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NASA CONTRACTOR REPORT

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DEVELOPMENT AND EVALUATION OF THE IMPULSE TRANSFER FUNCTION TECHNIQUE

By

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FOREWORD

The work reported herein was performed by the Grumman Aerospace Corporation under the NASA/Langley Master Agreement (Contract No. NAS 1-10635) for the Development and Implementation of Space Shuttle Structural Dynamics Modeling Technology. The Work Statement of Task Order No. 2, entitled "Development and Evaluation of the Impulse Transfer Function Technique", authorized and specified the tasks to be performed. The period of performance covered the months of July through December of 1971.

Overall supervision of programs under the Master Agreement is provided by Mr. E. F. Baird, Master Agreement Program Manager. Mr. M. Mantus was the Task Order No. 2 Project Manager and was the principal author of this report. Major contributors to the successful completion of the work were C. Birs, V. Zambrelli, M. Schnee, D. Williams, P. Anderson, D. Krasner and H. Pardo, as well as G. Patterson and several other members of the Grumman Data System Corporation.

Mr. J. Schoenster was the Langley Technical Monitor. His assistance in all phases of the program is gratefully acknowledged.

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1 SUMMARY

The work performed under this contract was an important step in the further development of the test/analysis technique known as the "Impulse Transfer Function" (ITF) method. This technique, when implemented with proper data processing systems, should become a valuable supplement to conventional dynamic testing and analysis procedures that will be used in the Space Shuttle development program. The method can relieve many of the problems associated with extensive and costly testing of the Shuttle for transient loading conditions. In addition, the time history information derived from impulse testing has the potential for being used to determine modal data for the structure under investigation. Thus, the technique could be very useful in determining the time-varying modal characteristics of structures subjected to thermal transients, where conventional mode surveys are difficult to perform.

Complete development of the ITF method has required a two phase approach. The first phase, funded by Langley in the subject contract, consisted of testing a realistic spacecraft structure and a partial verification of the accuracy of the ITF approach. The second phase, expected to begin shortly under NASA/MSC funding, is directed toward computer program development and a final verification of the accuracy of the method. Details of this program may be found in Reference 1.

The primary objective of the Langley effort was to demonstrate that standard test procedures and equipment could be used to collect a significant number of transfer functions from tests of the Lunar Module test article LTA-11. The testing, as outlined in Reference 2, consisted of suspending the vehicle from the apex fittings of the outrigger trusses through a set of air springs to simulate the "free-free" state. Impulsive loadings were delivered, one at a time, at each of the landing gear's attachment points, in three mutually perpendicular directions; thus a total of 36 impulses

were applied to the vehicle. Time histories of each pulse were recorded on magnetic tape along with 40 channels of strain response and 28 channels of accelerometer response. To insure that the data taken was valid, oscillograph playbacks of all channels were made. In addition, one channel of instrumentation was processed to determine its response to a set of forcing functions from a prior LTA-11 drop test. This prediction is compared with drop test results in Section 4 of this report.

How well were the objectives of this program met? The initial schedule estimated a six week impulse test period. Because of cost constraints, no special fixtures or test apparatus could be fabricated to insure the program would adhere to the schedule. Due to failures in some of the test equipment, not an uncommon occurance in test programs as complex as this one, the schedule slipped about $1\frac{1}{2}$ weeks. It is worth noting that the 28 acceleration and 40 strain responses taken for each of 36 impulses total 2448 time histories. Oscillograph playbacks of all 2448 time histories indicated that virtually all data recorded was valid with excellent signal to noise ratio. This appears to us to be no trivial accomplishment. In view of these facts, as well as the fact that this was the first time such an ambitious ITF test program was conducted, the schedule slippage, in our opinion, was tolerable.

While a more complete verification of the accuracy of the method must await the results of the MSC job, the comparison of predicted with drop test results for the one channel processed in this program, indicates that the ITF method is certainly promising. As indicated in Figure 13 of Section 4, the prediction using ITF data shows excellent wave-form agreement with the response recorded in the drop test, while the amplitude correlation, when all ITF's are used, leaves something to be desired. As discussed later, significant improvement in this correlation would be expected when the final data processing system is completed.

Section 2, which follows, gives a brief description of the assumptions and mathematical basis of the ITF method. Section 3 is concerned with the instrumentation and data acquisition equipment while Section 4 shows sample data and documents the results of our drop test comparison study.

2-BACKGROUND AND INTRODUCTION

The Impulse Transfer Function (ITF) technique is based on the fact that, for a linear structure, the dynamic response to any applied loading can be represented by the superposition of the responses to an equivalent series of impulsive loadings. Figure 1 provides a graphical illustration of the technique. A given time history of applied load, $F_j(t)$, is approximated by a series of pulses which are sufficiently short to be considered impulses. Since the response to an impulse is proportional to its magnitude (area), the time-history of response to each of the pulses is computed by multiplying the response to a unit impulse, $h_{ij}(t)$, (known as an ITF) by the area under the pulse. The responses are then superimposed, with the proper time shifts, to produce the response, $R_{ij}(t)$, to the applied loading A series approximation of Duhamel's integral is used to perform the necessary calculations, as shown in Figure 1.

The transfer functions employed in this analytical procedure are obtained experimentally by applying short-duration pulses which approximate impulses, one at a time, to each point in the structure where load is to be applied. Time histories of these pulses, as well as the responses (strains, accelerations, etc.) at selected locations throughout the structure are recorded. Dividing the response time-history at i (called a response point) due to the pulse applied at j (called a loading point) by the area under the pulse yields the Impulse Transfer Function, $h_{ij}(t)$. The process is illustrated in Figure 2.

Total response at i, in a structure loaded at several points, is obtained by summing the individual response to each applied load. This procedure is shown in Figure 3.

When the ITF technique was first considered, a number of valid questions concerning the difficulty of experimentally determining ITF's were raised. These had significant bearing on the feasibility of the technique. Among them were: Could a pulse be applied with sufficiently short duration

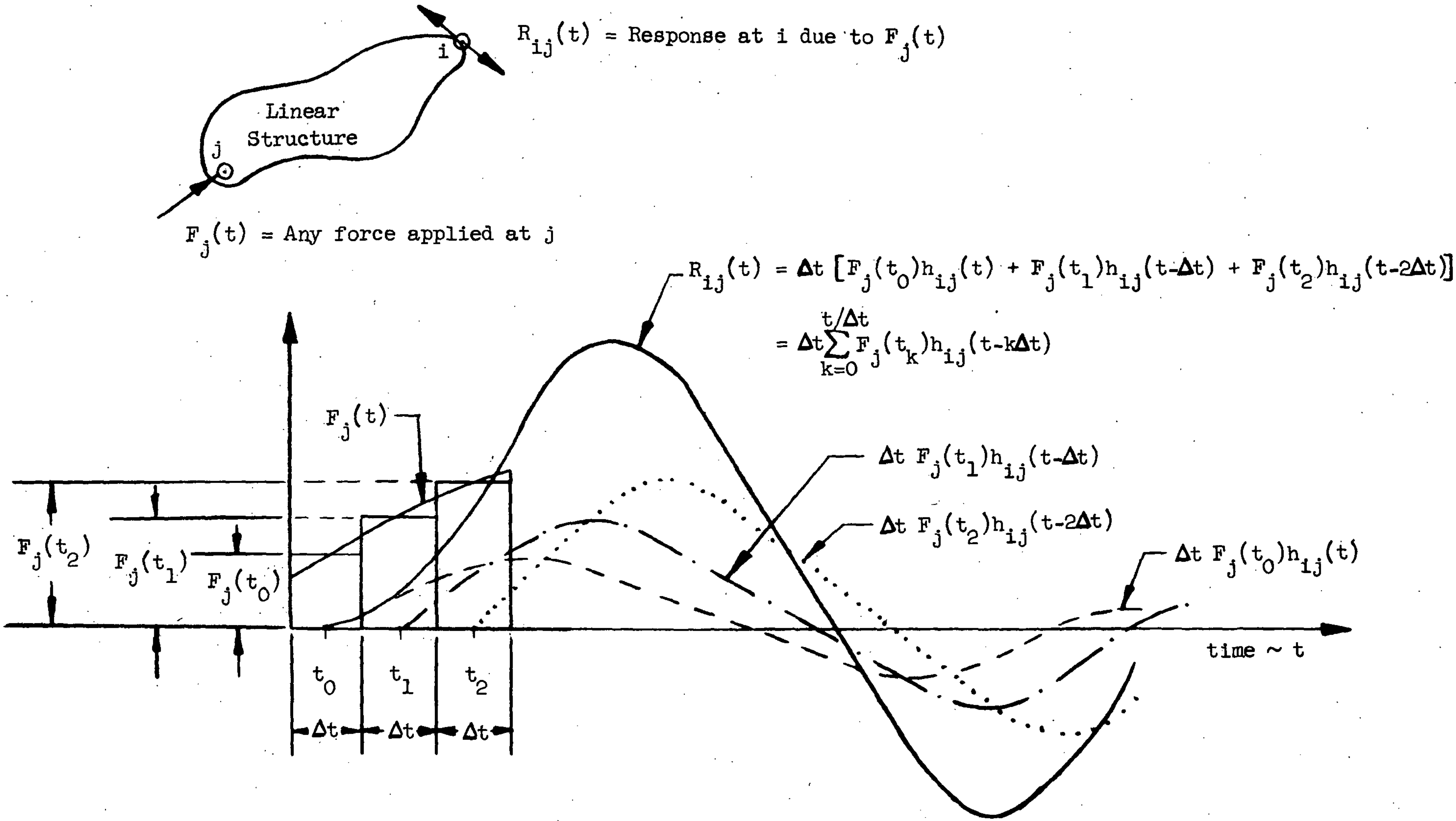
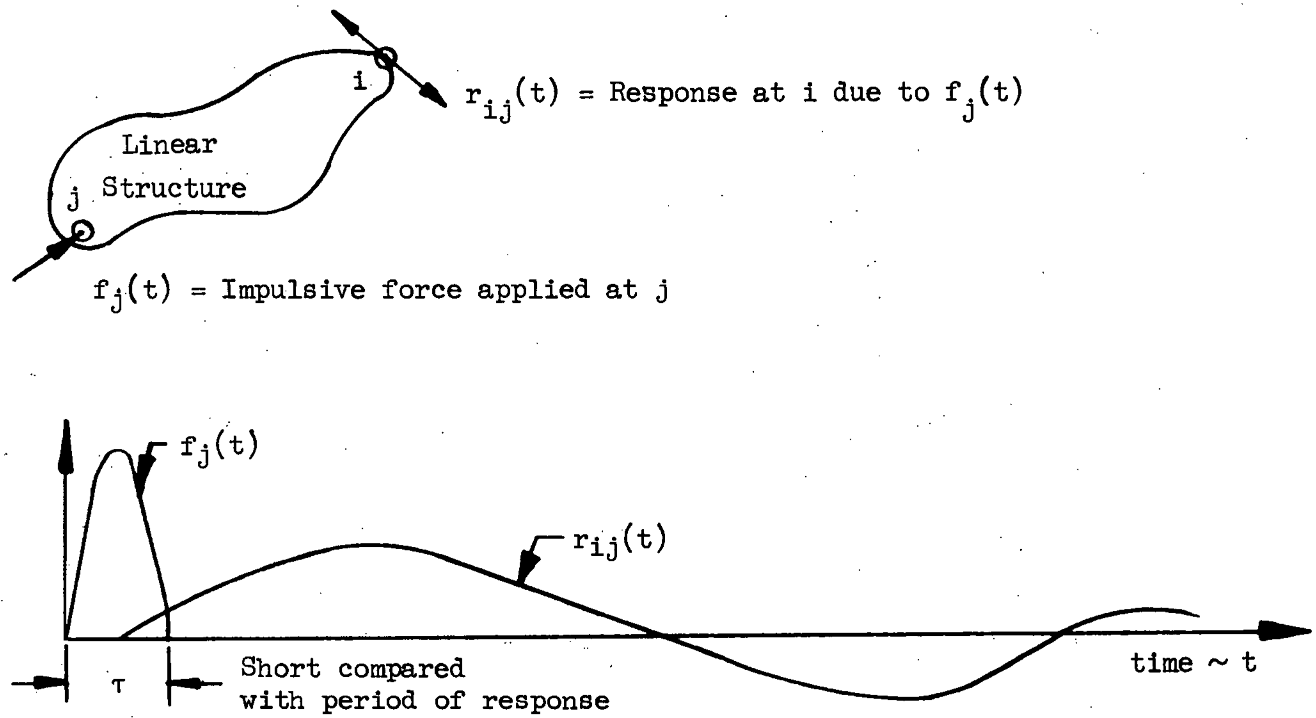


Figure 1 - Computing Response Using Impulse Transfer Functions

Apply $f_j(t)$ and measure $r_{ij}(t)$ & $f_j(t)$:



I_j = Impulse magnitude = $\int_0^{\tau} f_j(t)dt$

$h_{ij}(t)$ = Impulse transfer function between i & j
$= r_{ij}(t)/I_j$

Figure 2 - Measuring Impulse Transfer Function

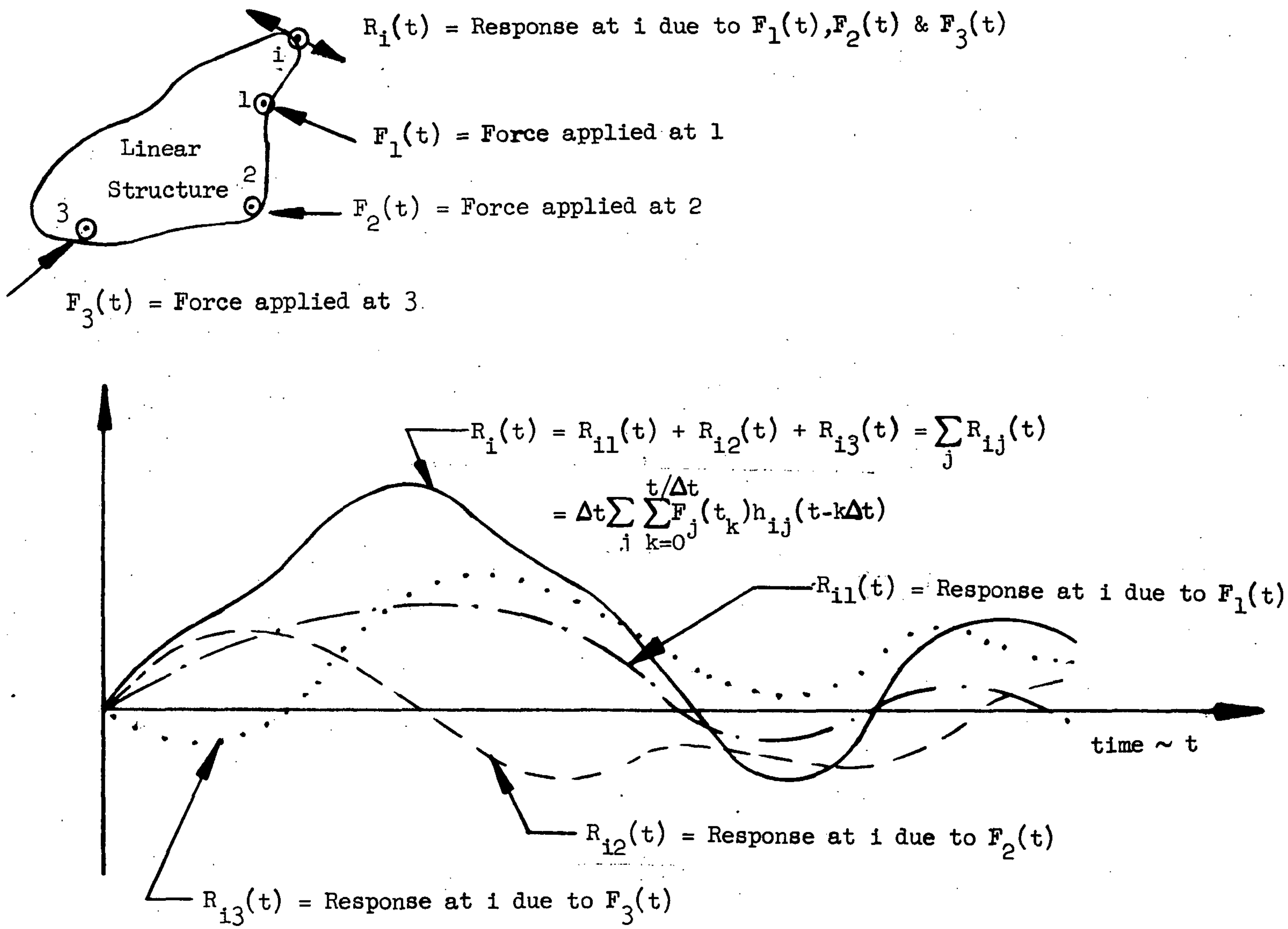


Figure 3 - Computing Response to a Number of Applied Forces

to provide a good approximation to an impulse and of sufficiently high amplitude to excite measurable response in a large, complex structure? Could the applied pulse and response be measured accurately?

The only way to answer these questions was to actually try the technique, and so a modest test-analysis program was initiated at Grumman. The test article used was a solid, uniform circular beam suspended to simulate a free-free condition and instrumented to measure strain response. Using a pendulum device, a short-duration loading was applied and recorded along with the strain responses. Impulse transfer functions were then computed from the test results. Subsequently, long-duration pulses were applied, and the attendant measured responses were compared with those calculated by using the ITF data. Except for a scale factor on amplitude, due to inaccurate measurement of the impulse magnitude, good agreement was indicated. This effort, which is reported in Reference 3, demonstrated that a sufficiently short duration pulse could indeed be applied and the response to it could be accurately measured. Poor accuracy in the applied pulse measurement was attributed to the crude instrumentation used in the program. The question of delivering a high pulse amplitude for a large structure was not answered since the test article was not representative in this respect.

Based on the promise shown in the initial study, a more ambitious program was undertaken using the LTA-3 Lunar Module test article. The structure was suspended in a free-free configuration and instrumented to measure strain and acceleration response at a number of locations. An electrodynamic shaker, programmed with an exact-wave-form synthesizer to produce a single pulse, replaced the pendulum. The shaker was selected because it could apply high amplitude pulses and could readily be used to load various points in the structure in any desired direction. A more suitable force transducer eliminated the previous difficulties encountered in pulse measurement, but the 5,000 force-pound shaker initially employed provided too small a pulse to excite measurable response at points remote from the point of load application. A 15,000 force-pound shaker was then substituted and proved more than adequate in exciting measurable response at the most remote of the instrumented points.

These were as far as 15 feet away, on the vehicle's aft equipment bay. Figure 4 shows a typical impulse and several Impulse Transfer Functions obtained for various amplitude short-duration pulses. Excellent repeatability of experimentally determined ITF's is illustrated.

In addition to the impulse loadings, relatively long duration pulses were applied to the test article and the responses measured. The ITF method was then used to predict response. A comparison of the measured and predicted response at a single point are shown in Figure 5, along with the time history of the long duration pulse. Reference 4 contains an extensive sample of LTA-3 results. Of the 40 comparisons, half showed predicted peak amplitude agreement within 10% and within 5 milliseconds in time of occurrence. Some had peak amplitude predictions within 5% agreement. In general, all records showed good waveform agreement.

The reason that Grumman has pursued the development of the ITF method (References 1, 5 and 6) is that it can be a valuable supplement to current analytical and experimental techniques and offers certain advantages over both.

Compared with a purely analytical approach to transient response calculations, the ITF's provide a more realistic representation of the structure than that afforded by usual modal analysis methods. The system's mass, damping and stiffness properties are not needed, since these properties are implicitly reflected in the ITF's, and thus the approximations usually involved in their determination are eliminated. The method is particularly advantageous when dealing with large complex structural systems, such as the Space Shuttle, which do not yield readily to analysis. This is not intended to imply that modal and transient response analysis will be replaced. Since the ITF approach requires hardware to be available before it can be employed, conventional analysis procedures will still be needed in the design stages.

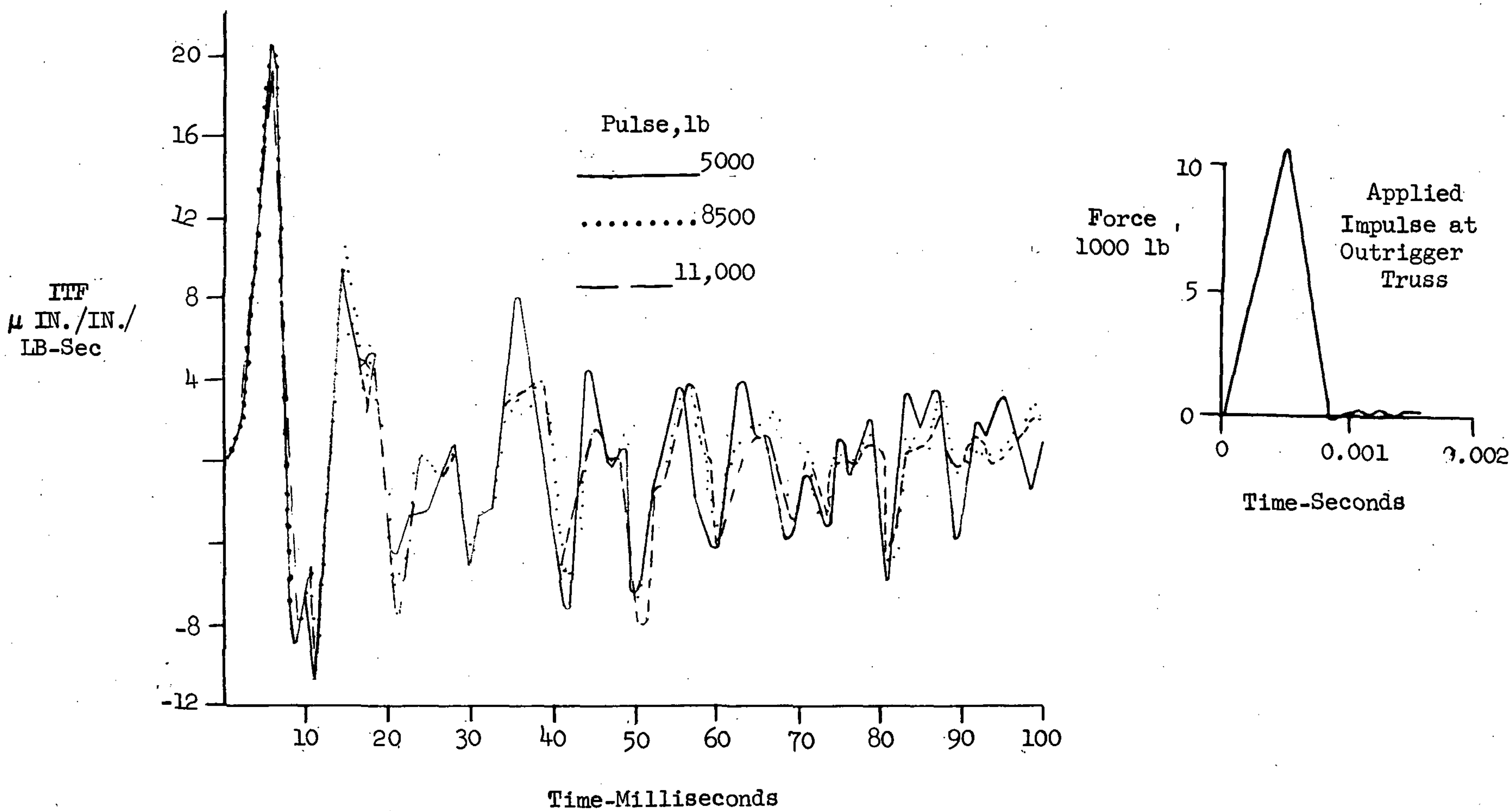


Figure 4 - Left-Hand Forward Interstage Fitting Impulse Transfer Function

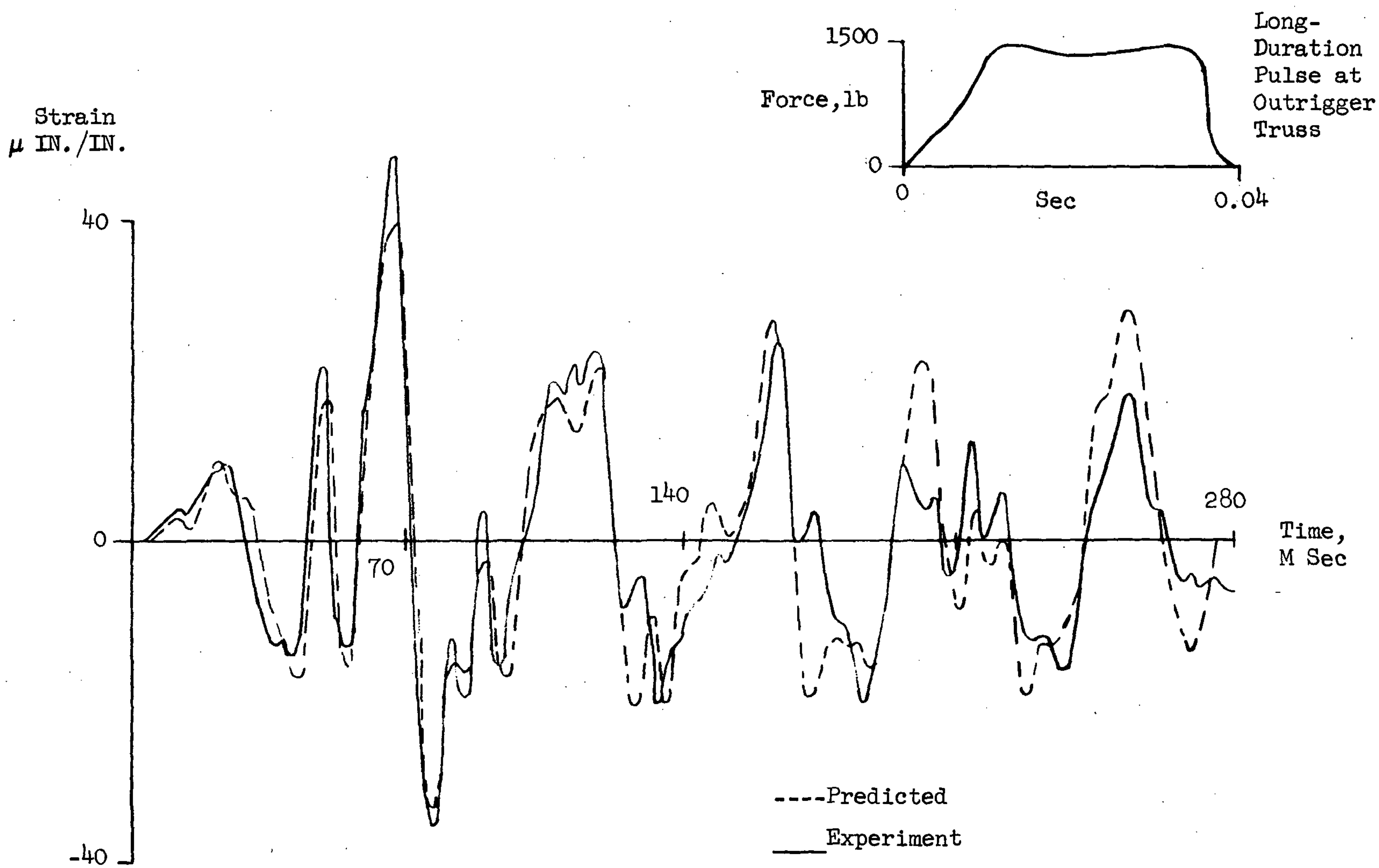


Figure 5 - Right-Hand Aft Equipment Bay Lower Outboard Strut Response

Conventional aerospace practice makes extensive use of testing, including mode surveys and dynamic simulation, such as drop testing. Modal information obtained from tests is still difficult to use to predict internal load distributions, stress levels, and component accelerations. Dynamic simulations verify the integrity of the structure, but do not yield basic information which can be applied to conditions that were not tested or which arise after testing is completed. Measured ITF's, on the other hand, would be available for calculation of responses to any loading condition. A considerable reduction in cost can be effected by using the ITF technique to reduce the number of loading conditions to be simulated, as well as to study loading conditions which are difficult to simulate in a test. It should be noted that the instrumentation required for impulse testing is normally found on simulation test articles; thus, no additional cost would be incurred in this area. One further advantage of the ITF technique lies in the fact that testing may be accomplished at low load levels, minimizing the inherent risk of premature failure and resulting structural damage which exists in simulation. The above discussion is particularly applicable to the Shuttle, due to its size and complexity, and the variety of transient loading conditions to which it will be subjected.

The ITF technique can be profitably applied to the Shuttle program through the use of "replica" models to provide design information, or through the use of full scale impulse testing can be employed in checking conventional modal transient response analysis. Shuttle transient loading conditions which can be handled by the method include: lift-off (engine start-up and vehicle release), end of boost, separation, docking and landing. Further discussion of the applicability of the ITF technique to the Space Shuttle may be found in Reference 7.

3-INSTRUMENTATION & DATA ACQUISITION

Although the test plan, Reference 2, documents all the testing procedures, equipment and data acquisition systems, a brief summary is included here for completeness.

The test program was conducted at Grumman Aerospace Corporation's Bethpage facility in the Plant 31 Structural Test Laboratory. The test began in late August and was concluded in late October of 1971. The test article was a structurally complete LM vehicle, designated as the LTA-11. It consisted of the LTA-3 ascent stage mated to the LTA-11 descent stage. In addition to it being structurally complete, most major mass items and systems were either mass-represented or inert production units. This vehicle had been used in several LM structural test programs, including the May 1970 series of drop tests. (Weight data and drawing numbers that describe the vehicle are given in Reference 2).

The test article was installed in a structural steel frame that provided the hoist and support points required to position the vehicle, as well as the points necessary to install the suspension system. The vehicle was supported at each outrigger apex fitting by a hydraulic actuator and an air spring arranged in tandem. The actuators were used to provide for vertical positioning while the air springs simulated the "free-free" conditions. For test conditions that required the application of impulses to the apex point itself, it was necessary to remove the suspension at that apex. For these conditions, a tie-down to ground was installed opposite to the point of excitation application to resist any vehicle overturning moment.

The impulses were generated using an electrodynamic shaker (Ling Model 335), programmed through an Exact Waveform Synthesizer, to drive an impact head into a striker plate mounted at the impact point on the vehicle. Both the impact head and the striker plate were fabricated from a cemented tungsten carbide alloy; this high modulus of elasticity material had been used with success in previous testing. A Kistler 905A force transducer, mounted in the impact head, was used to measure the applied pulse.

Schematic representations of the test set-up and impulse generating and monitoring systems are shown in Figures 6 and 7.

Impulses were applied to the freely suspended vehicle at each of the attachments to the deployment trusses. At each point 3 mutually perpendicular pulses were applied. Thus, the vehicle was excited by 36, individually applied impulsive loads.

Vehicle response, both strain and acceleration, were measured close to and remote from the points of load application. Forty strain gage measurements were selected from those used in the LM qualification drop test program based on their response to the various drop test conditions. Twenty-eight accelerometers were selected from those used in the LTA-11 mode survey for their usefulness in identifying the 5 lowest modes of vibration of the LM in the landing configuration.

A detailed list of this instrumentation is presented in Appendix 1.

Response of all the instrumentation to an applied pulse was recorded on magnetic tape and played back immediately on an oscillograph. These oscillograph records were inspected to insure that all channels were operational and that response did not exceed the range assigned to it. In addition to the responses, the time history of the applied pulse was also recorded on magnetic tape. Permanent oscillograph playbacks are made at a later time to further insure the validity of the data taken. The tapes collected during this program will be saved for at least one year and be used in the correlation effort involved in a contract with MSC expected to get underway shortly.

Further details of data acquisition system may be found in Reference 2.

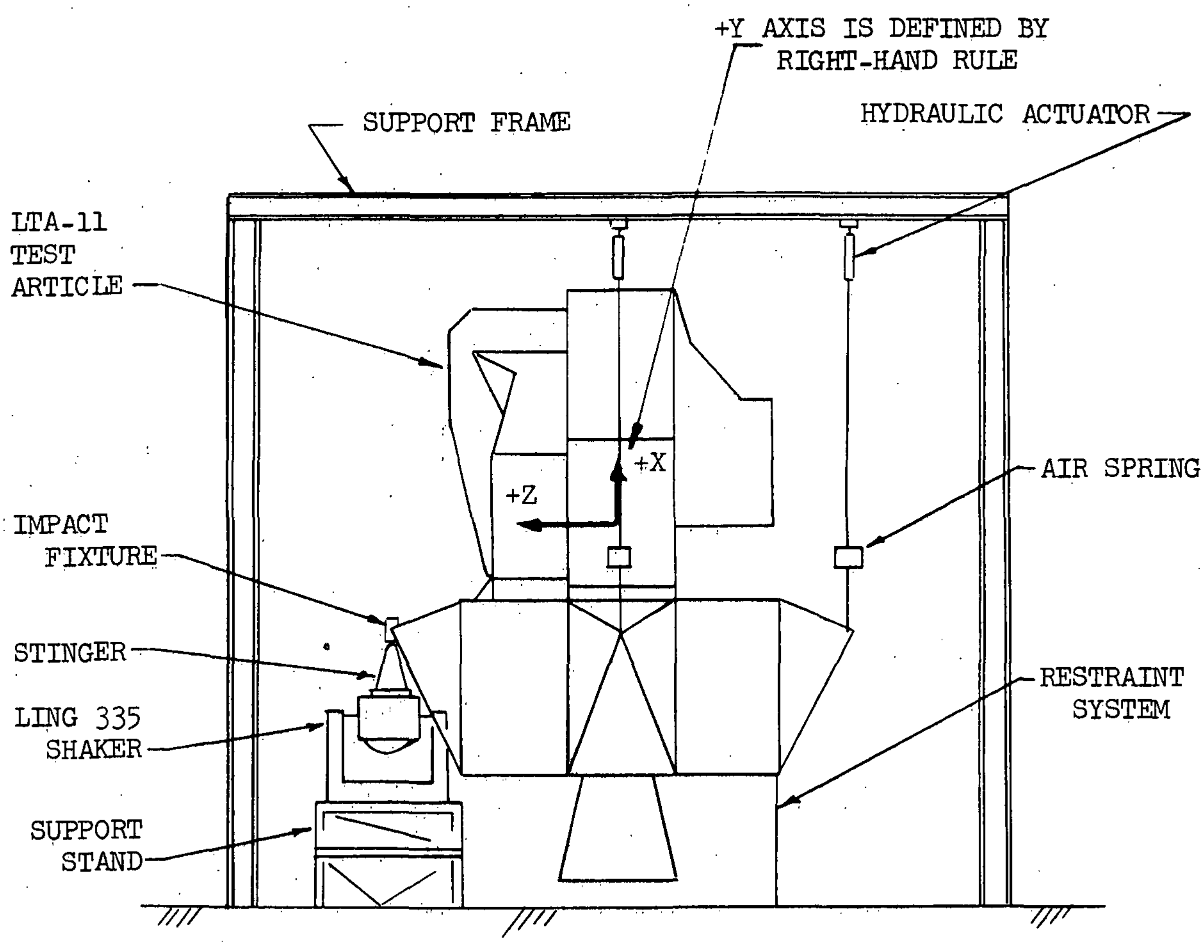


Figure 6 - Schematic Representation of the Impulse Test Set-Up

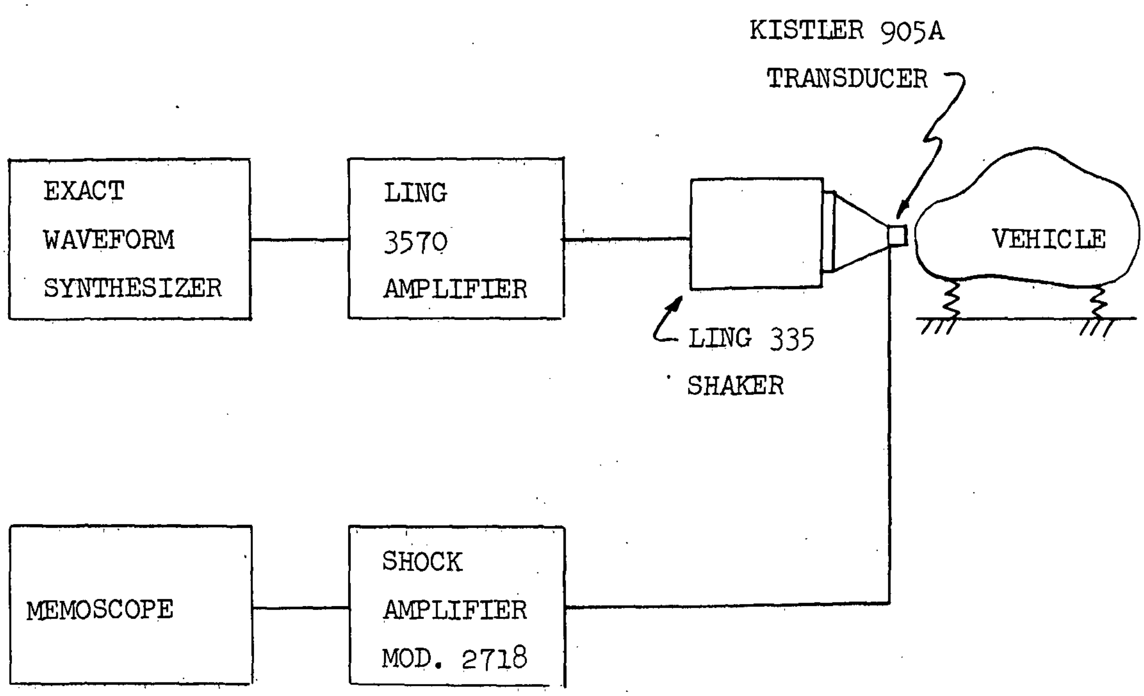


Figure 7 - Equipment for Generating and Monitoring Impulses

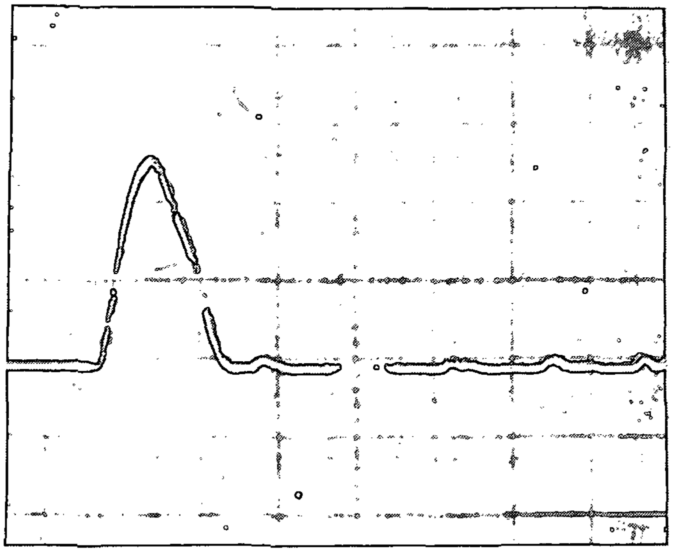
4-RESULTS

Impulse time histories, typical of the 36 applied to the test article are shown in Figures 8, 9 and 10. All 36 pulses closely resemble a half of a sine wave and are about .5 milliseconds in duration. The peak force levels are about 5,000 pounds for impulses applied to the deployment truss and 10,000 lbs. for impulses applied to the apex fitting of the outrigger truss.

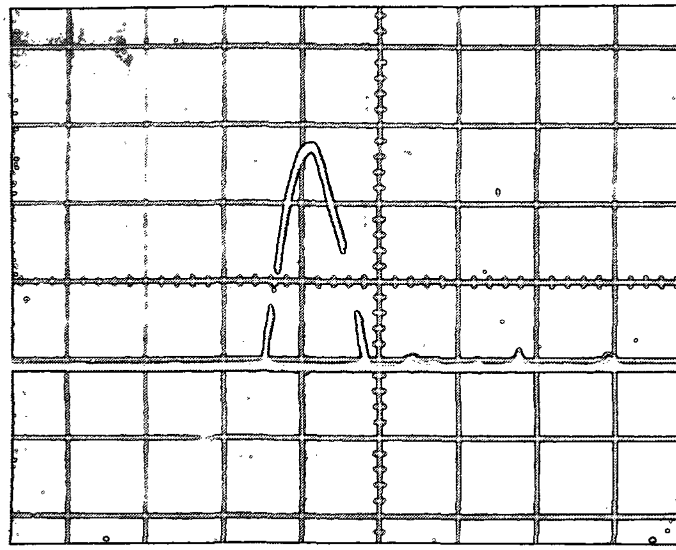
Two response time histories, typical of the response throughout the vehicle are shown in Figure 11. One strain gage and one accelerometer response, played back from the magnetic storage tape, are given. The only filter in the system was the 1000 cps filter that was used in the data acquisition system.

As a first-step in checking the accuracy of the ITF method for a complex act of forcing functions, one channel of instrumentation was processed to determine its response to a set of LTA-11 drop test forcing functions. The drop test selected was a level landing where all four footpads impact horizontal platforms designed to restrain the pads against in-plane motion. In this landing the primary rigid body acceleration of the vehicle is in the vertical direction. Translational acceleration in other directions, and rotational accelerations of the vehicle are small and only arise because of slight differences in the load-stroke characteristics of the landing gear energy absorbing devices.

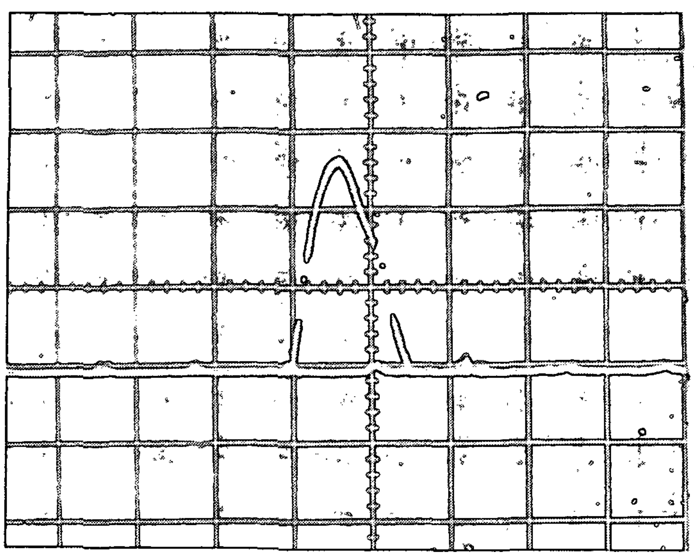
Figure 12 illustrates the forcing functions applied to the vehicle in the drop test. These forces were computed from measurements recorded during drop testing in the following manner. For the drop tests, each member of the outrigger trusses and each member of the deployment trusses was instrumented to record axial force. After the test, the member forces were resolved and summed into X, Y, and Z components at each of the points where a landing gear member attaches to the basic structure. These processed time histories are illustrated in Figure 12. Note, that of the 36 possible applied



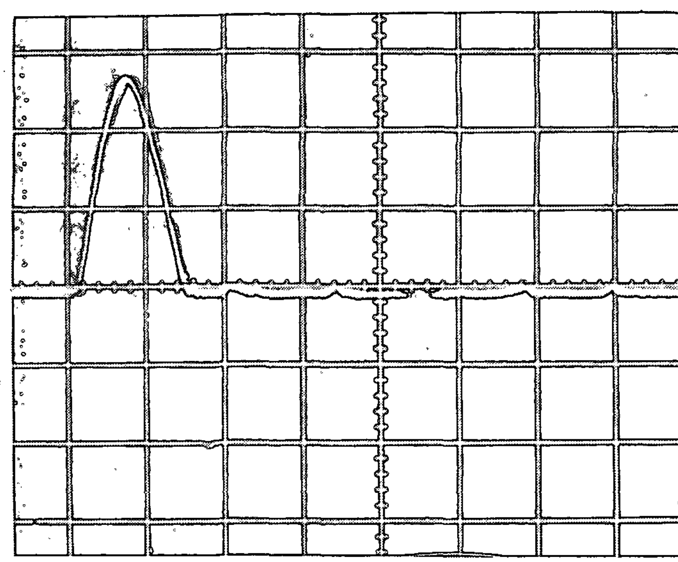
+Z APEX



-Z APEX



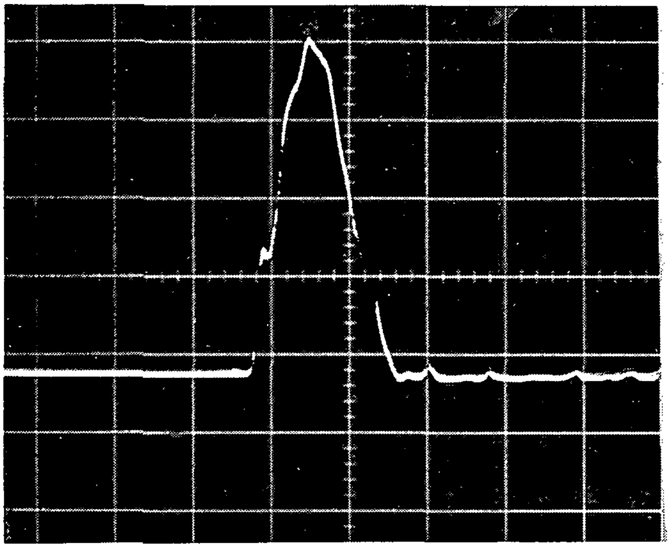
+Y APEX



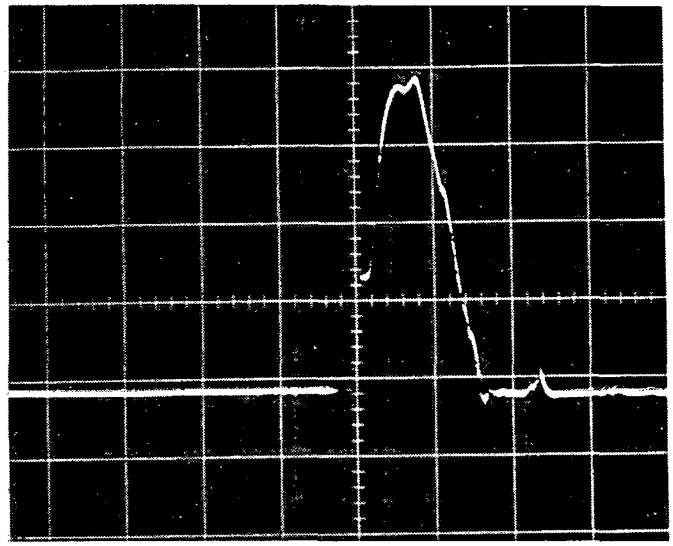
-Y APEX

Vertical Scale = 5000lb./division
Horizontal Scale = .5 millisecond/division

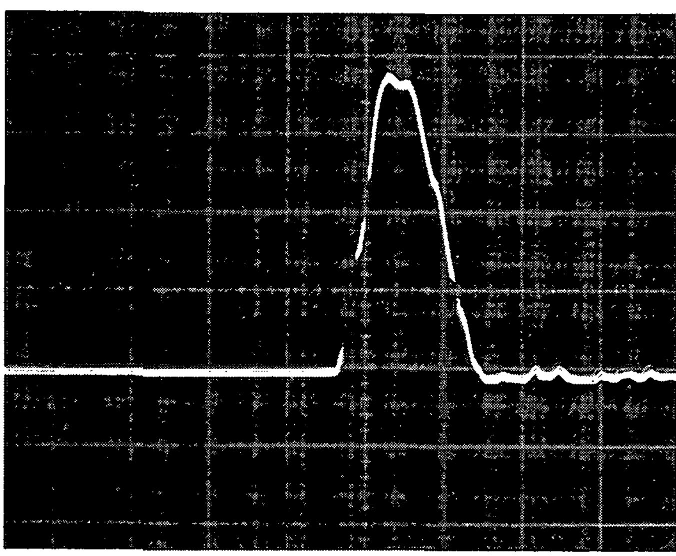
Figure 8 - Pulses Applied to Outrigger Truss Apex Fittings in the X Direction



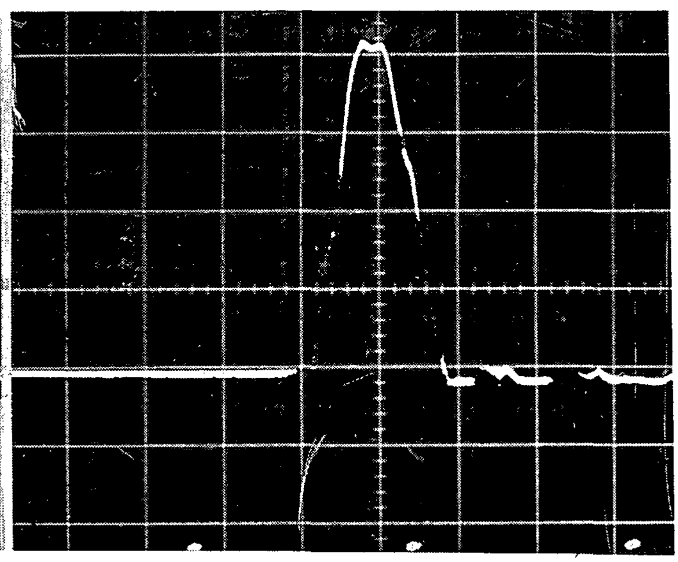
-Y APEX, +Z DIRECTION



-Y APEX, +Y DIRECTION



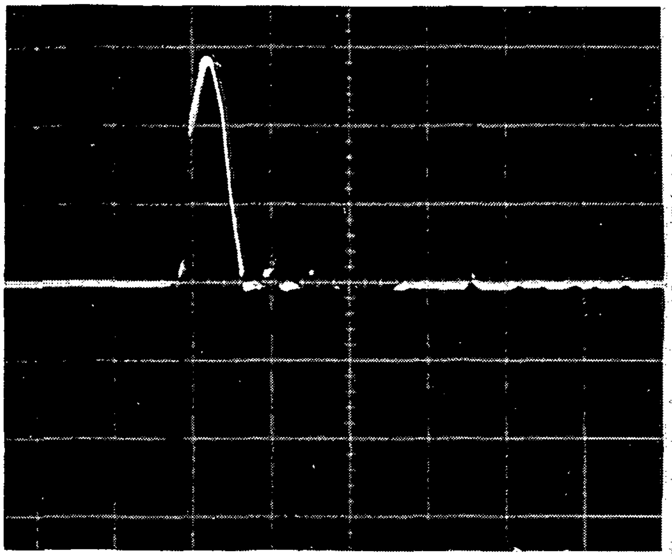
+Z APEX, +Y DIRECTION



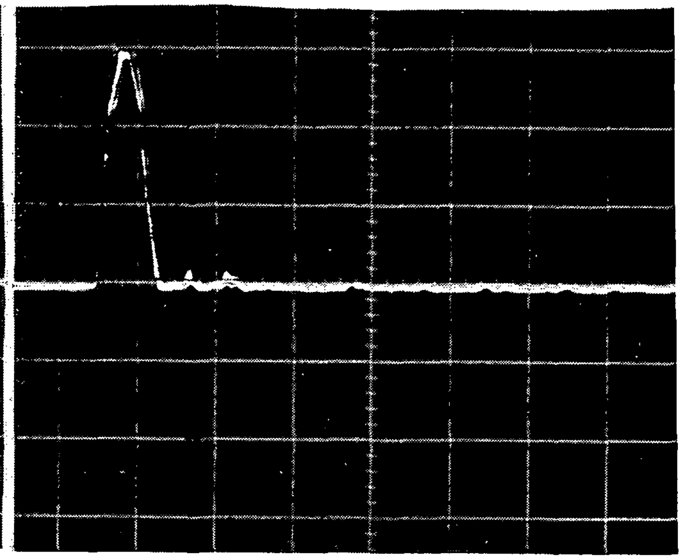
- Z APEX, -Y DIRECTION

Vertical Scale = 2500 lb./division
Horizontal Scale = .5 milliseconds/division

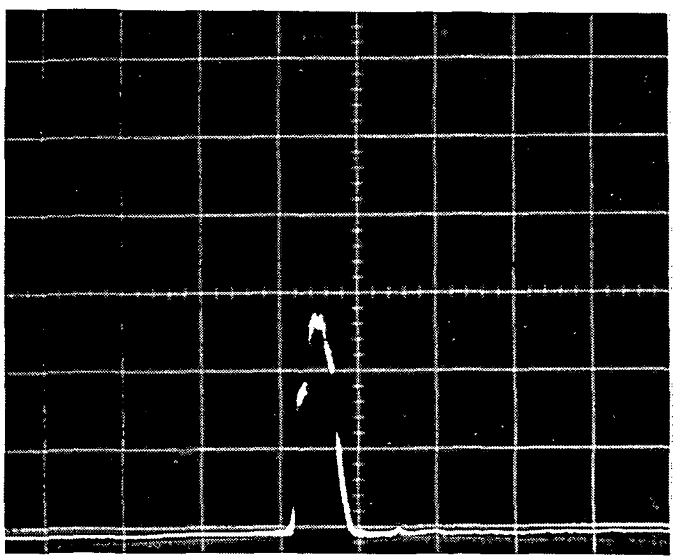
Figure 9 - Pulses Applied to Outrigger Truss Apex Fittings in Y & Z Directions



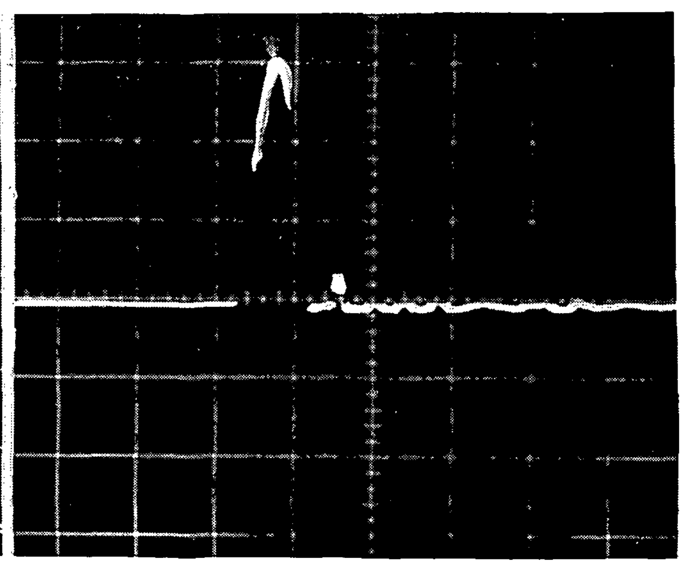
+Z BAY, +Y SIDE, -Z DIRECTION



-Z BAY, -Y SIDE, +Z DIRECTION



+Y BAY,+Z SIDE, -Y DIRECTION



-Z BAY, +Y SIDE, -Y DIRECTION

Vertical Scale = 2500lb./division
Horizontal Scale = .5 milliseconds/division

Figure 10 - Pulses Applied to the Deployment Trusses

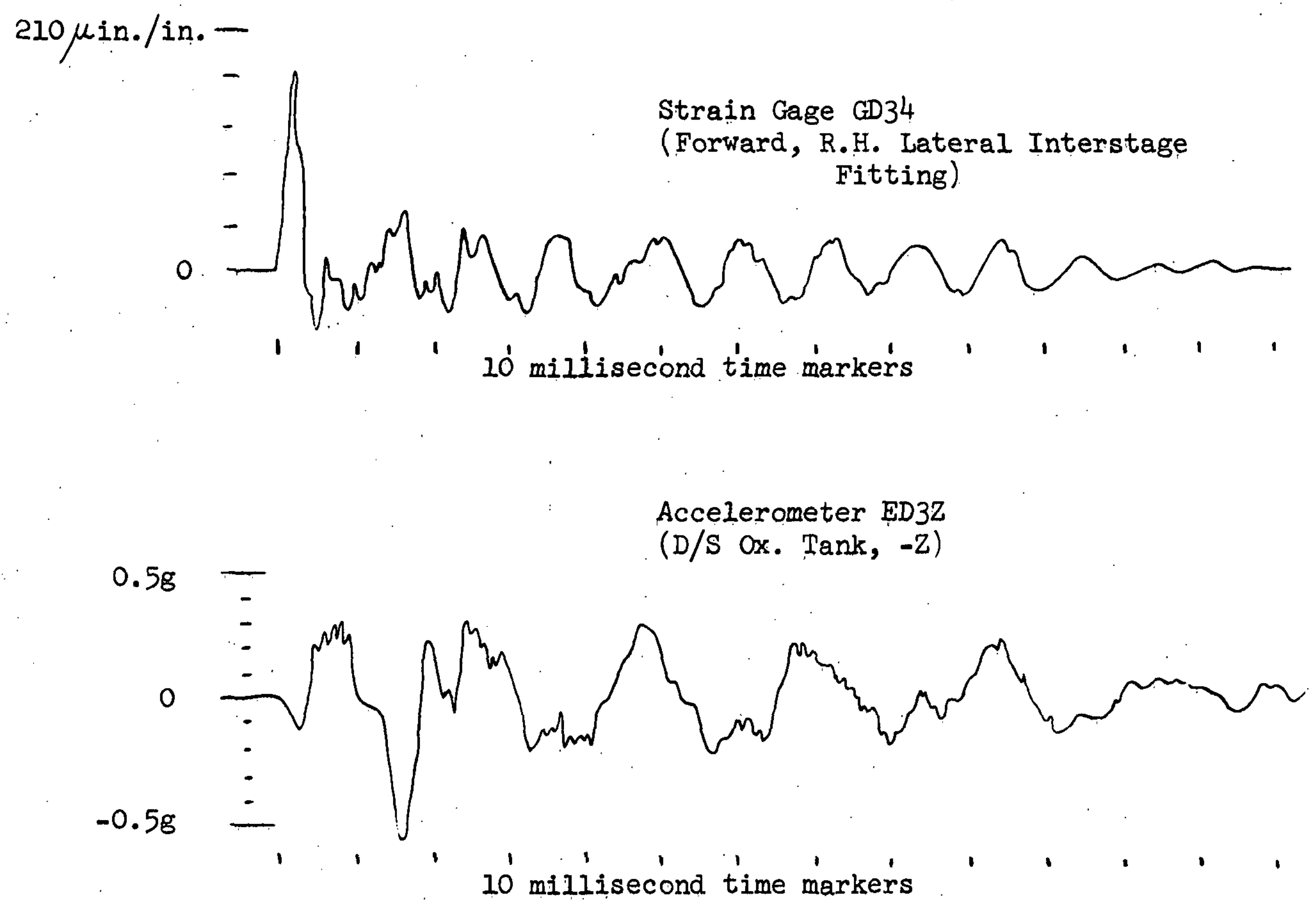


Figure 11 - Typical Impulse Response Time Histories

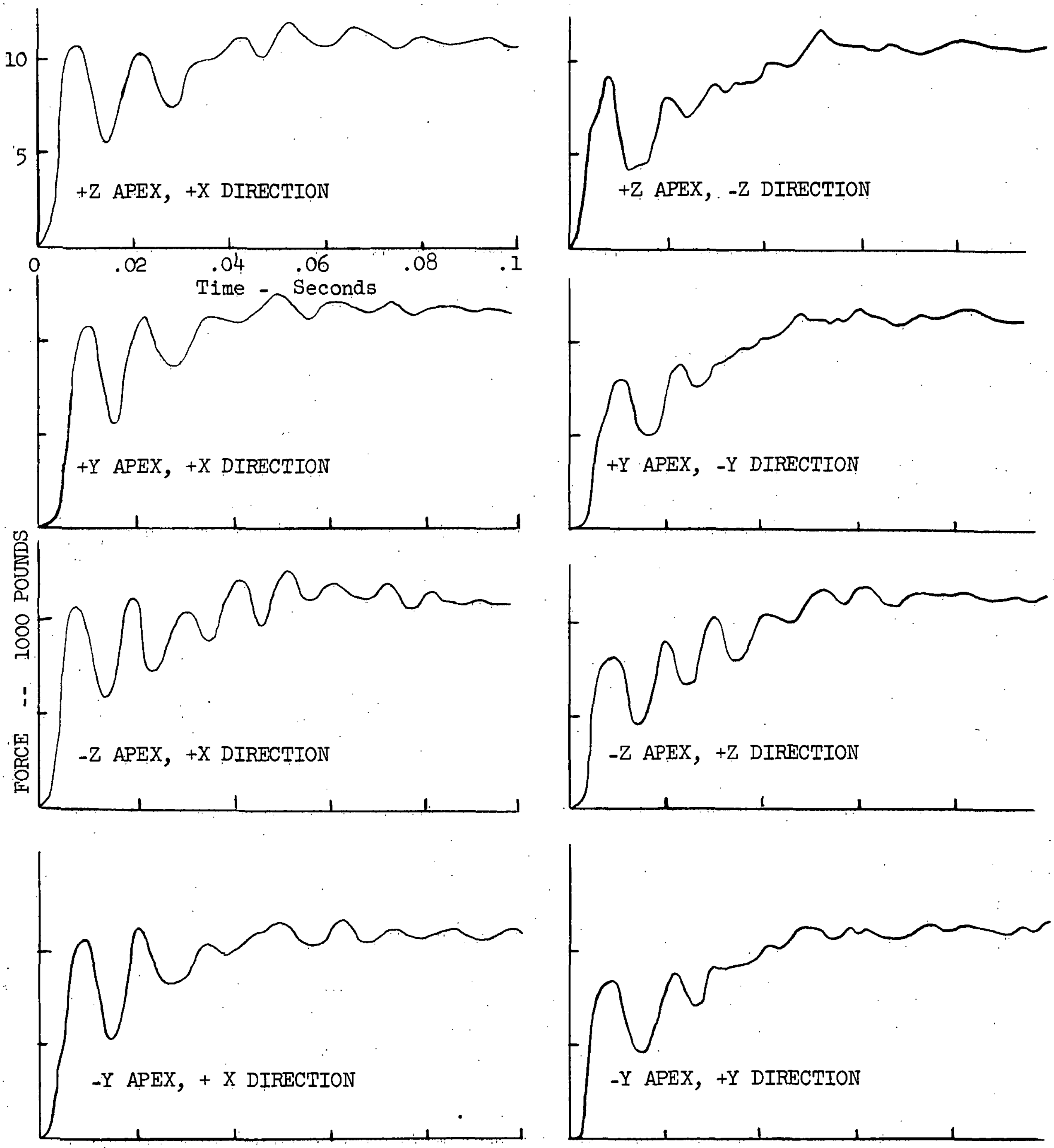


Figure 12a - Forces Applied to Outrigger Truss Apex Fittings From Drop Test Used in Correlation Study

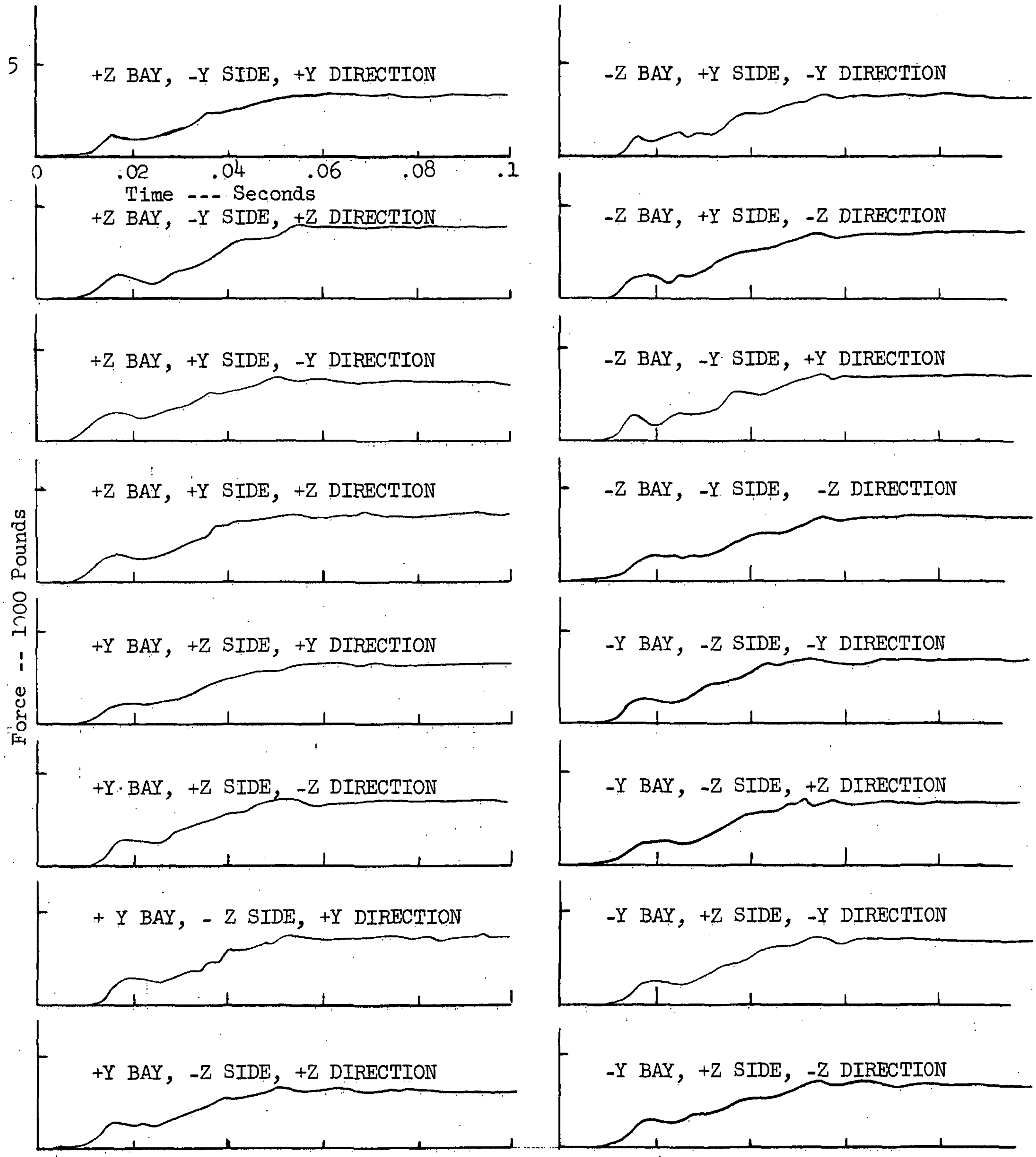


Figure 12b - Forces Apllied to Deployment Trusses From Drop Test Used in the Correlation Study forces only 24 are shown; the remainder are very close to zero due to the nature of the landing condition. For example, since the landing induces only vertical rigid body acceleration and each gear is loading the structure in an identical manner, there are only two-non-zero forces at each apex fitting. These are a vertical component of load and a horizontal component directed toward the center of the vehicle. At the deployment truss connection points, only horizontal forces exist since in this drop test the secondary struts were almost parallel to the horizontal plane. Thus a total of 12 loads (4 from the apex fittings and 8 from the deployment trusses) are taken as zero.

The response gage selected for detailed investigation is the left-hand outer, aft interstage truss member, GA-12, calibrated for axial force. The time history of load recorded in the drop test along with predicted time histories using the ITF's recorded in the present program are shown in Figure 13. As indicated in the figure, when all the ITF's that correspond to the non-zero forcing functions are used, the correlation with drop-test results is good with respect to wave form and poor with respect to amplitude. When a suspect transfer function, the one corresponding to an X directed impulse at the +Z apex fitting is removed, the correlation becomes good in all respects with only a 10% descrepency in amplitude. The reason this transfer function is suspect is due to the character of the response it produces for the vertical forcing function applied. Rather than being periodic, with oscillation occuring about a near-zero level, it remains zero for approximately 20 milliseconds and then rises like a ramp for the remainder of the period of interest. The type of error in the data reduction process that could produce this kind of response is involved in selecting the zero level for the ITF; other sources of error such as improper filtering or structural non-linearities cannot be ruled out. Time restraint during this present effort prevented a thorough investigation of the effects. However, during the MSC program, when a proper data reduction procedure is implemented and when a detailed correlation study will be undertaken, all of these effects will systematically studied.

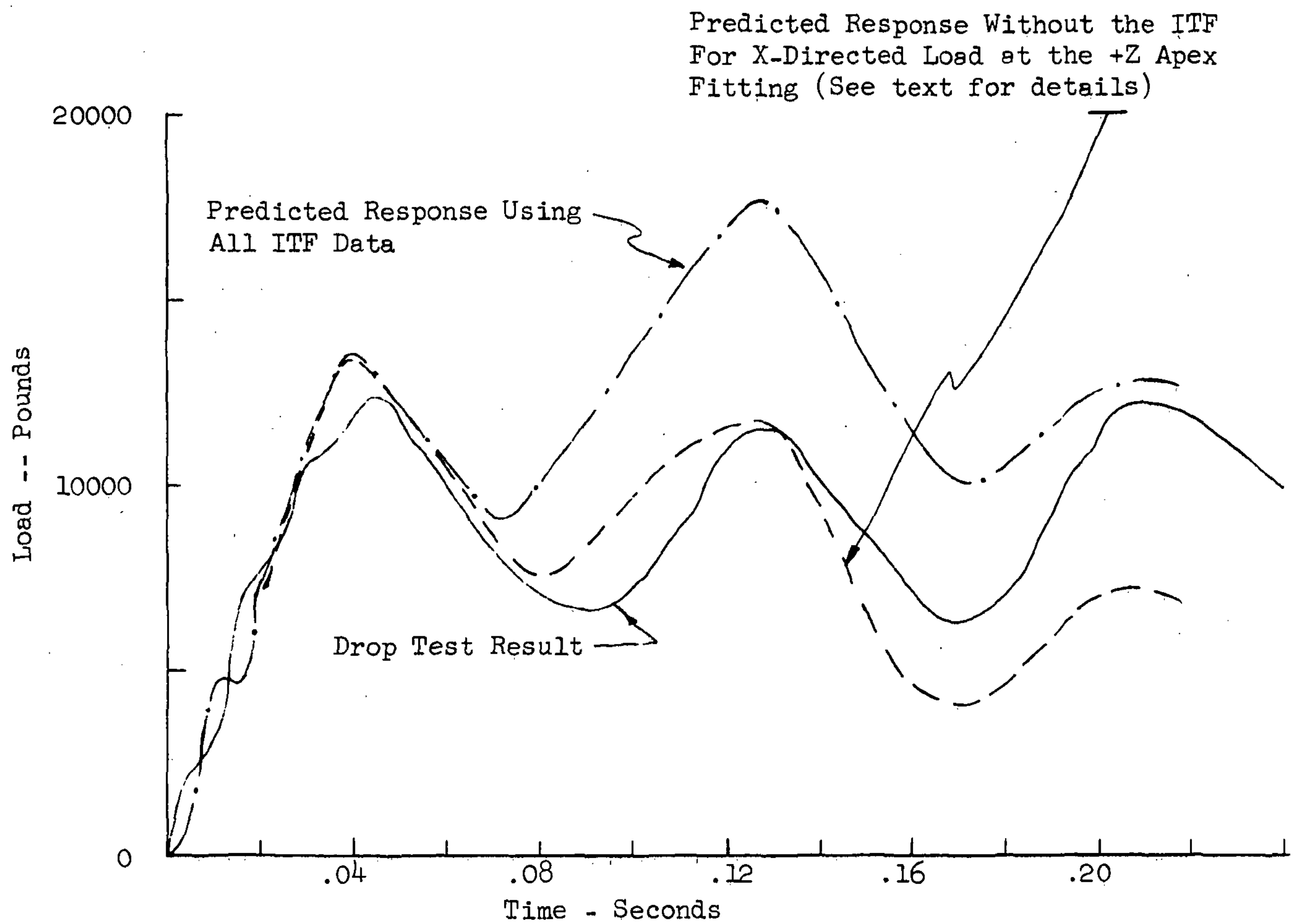


Figure 13 - Load in Left-Hand Outer Aft Interstage Truss Member(GA-12) ---
-- Drop Test Result vs. Prediction Using ITF Method

5-CONCLUSIONS AND RECOMMENDATIONS

The results detailed in this report indicate that:

- It is possible to perform an impulse test on a complicated a aerospace structure in a timely fashion. Improvements can be accomplished by fabricating fixtures to minimize the physical problems of moving shakers and other equipment. Improvements in data acquisition equipment should also be considered to improve reliability and minimize the time required to set up for a run.
- The ITF method for determining transient response to a complicated set of forcing functions is promising. This conclusion is based on the one channel that was studied in this effort using the crude data reduction system available to us. However our study did reveal several important sources of error that will require careful consideration. The level taken as the zero value for a recorded ITF must be accurately determined. Requirements must be established for filters in the data reduction system to remove unimportant, but difficult to handle, high frequency response or to remove low frequency response caused only by the suspension system used to simulate the free-free state. In addition, a system of checks will have to be established to assure that the data reduced to digital form is valid. All these items will be given attention during the MSC contract which will also provide a final verification of the accuracy of the ITF technique.

Based on the work reported herein and assuming the MSC contract does not reveal any major short-comings in the approach, Grumman recommends that further development of the ITF method be considered by NASA. The paragraphs which follow outline where extensions of the ITF approach could be useful in the Shuttle program.

Work performed to date has been concerned with determining ITF's from tests performed on free-free structures. Since it may be undesirable to suspend the Space Shuttle to simulate a free-free state, procedures for obtaining free-free transfer functions from tests performed with the supported structure may be required. There are a number of possible ways in which to perform this transformation. They all involve measurement of support forces, calculation of responses due exclusively to these support forces, and subtraction of these responses from the supported ITF's to obtain a free-free ITF's. Responses to support forces would be computed by the ITF technique, and therefore, ITF's between support points and response points must be obtained along with those between loading points and response points. The various means of obtaining free-free ITF's differ in the manner in which the structure is supported during impulse testing and in the analytical techniques employed for the calculation of free-free transfer functions from data obtained for the supported structure.

An indication of the scope of this work may be of interest. A first phase could be concerned with exploring and evaluating possible transformation techniques in order to select the most promising one from the standpoint of minimizing the testing, data handling, and programming requirements. The selected technique could then be programmed and demonstrated analytically, for a small structure. This initial study could be performed at relatively low cost. A second phase might consider a demonstration test and analysis on a realistic structure.

For the Shuttle project, a great deal of interest is currently centered on methods of independently testing the orbiter and booster vehicles to determine component modal data that would be coupled analytically to obtain total vehicle modes. Similar ideas can be entertained for ITF's. That is, ITF's can be determined during the component vibration test program and later analytically coupled to obtain total vehicle ITF's. This data would be especially useful in handling the transient problems associated with lift-off and booster engine burnout. The coupling process would be similar in nature to the methods outlined for determining free-free ITF's from tests of a supported structure.

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APPENDICES

Appendix 1 - List of Instrumentation

MEAS. NO.	MEASUREMENT NAME AND LOCATION	TRANSDUCER TYPE & RANGE
1	Input Force	Piezoelectric Impact Force 30,000 lbs
2	Aft Interstage Truss, Outer L.H. GA-12	Axial Strain Gage Ckt 25,000 lbs
3	Aft Interstage Truss, Inner L.H. GA-13	Axial Strain Gage Ckt 10,000 lbs
4	Aft Interstage Truss, Outer R.H. GA-14	Axial Strain Gage Ckt 25,000 lbs
5	Aft Interstage Truss, Inner R.H. GA-15	Axial Strain Gage Ckt 10,000 lbs
6	+Z Outrigger Strut, Upper +Y Side GD-1	Axial Strain Gage Ckt 30,000 lbs
7	+Z Outrigger Strut, Upper -Y Side GD-2	Axial Strain Gage Ckt 30,000 lbs
8	+Z Outrigger Strut, Lower +Y Side GD-3	Axial Strain Gage Ckt 16,000 lbs
9	+Z Outrigger Strut, Lower -Y Side GD-4	Axial Strain Gage Ckt 16,000 lbs
10	Diag. Strap Quad I Upper Center GD-17	Axial Strain 2500 u"/in
11	Diag. Strap Quad I Lower Center GD-18	Axial Strain 2500 u"/in

MEAS. NO.	MEASUREMENT NAME AND LOCATION	TRANSDUCER TYPE & RANGE
	Diag. Strap Quad II Lower Forward GD-20	Axial Strain 2500 u"/in
13	Diag. Strap Qual III Lower Center GD-23	Axial Strain 2500 u"/in
14	Diag. Strap Quad IV Lower Center GD-25	Axial Strain 2500 u"/in
15	Side Panel Quad II -Z27 Shear GD-28	Shear Strain 2000 u"/in
16	Side Panel Quad II -Y27 Shear GD-29	↓
17	Side Dec, Quad III +Y27 Shear GD-31	↓
18	Side Deck Quad IV +Z27 Shear GD-32	↓
19	Forward Interstage Support R.H. Lateral GD-34	Axial Strain 2500 u"/in
20	Forward. Interstage Support, L.H. Diag. "Tee" GD-35	↓
21	Forward Interstage Support, L.H. Vertical GD-36	↓
22	Forward Interstage Support, L.H. Lateral GD-37	↓

MEAS. NO.	MEASUREMENT NAME AND LOCATION	TRANSDUCER TYPE & RANGE
23	Forward Interstage Support, R.H. Diag. "Tee" GD-38	Axial Strain 2500u"/in
24	Forward Interstage Support, R.H. Vertical GD-39	↓
25	Fwd. (+Z) Deployment Int. Cross Member GD-40	Axial Strain 7500 lbs
26	Fwd. (+Z) Deployment -Y Side Member GD-44	Axial Strain 4000 lbs
27	Fwd. (+Z) Deployment -Y Down Lock Member GD-45	Axial Strain 2000 lbs
28	Left (-Y) Upper Deck Fwd. Shear +Z Side GD-65	Shear Strain 4000 u"/in
29	Right (+Y) Upper Deck Fwd. Shear +Z Side GD-68	Shear Strain 1000 u"/in
30	Upper Cap Strip +Y27 Quad IV GD-82	Axial Strain 2000 u"/in
31	Upper Cap Strip -Y27 Quad I GD-83	Axial Strain 2000 u"/in
32	Upper Cap Strip -Z27 Quad III GD-84	Axial Strain 2000 u"/in
33	Upper Cap Strip +Z27 Quad IV GD-85	↓
34	Upper Cap Strip +Y27 Quad III GD-86	↓

MEAS. NO.	MEASUREMENT NAME AND LOCATION	TRANSDUCER TYPE & RANGE
35	Upper Cap Strip -Y27 Quad II GD-87	Axial Strain 2000u"/in
36	Upper Cap Strip -Z27 Quad II GD-88	↓
37	Upper Cap Strip +Z27 Quad I GD-89	Axial Strain 2000 u"/in
38	Mesa End Strut Forward (+Z81) GD-118	Axial Strain 2500 u"/in
39	Mesa End Strut Right Side (+Y81) GD-119	Axial Strain 2500 u"/in
40	Payload Vert. Strut Left Side (-Y) GD-130	Axial Strain 2500 u"/in
41	Payload Vert. Strut Forward (+Z) GD-131	Axial Strain 2500 u"/in
42	Acceleration EA-108 X	Piezoelectric Accelerometer ±1000G
43	Acceleration EA-57 X	↓
44	Acceleration EA-57 Z	↓
45	Acceleration EA-58 X	↓
46	Acceleration EA-58 Y	↓

MEAS. NO.	MEASUREMENT NAME AND LOCATION	TRANSDUCER TYPE & RANGE
47	Acceleration EA-58 Z	Piezoelectric Accelerometer ± 1000G
48	Acceleration ED-1 Z	Piezoelectric Accelerometer ±1000G
49	Acceleration ED-2 Z	Piezoelectric Accelerometer ±1000G
50	Acceleration ED-4 Z	
51	Acceleration ED-11 X	
52	Acceleration ED-11 Y	
53	Acceleration ED-12 X	
54	Acceleration ED-12 Z	
55	Acceleration ED-13 X	
56	Acceleration ED-13 Y	
57	Acceleration ED-13 Z	
58	Acceleration ED-14 X	

MEAS. NO.	MEASUREMENT NAME AND LOCATION	TRANSDUCER TYPE & RANGE
59	Acceleration ED-14 Z	Piezoelectric Accelerometer ±1000G
60	Acceleration EA-99 X	Piezoelectric Accelerometer ±1000G
61	Acceleration EA-101 Z	Piezoelectric Accelerometer ±1000 G
62	Acceleration EA-100 X	
63	Acceleration EA-104 Z	
64	Acceleration EA-78 Z	
65	Acceleration EA-95 X	
66	Acceleration EA-95 Y	
67	Acceleration ED-3 X	
68	Acceleration ED-3 Y	
69	Acceleration ED-3 Z	Piezoelectric Accelerometer ±1000G

Appendix 2 - Summary of LTA-11 Impulse Testing (1971)

Run No.	Date	Pulse Location	Pulse Direction
1	Aug. 25	+Z Deployment Truss, -Y side	+X
2	Aug. 27	+Z " " , -Y "	-Z
3	Aug. 30	+Z " " , -Y "	+Y
4	Aug. 31	-Y " " , +Z "	-Z
5	Sept. 1	-Y " " , +Z "	+Y
6	Sept. 2	-Y " " , +Z "	+X
7	Sept. 2	-Y " " , -Z "	+X
8	Sept. 3	-Y " " , -Z "	+Y
9	Sept. 3	-Y " " , -Z "	+Z
10	Sept. 7	-Z " " , -Y "	+Y
11	Sept. 9	+Z Apex Fitting	-Z
12	Sept. 10	+Y " "	-Y
13	Sept. 13	-Z " "	+Z
14	Sept. 14	-Y " "	+Y
15	Sept. 15	-Y " "	+Z
16	Sept. 16	+Z " "	+Y
17	Sept. 17	+Y " "	-Z
18	Sept. 17	-Z " "	-Y
19	Sept. 20	-Z " "	+X
20	Sept. 23	+Y " "	+X
21	Sept. 24	+Z " "	+X
22	Sept. 27	-Y " "	+X
23	Sept. 29	-Z Deployment Truss, -Y side	+X
24	Oct. 1	-Z " " , -Y "	+Z
25	Oct. 7	+Z " " , +Y "	-Z
26	Oct. 8	+Z " " , +Y "	-Y
27	Oct. 11	+Z " " , +Y "	+X
28	Oct. 12	+Y " " , +Z "	+X
29	Oct. 12	+Y " " , +Z "	-Z
30	Oct. 13	+Y " " , +Z "	-Y
31	Oct. 15	-Z " " , +Y "	+Z
32	Oct. 15	-Z " " , +Y "	-Y
33	Oct. 18	-Z " " , +Y "	+X
34	Oct. 19	+Y " " , -Z "	+X
35	Oct. 21	+Y " " , -Z "	+Z
36	Oct. 22	+Y " " , -Z "	-Y

NOTE: The pulse direction indicated refers to the ITF testing only. In using the ITF's for the prediction of response, a reversal of sign may be required depending on the direction of a particular forcing function.