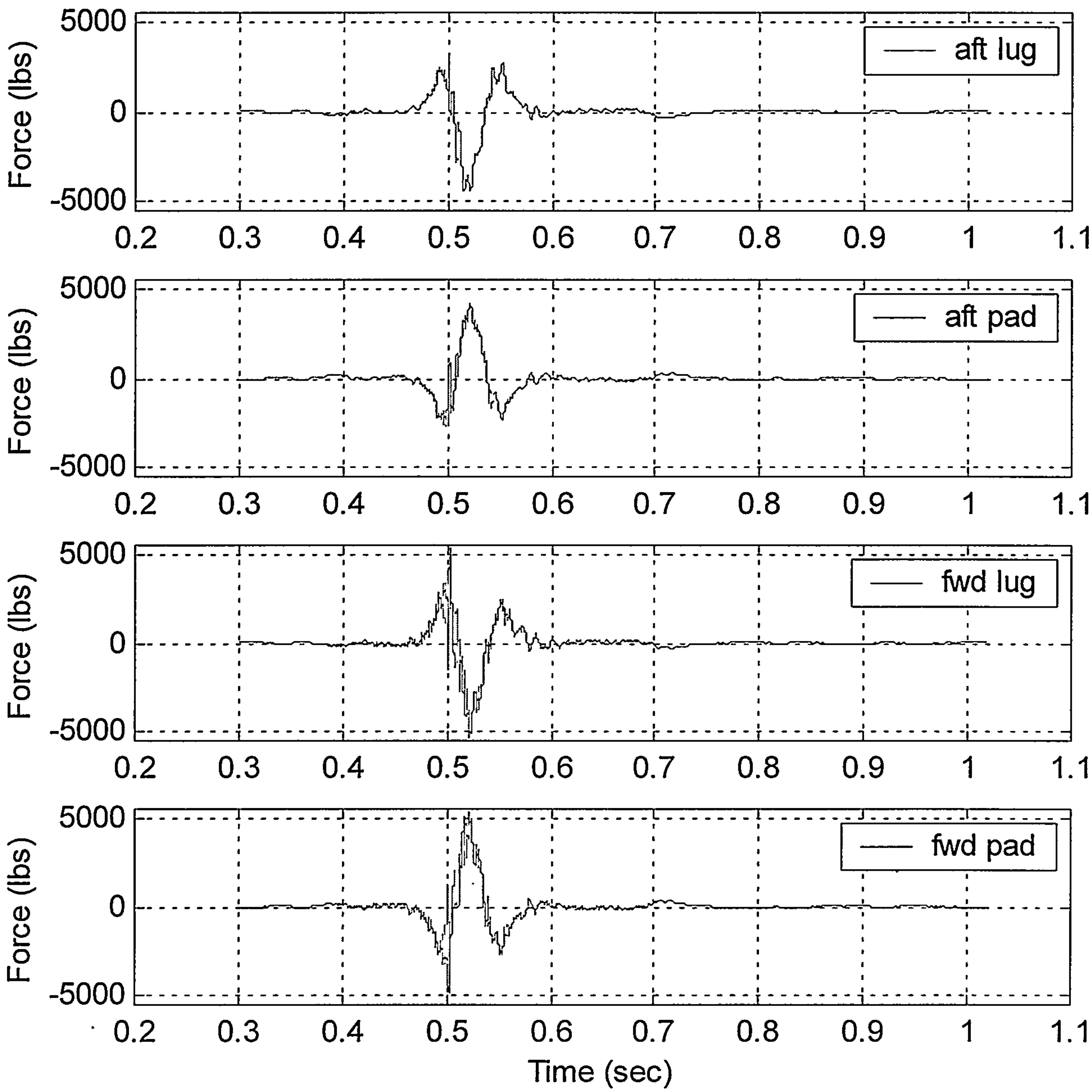

Figure 4: Estimated Input Forcing Functions for an Ejection Test

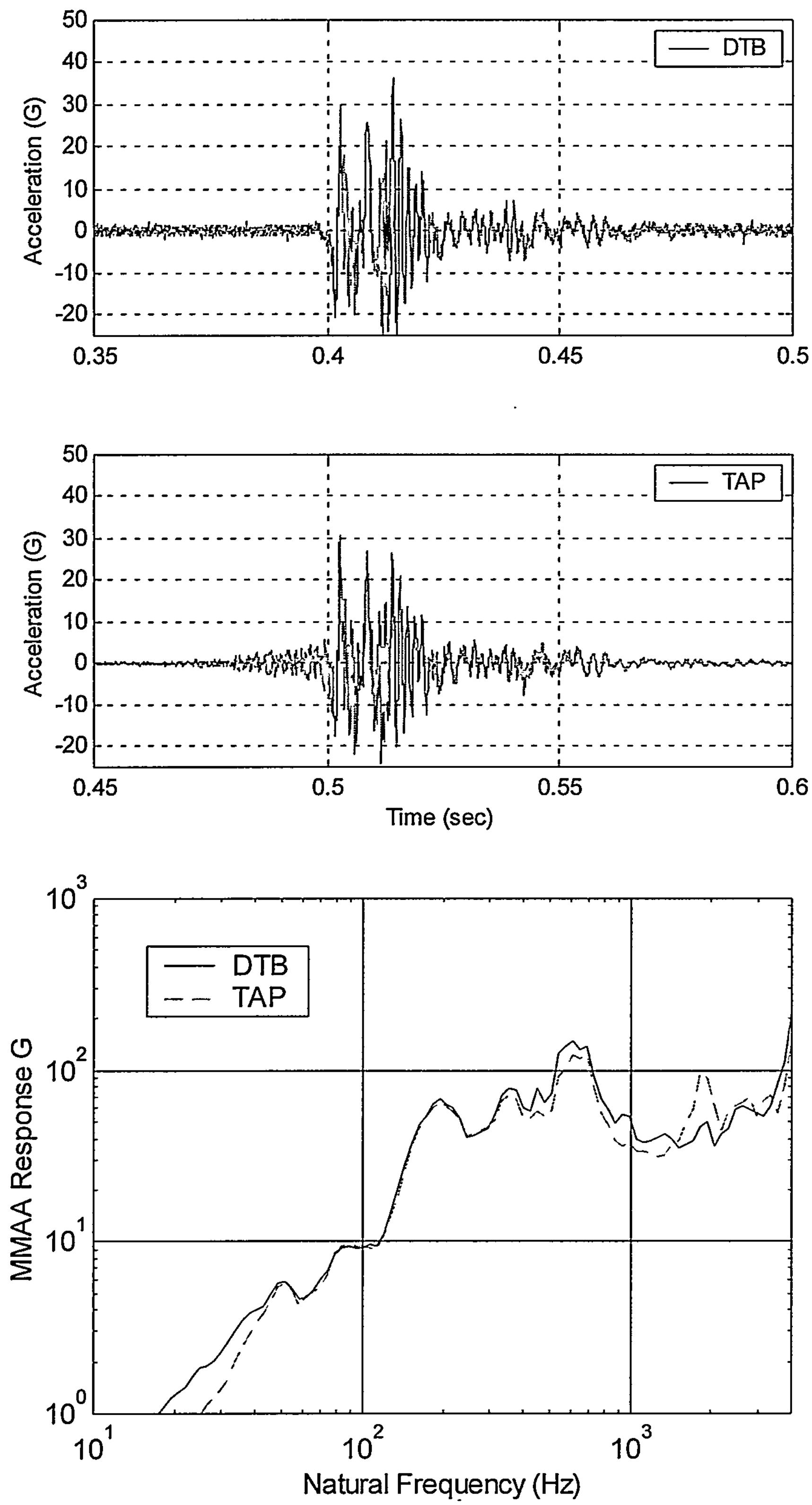

Figure 5: Estimated Versus Measured Acceleration Time Histories and 3% Damped SRS
Forward Component — Vertical (Z) Axis

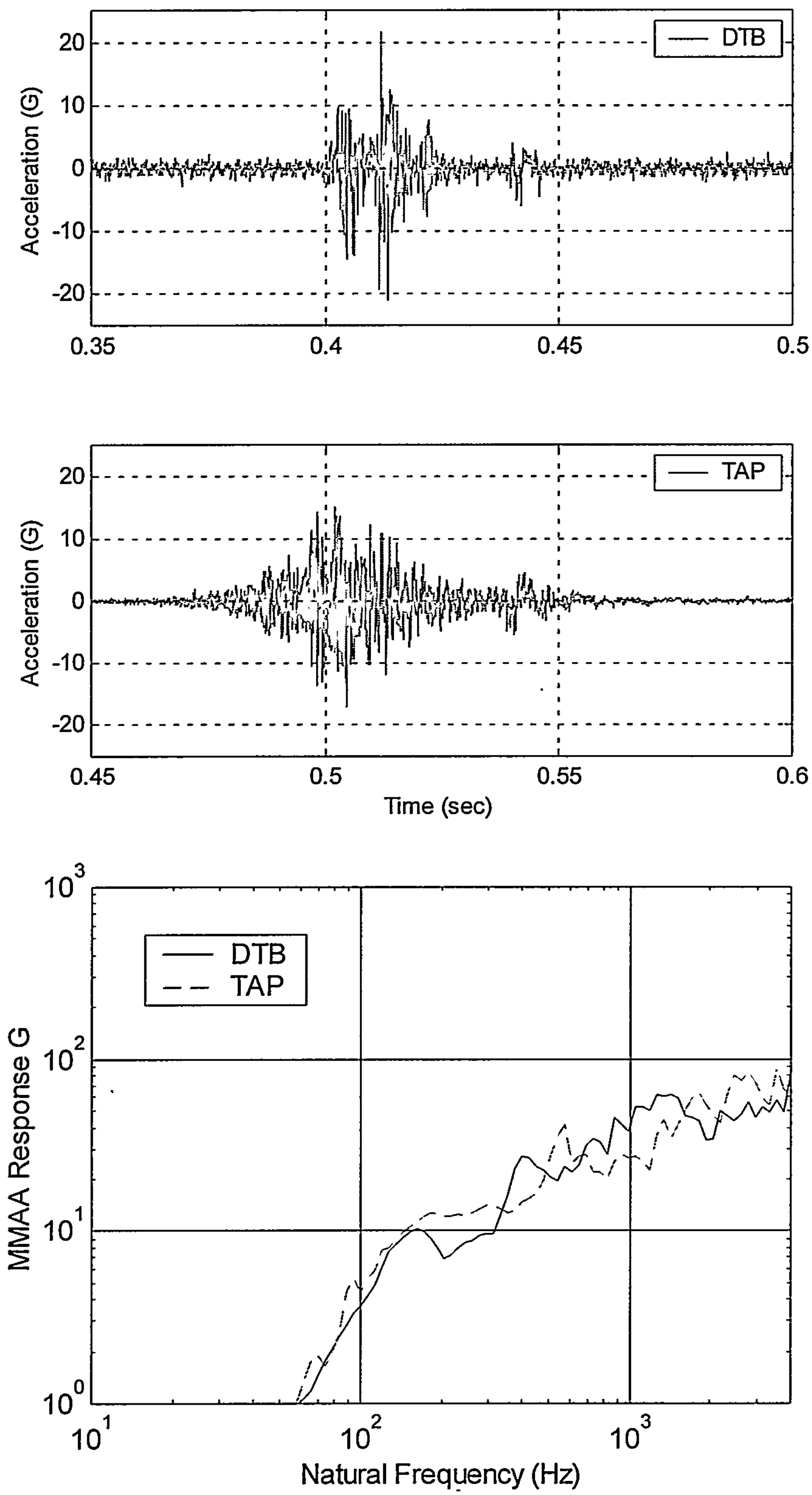

Figure 6: Estimated Versus Measured Acceleration Time Histories and 3% Damped SRS
Mid Component — Axial (X) Axis

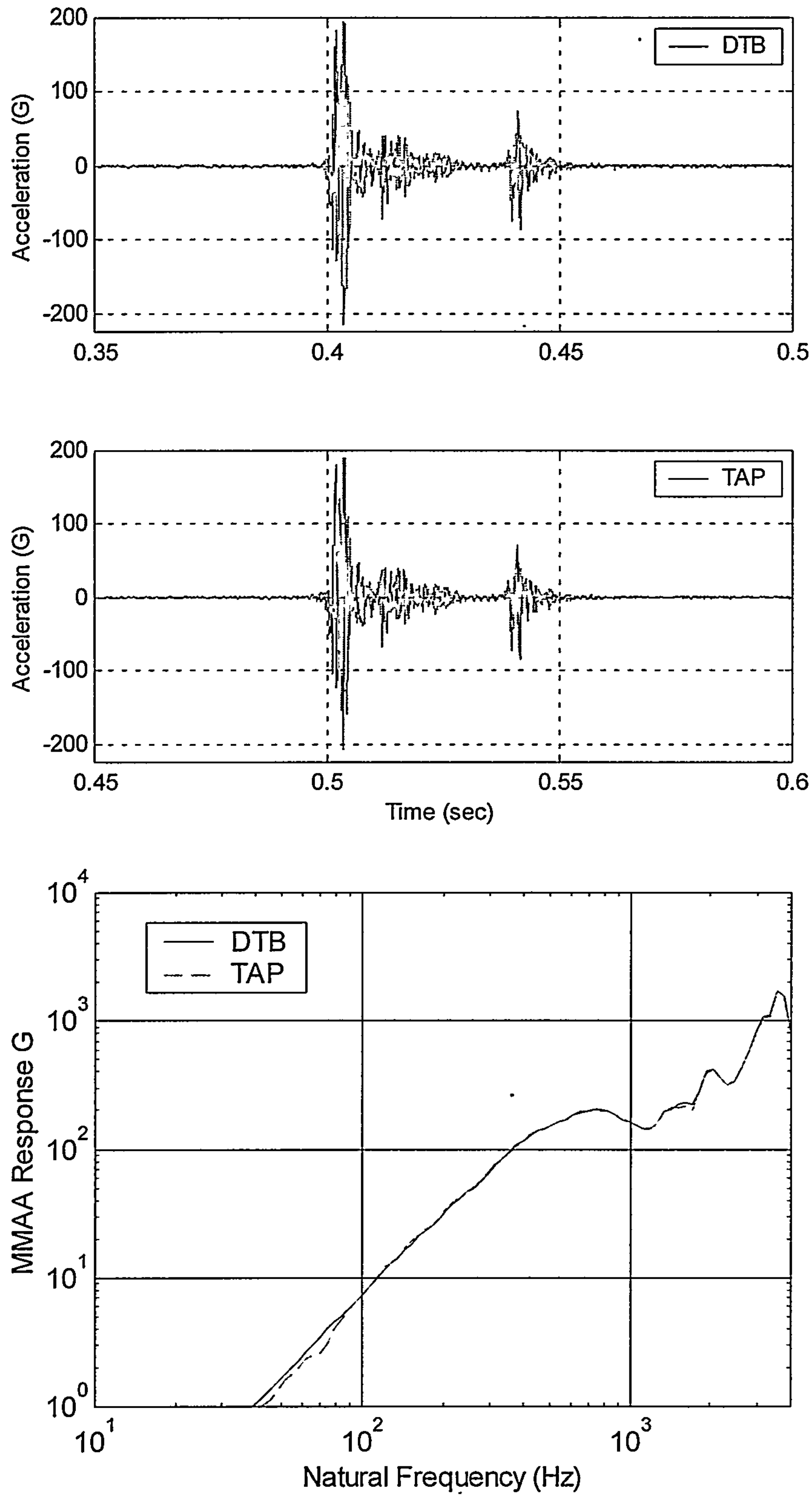

Figure 7: Estimated Versus Measured Acceleration Time Histories and 3% Damped SRS
Aft Component — Lateral (Y) Axis

Figure 8 is a flowchart summarizing the steps used to process and analyze the data for the figures in this paper.

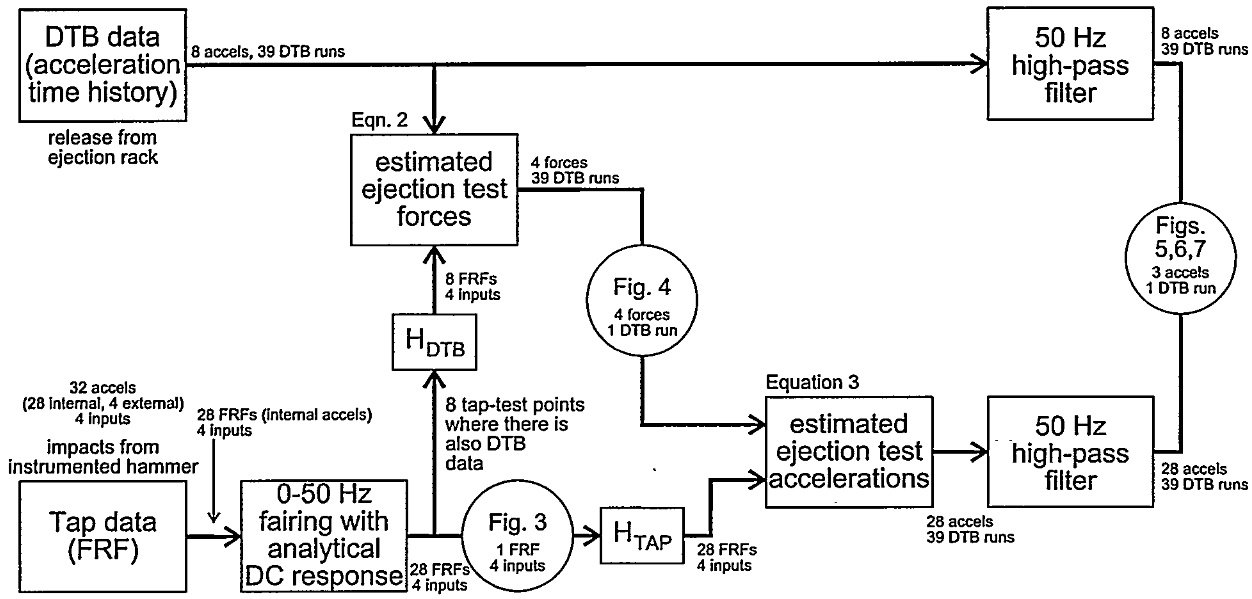

Figure 8: Flowchart of Data Processing Steps

CONCLUSIONS

In general the technique for estimating component response due to an ejection shock appears to have worked extremely well. The quality of the response estimate is the worst for components buried deeply in foam (Mid Component) and the best for locations for components that are rigidly-bolted to the store's outer case (Aft Component). This would appear to be a function of two somewhat-related items:

- The accuracy of the force reconstruction technique will obviously be better if the structure behaves in a linear manner. The linearity of the structural response will degrade as you cross more joints and/or more high damping materials such as rigid foams and elastomeric pads. This affected the responses for the Forward and Mid Components.
- It was extremely difficult to excite the store with a tap test to levels comparable to those measured during the live ejection test (although we came fairly close). For locations where the signals were weakest, this resulted in a poorer signal-to-noise ratio (especially at high frequency (> 2 kHz)). This was most noticeable for the Mid Component.

Fortunately, the net effect of this will be that we are possibly over-predicting the response for locations where the response is relatively benign and making more accurate predictions for locations where the responses are highest. Because of the accuracy with which we have been able to reconstruct the original ejection test data, we believe that the estimated responses of components that were not instrumented during the ejection tests are sufficiently accurate to use in establishing component response levels.