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Experimental Investigation of Launch Vehicle Transient Input Simulation in Payload Tests

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16. Abstract

The technique of electronically simulating the structural dynamics of a launch vehicle in transient tests of payloads using multiple vibration excitation systems was investigated. The development of computer programs to determine transfer functions, synthesize shaker forcing functions, and control vibration exciters is described. A demonstration test using the techniques is described and results are presented. The evaluation of the potential for applying this technique to large Shuttle payloads is discussed.

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EXPERIMENTAL INVESTIGATION OF LAUNCH VEHICLE TRANSIENT INPUT SIMULATION IN PAYLOAD TESTS

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SUMMARY

The purpose of this study was to investigate the technique of electronically simulating the structural dynamics of a launch vehicle in transient tests of payloads using multiple vibration excitation systems.

The study consisted of three tasks:

1. Development of computer programs to determine the transfer functions, synthesize the shaker forcing functions, and control vibration exciters in a two-input system;

2. Conduct of a demonstration test on a truss-type physical structure;

3. Evaluation of the potential for applying this technique to large Shuttle payloads.

Results indicate that the simulation of flight transients in tests of payloads is technically and economically feasible.

INTRODUCTION

The design of primary structure for space vehicles includes the consideration of maximum loads induced by vehicle transients such as staging events, engine ignition and shutdown, gust loading, and landing shock. Analytical techniques are used to calculate the dynamic behavior and associated loads in structural members. To date, test verification of the structural integrity has been accomplished using sine sweep techniques requiring complex fixtures, and extensive control and abort instrumentation to ensure protection for the payload from unrealistic test-peculiar failures.

This study was conducted to investigate the feasibility of providing realistic simulation of vehicle transients at multiple locations on a complex structure to account for the dynamic characteristics of the launch vehicle and vibration exciters. The information presented in this report includes a description of the software generated to provide the necessary control of the vibration exciter systems, a description of the demonstration test and results obtained, and a discussion of the feasibility and costs of applying the technique to large payloads.

SYMBOLS

A/D	analog to digital
ATTN	analog to digital attenuator code
C_i	magnitude of i^{th} component
D/A	digital to analog
DAC	digital to analog converter
DFT	direct Fourier transform
e	base of natural logarithms
E(t)	error as a function of time
f	frequency, Hz
$F_{cal}(t)$	calibration transient in the time domain
FILTER	analog to digital antialiasing filter cutoff frequency
FS	sample frequency, samples per second
g	acceleration due to gravity
Hz	hertz
IFT	inverse Fourier transform
j	the square root of minus one
m	number of frequency components
MAX	maximum
N	time domain frame size
NS	number of samples (size N) used to calculate transfer function
STS	Space Transportation System
t	time
TF	transfer function
TSL	time series language

TYP	typical
VMAX	maximum output voltage
VREF	reference voltage
$\begin{Bmatrix} XA \\ XB \end{Bmatrix} jw$	complex acceleration inputs at points A and B
XRA(t)	required time domain waveform at point A
XRB(t)	required time domain waveform at point B
$\begin{Bmatrix} YA \\ YB \end{Bmatrix}_{j\omega}$	complex acceleration response at points A and B
YDA(t)	specified time domain waveform at point A
YDB(t)	specified time domain waveform at point B
ζ	damping ratio
ω	frequency, rad/s

TRANSIENT CONTROL SYSTEM

Software Development

The program's objective was to produce two independent transient waveforms to be applied simultaneously to two shaker systems, designated A and B. The implementation of multiple shaker control to specified transient waveforms required the development of unique software written in Time Series Language (TSL) for operation on a digital Fourier-Analyzer-type test control system.

Initially, each shaker is used individually to input a calibration transient into the structure to obtain transfer functions to response points A and B. The calibration transient is a rapid sine sweep from ω_o to ω_c where ω_c is the upper frequency of interest. It has the mathematical form:

$$F_{CAL}(t) = A \sin \omega(t) t$$
$$\omega(t) = \omega_o + \Delta \omega t \qquad (1)$$

The calibration transient is output to the structure a number of times and the resultant transfer functions are calculated to response points A and B using the Fourier Analyzer. In the frequency domain, the procedure is expressed as

$$\underset{\text{(response)}}{\begin{Bmatrix} YA \\ YB \end{Bmatrix}_{j\omega}} = \begin{bmatrix} TFAA & TFAB \\ TFBA & TFBB \end{bmatrix}_{j\omega} \underset{\text{(input)}}{\begin{Bmatrix} XA \\ XB \end{Bmatrix}_{j\omega}} \qquad (2)$$

where,

TFAA = transfer function, response at point A due to shaker A input

TFAB = transfer function, response at point A due to shaker B input

TFBA = transfer function, response at point B due to shaker A input

TFBB = transfer function, response at point B due to shaker B input.

Equation (2) is three dimensional with frequency ($j\omega$) as the third dimension.

Next, the desired response transients, YDA(t) and YDB(t), at points A and B are specified and transferred to the frequency domain via a Fourier transformation. Equation (2) is then solved for the frequency domain shaker inputs, XRA(ω) and XRB(ω), by the procedure,

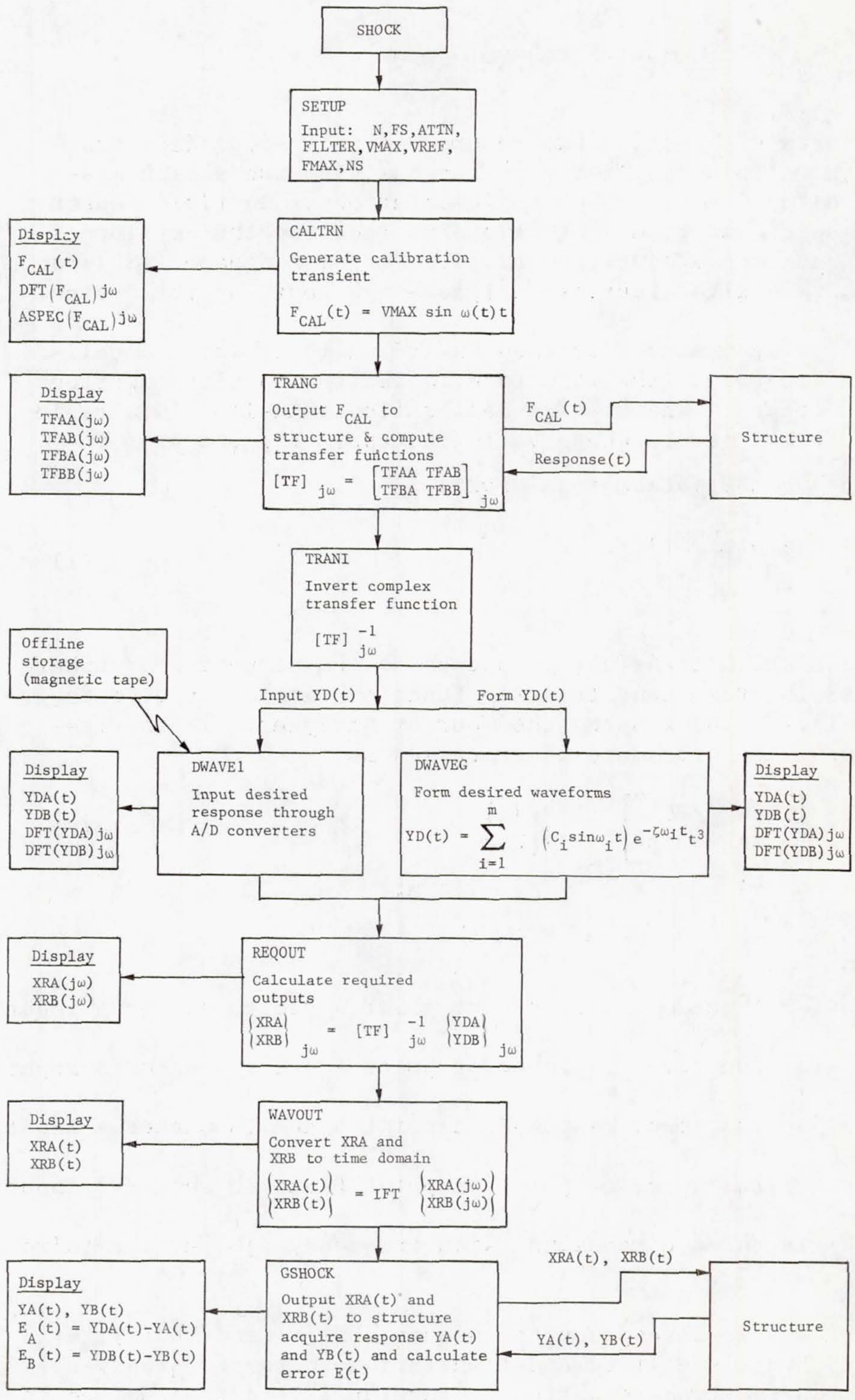

Figure 1. - Program SHOCK flow diagram.

$$\begin{Bmatrix} XRA \\ XRB \end{Bmatrix}_{j\omega} = \begin{bmatrix} TFAA & TFAB \\ TFBA & TFBB \end{bmatrix}^{-1}_{j\omega} \begin{Bmatrix} YDA \\ YDB \end{Bmatrix}_{j\omega} \qquad (3)$$

(input) (response)

The inverse Fourier transform of XRA(jω) and XRB(jω) results in the simultaneous shaker inputs required to obtain the desired response at points A and B.

$$\begin{Bmatrix} XRA(t) \\ XRB(t) \end{Bmatrix} = IFT \begin{Bmatrix} XRA(j\omega) \\ XRB(j\omega) \end{Bmatrix} \qquad (4)$$

The computer program was coded in a modular form. Figure 1 is a flow diagram of the major modules. Each module is briefly discussed below.

SHOCK. - SHOCK is the main executive program that calls the main subroutines and controls the flow of the program.

SETUP. - This subroutine allows user selection of A/D and D/A parameters. The inputs are as follows:

N = time domain frame size, power of 2

FS = A/D - D/A sample frequency, samples/s

ATTN = Analog/digital (A/D) attenuator code, ±V

FILTER = A/D antialiasing filter cutoff frequency, Hz

VMAX = MAX output voltage for D/A (calibration transient only), V

VREF = D/A reference voltage (max output capability of DAC), 10 V

FMAX = maximum frequency of interest, Hz

Ns = number of samples used to calculate the transfer functions

The maximum frequency analyzed is FS/2. The resulting frequency resolution is FS/N, Hz.

CALTRN. - CALTRN generates the calibration transient.

$$F_{CAL}(t) = VMAX \sin \omega(t)t \text{ , V} \qquad (5)$$
$$\omega = \omega_o + \Delta\omega t$$

TRANG. - TRANG outputs calibration transients, in sequence, to shakers A and B and calculates the transfer functions.

$$\left[TF(j\omega)\right] = \begin{bmatrix} TFAA & TFAB \\ TFBA & TFBB \end{bmatrix}_{j\omega}, \text{ units/V} \tag{6}$$

TRIANI. - This subroutine inverts the complex transfer function via the following algorithm.

$$\left[TF(j\omega)\right]^{-1} = \left[\alpha + j\beta\right]^{-1}_{j\omega} = \left[\bar{\alpha} + j\bar{\beta}\right]_{j\omega}, \text{ V/unit} \tag{7}$$

where,

$$\bar{\alpha} = \left[\alpha + \beta A^{-1}\beta\right]^{-1}$$

$$\beta = -\alpha^{-1}\beta\bar{\alpha}$$

DWAVE. - DWAVEI or DWAVEG.

DWAVEI. - Input through A/D converters desired transients YDA(t), YDB(t) (units versus time) and compute Fourier transforms

DWAVEG. - Allows analytical generation of desired transients YDA(t), YDB(t) of the form,

$$YD(t) = \sum_{i=1}^{m} \left(C_i \sin \omega_i t\right) e^{-\zeta_i \omega_i t} t^3, \text{ (units versus time)} \tag{8}$$

where,

m = number of frequency components

C_i = magnitude of i^{th} component

ω_i = frequency of i^{th} component

ζ_i = damping ratio of i^{th} component

REQOUT. - Calculates required outputs for shakers A and B to give desired transients in the frequency domain.

$$\begin{Bmatrix} XRA \\ XRA \end{Bmatrix}_{j\omega} = \left[TF\right]^{-1} \begin{Bmatrix} YDA \\ YDB \end{Bmatrix}_{j\omega}, \text{ V} \tag{9}$$

WAVOUT. - Converts XRA(jω) and XRB(jω) to time domain via inverse Fourier transform resulting in,

$$\begin{vmatrix} XRA(t) \\ XRB(t) \end{vmatrix}, \text{ V versus time} \qquad (10)$$

GSHOCK. - Outputs XRA(t) and XRB(t); acquires the response, YA(t) and YB(t); compares to the desired response, YDA(t) and YDB(t); and calculates time domain error functions.

Demonstration Test

A test program was conducted to demonstrate the applicability of the technique in the laboratory. A Titan instrumentation truss simulating a complex payload structure, was used as the test article. (See Figure 2.) Two electrodynamic exciters were attached to the truss mounting points, and accelerometers were attached to the truss near each of the shaker mounting points. Figure 3 is a block diagram of the control and instrumentation system. Three test conditions were investigated.

1. The same transient input was applied at different locations in one direction.

2. Different transient inputs were applied at different locations in one direction.

3. Multidirectional inputs of different transients were applied.

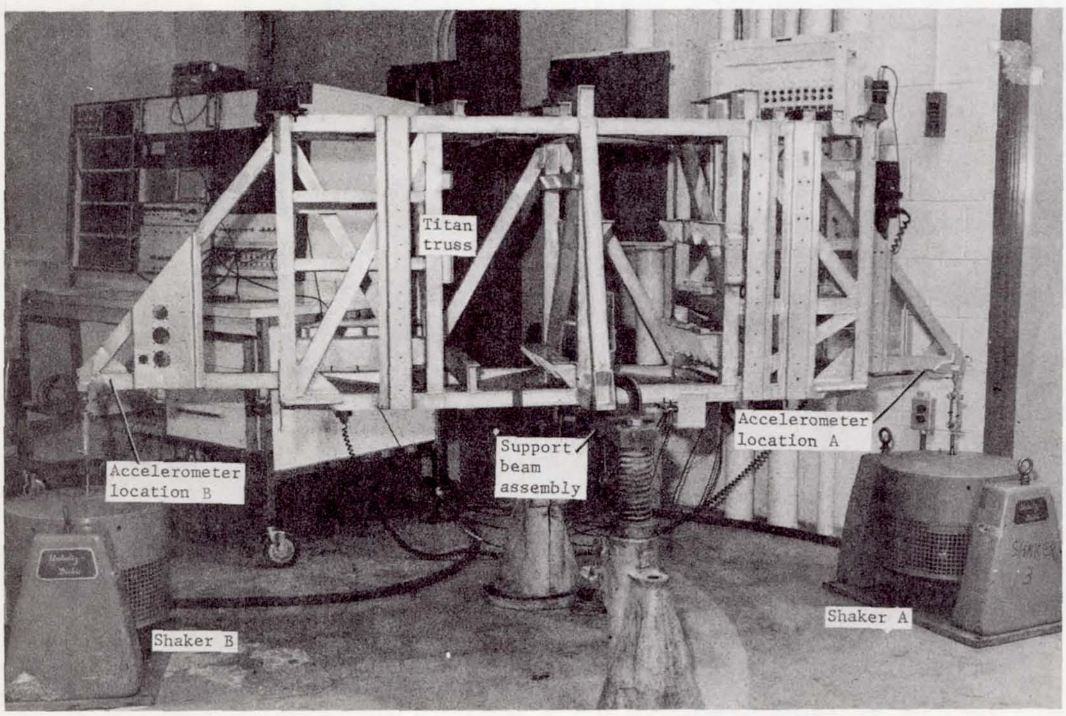

Figure 2. - Demonstration test installation.

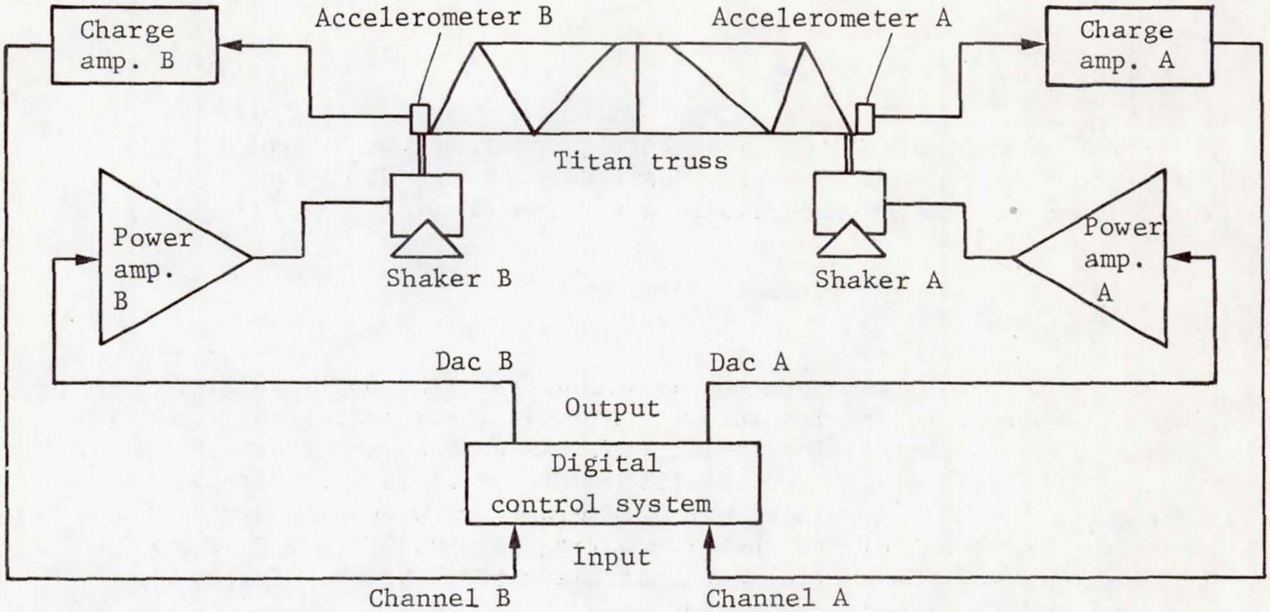

Figure 3. - Control and instrumentation system.

Test condition 1. - The desired transient to be generated at points A and B was defined as a decaying 15-Hz sinusoid with a damping ratio of 0.2. The specified time history and measured responses at points A and B are shown in Figures 4, 5 and 6. Figures 7 and 8 show a direct comparison of the specified and measured response transients.

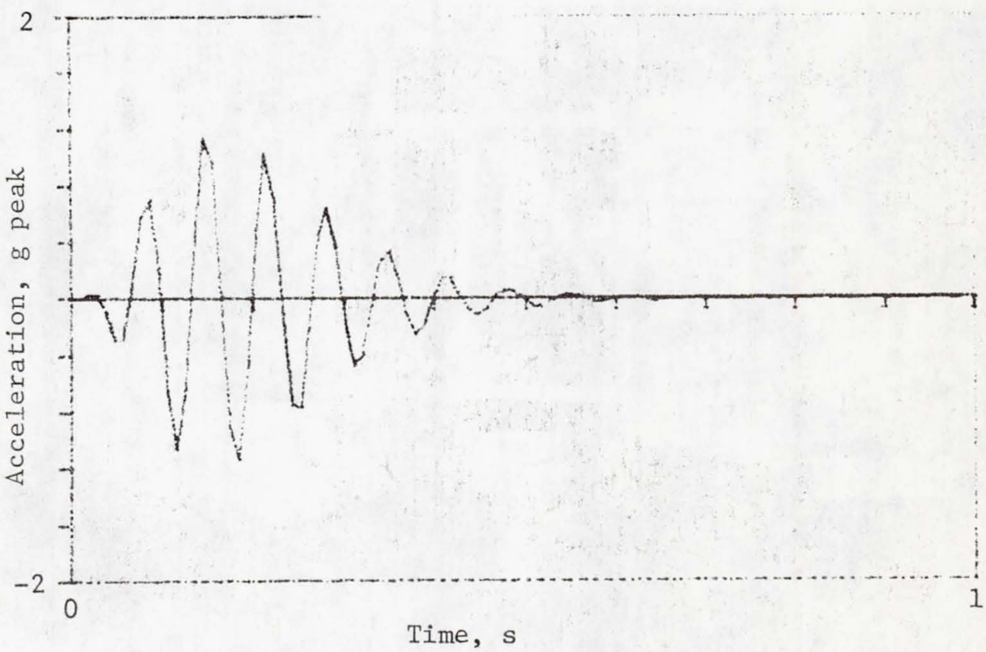

Figure 4. - Specified transient at locations A and B--test condition 1.

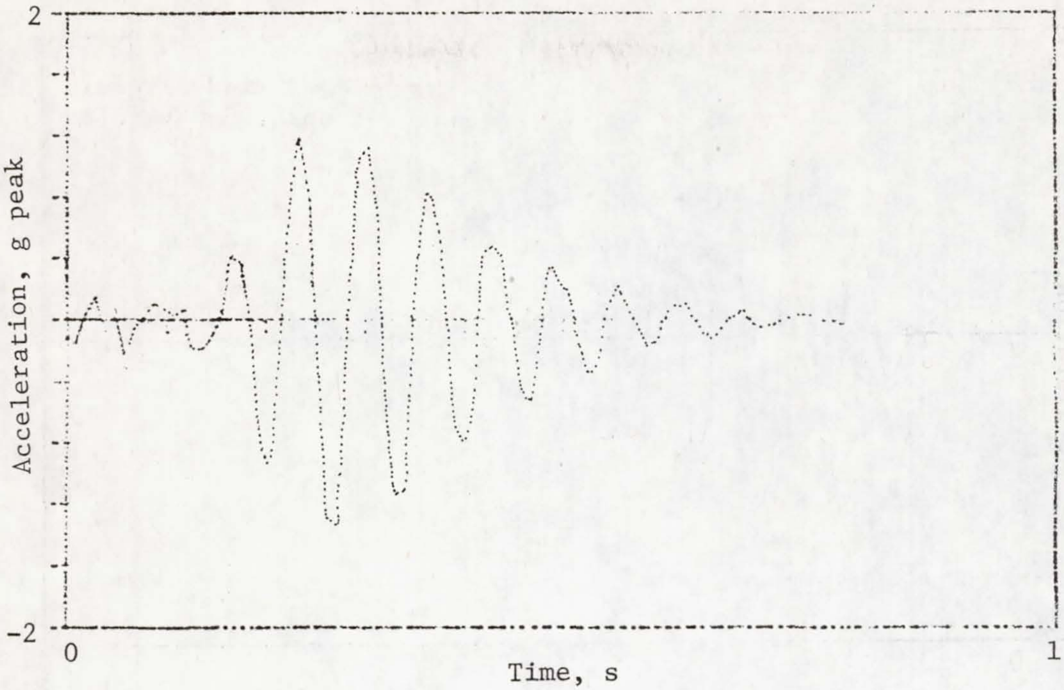

Figure 5. - Measured transient at location A--test condition 1.

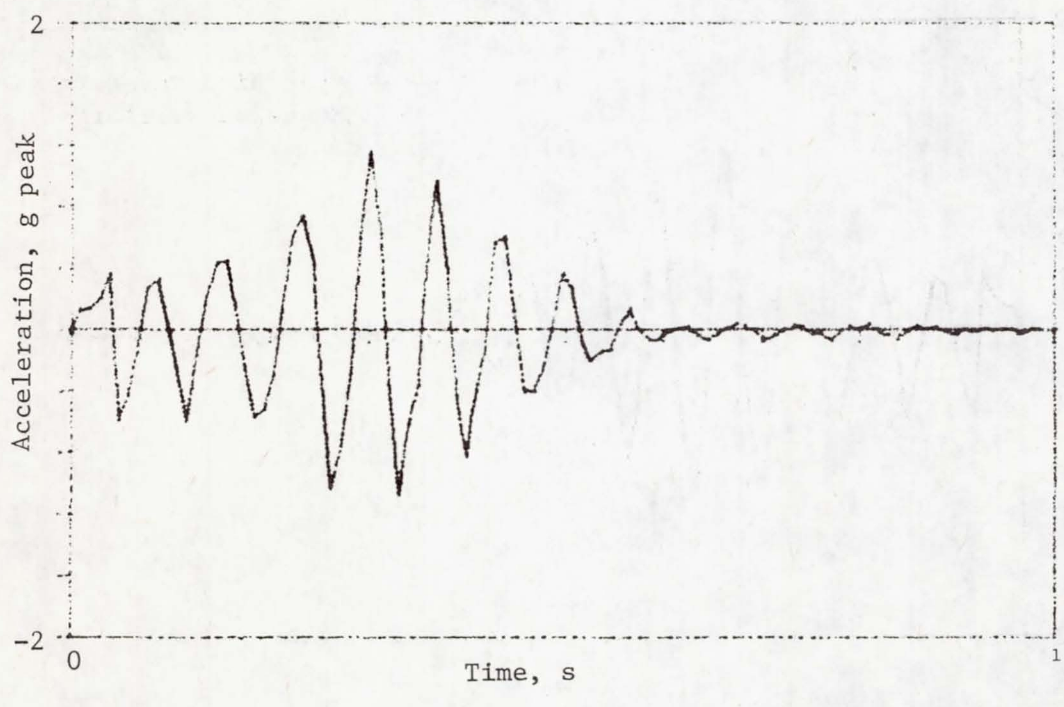

Figure 6. - Measured transient at location B--test condition 1.

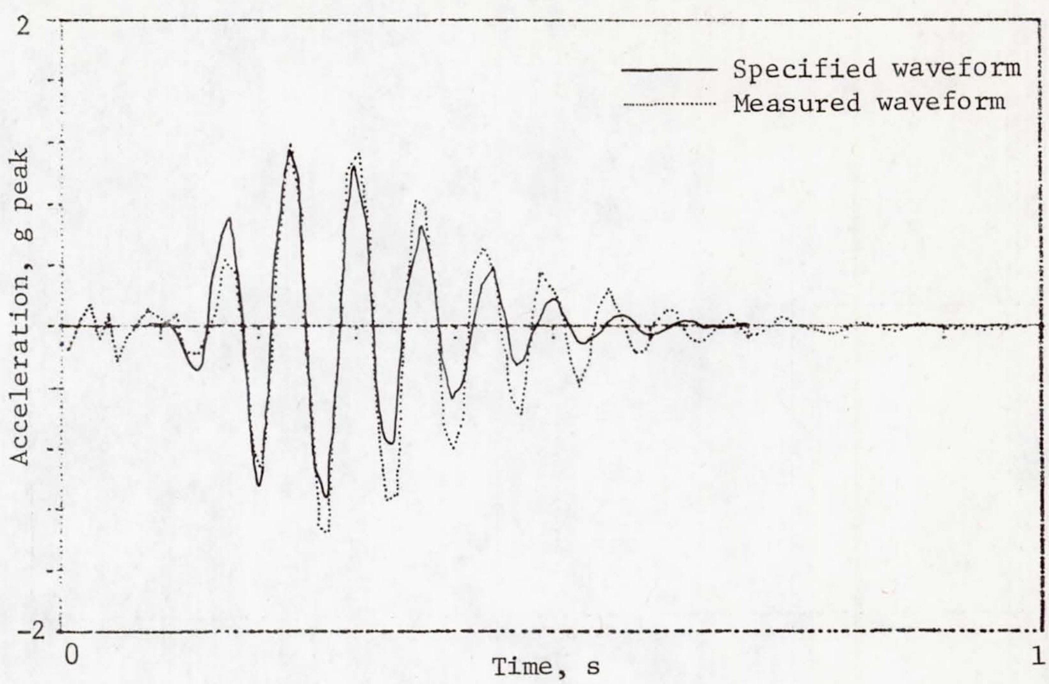

Figure 7. - Comparison of measured and specified waveforms at location A--test condition 1.

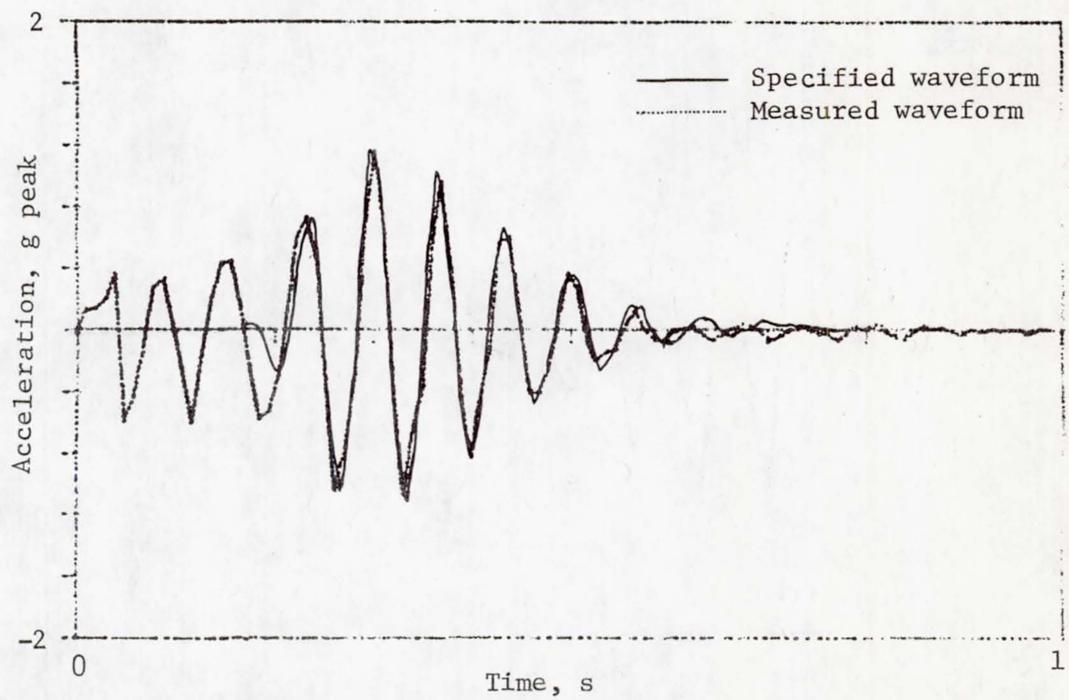

Figure 8. - Comparison of measured and specified waveforms at location B--test condition 1.

Test condition 2. For this case, different transient inputs were applied at the two shaker locations. At location A, the amplitude of the desired waveform was approximately twice the amplitude specified for shaker location B. Comparisons of the measured and specified waveforms at locations A and B are shown in Figures 9 and 10, respectively. For this case, the amplitude of the measured waveform was lower than that specified at location A, whereas the response at B was significantly greater than desired. In fact, the difference between the two is much less than the specified factor of two. However, the wave shapes appear to be satisfactory.

Test condition 3. - For this final test case, shaker B was rotated 90° such that the input was in the truss lateral axis. The desired waveforms were 30 Hz decaying sinusoids with a damping ratio of 0.2. The amplitude at location B was approximately twice that at location A. The specified waveforms are shown in Figures 11 and 12. Comparisons of the specified and measured time histories are presented in Figures 13 and 14. For this case, the amplitudes of the measured transients were significantly lower than those specified. However, the frequency contents of the transients were essentially the same as those specified as shown by the comparison of typical Fourier transforms presented in Figure 15.

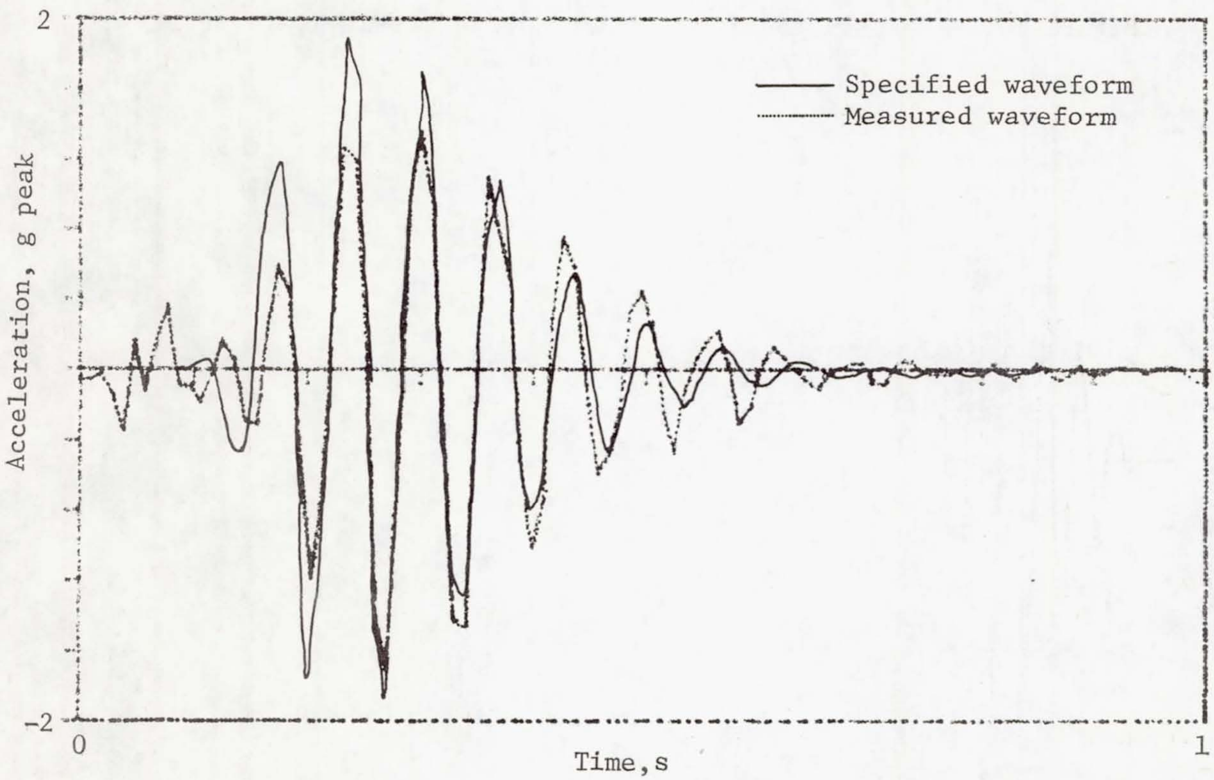

Figure 9. - Comparison of measured and specified waveform at location A--test condition 2.

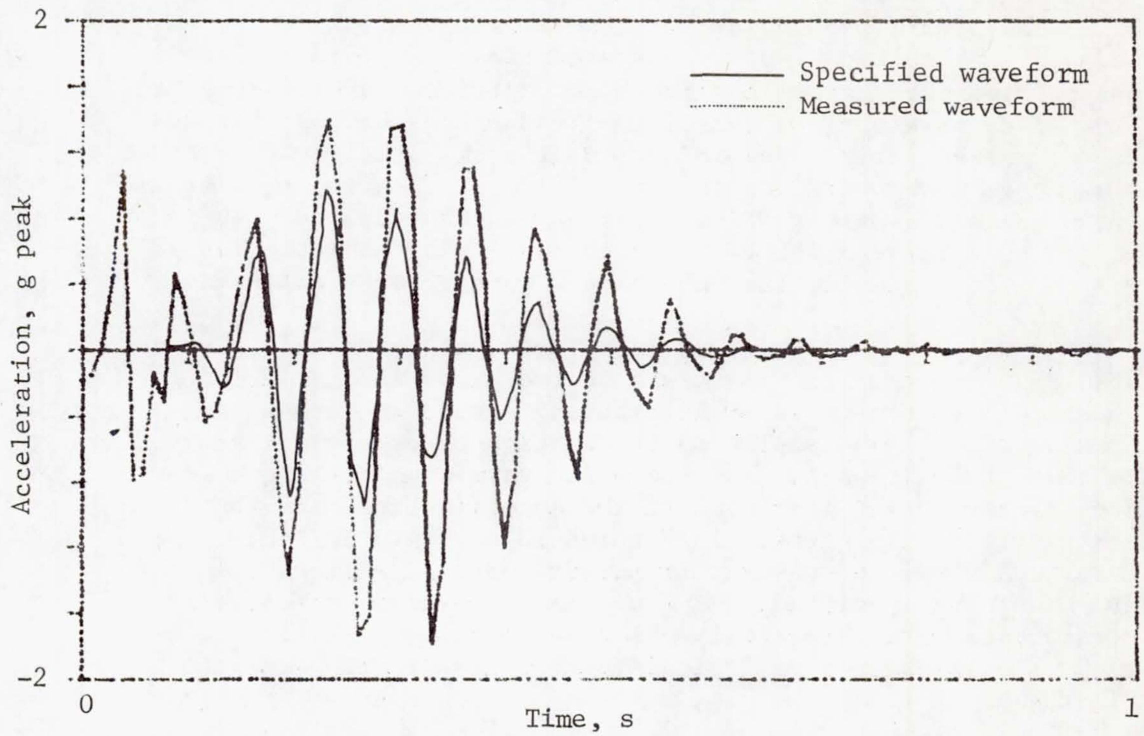

Figure 10. - Comparison of measured and specified waveforms at location B--test condition 2.

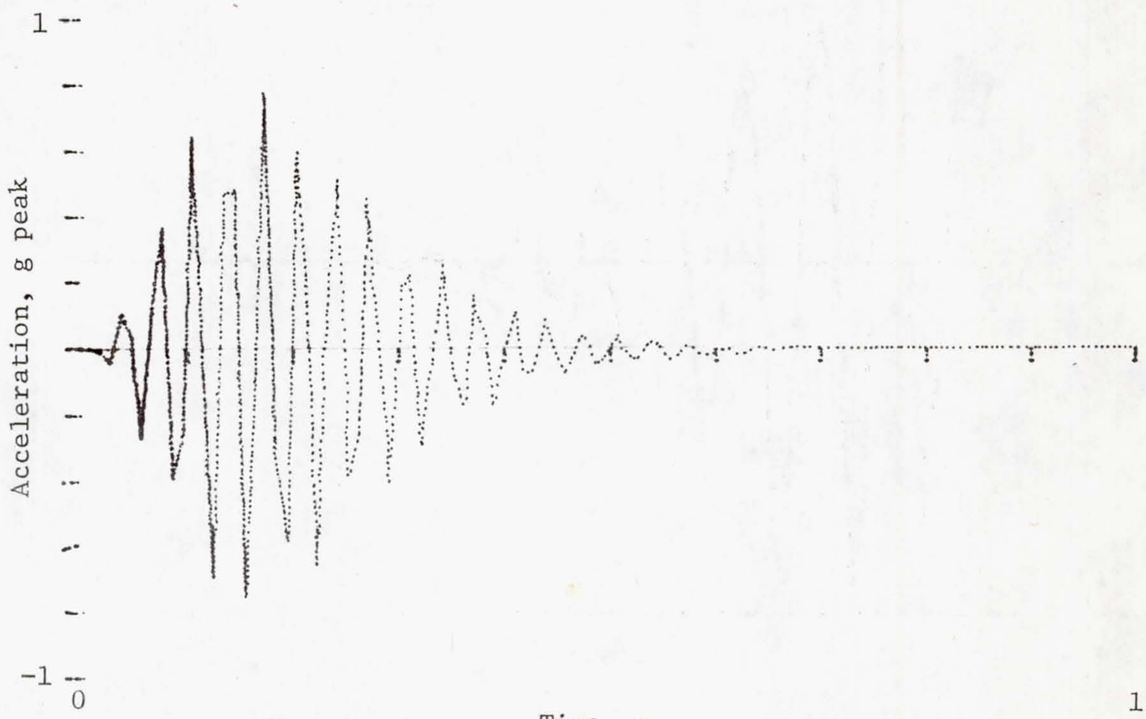

Figure 11. - Specified transient at location A--test condition 3.

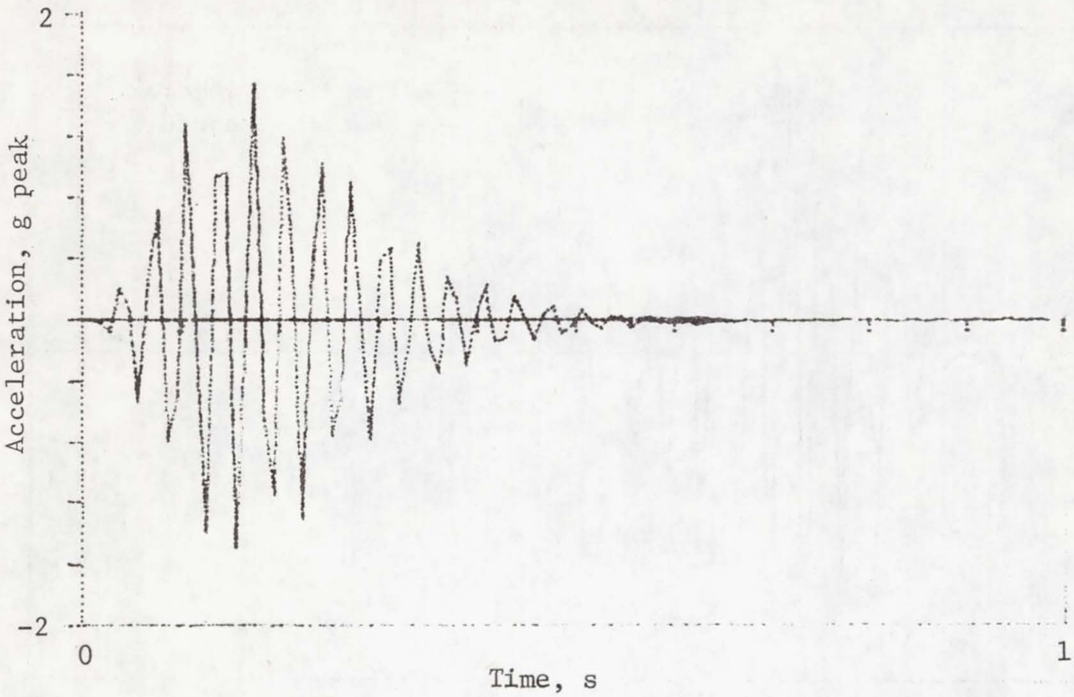

Figure 12. - Specified transient at location B--test condition 3.

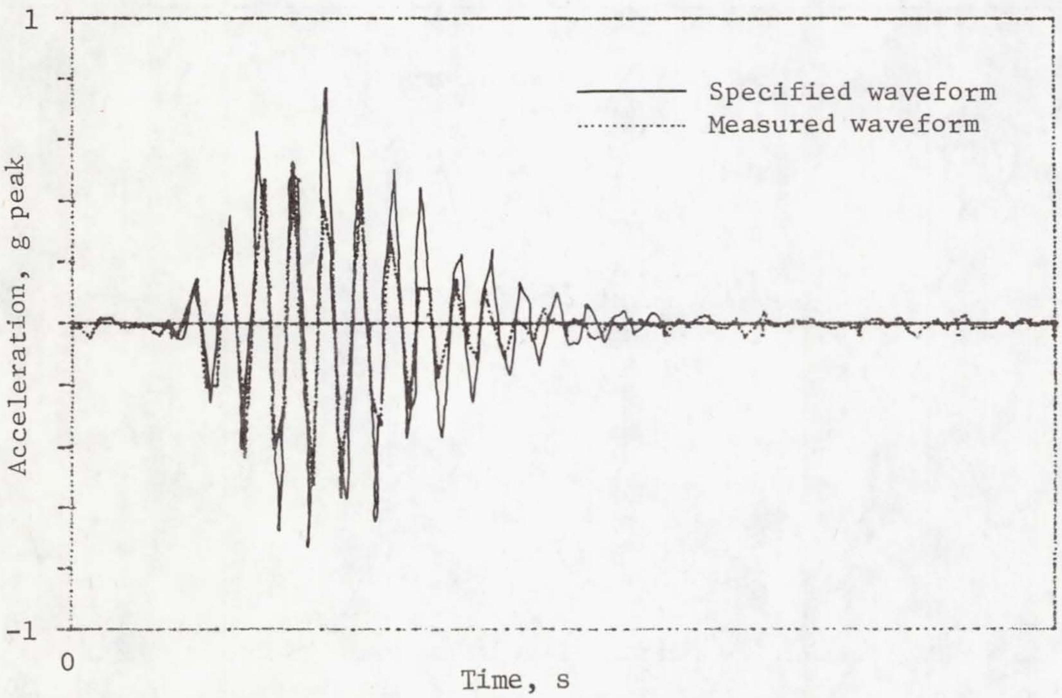

Figure 13. - Comparison of measure and specified waveforms at location A--test condition 3.

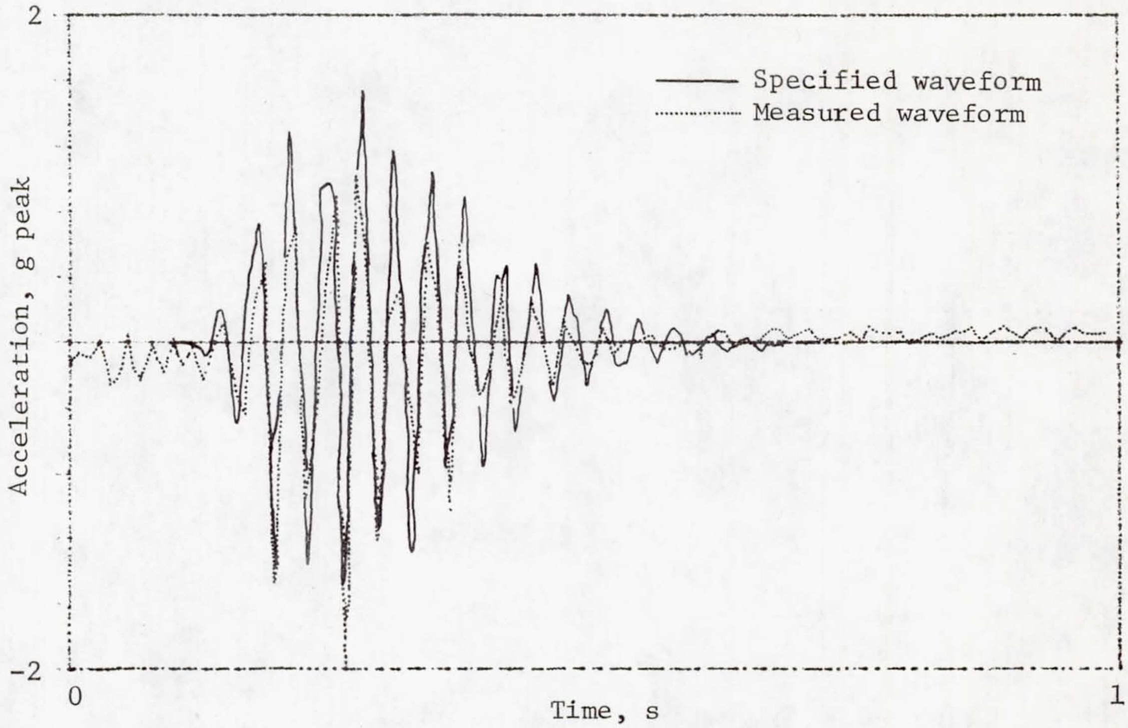

Figure 14. - Comparison of measured and specified waveforms at location B--test condition 1.

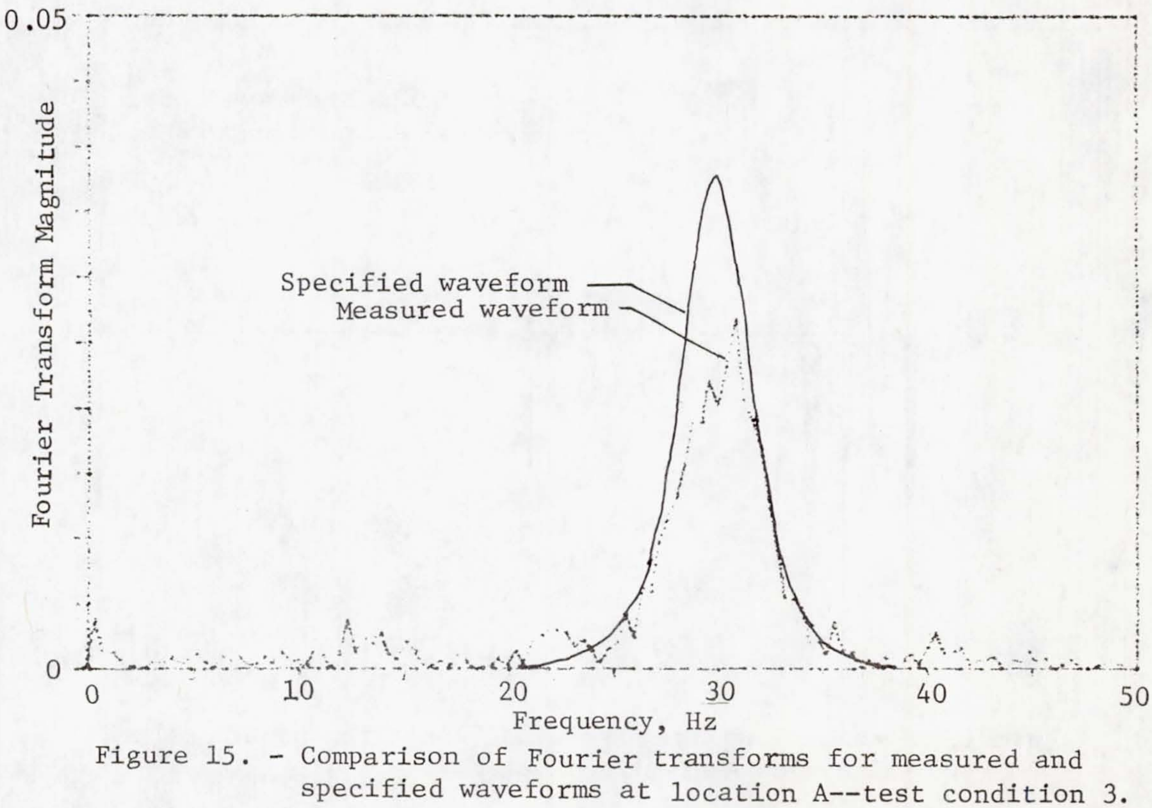

Figure 15. - Comparison of Fourier transforms for measured and specified waveforms at location A--test condition 3.

Discussion of results. - The test series demonstrated that the technique of controlling multiple shakers to specified transients is feasible. The accuracy of control, particularly with respect to amplitude, was not as good as desired; however, the results were encouraging when the limitations of the control system are considered.

The control system computer has only 24 000 words of memory. This limited the resolution to 128 lines over the 50-Hz bandwidth, equivalent to approximately 0.4 Hz. The effect is evident in a number of the transients, where peaks appear to be truncated.

The quality of the results is dependent upon the accuracy of the calculated transfer functions. In this study, an iteration scheme was devised to converge the actual response to the desired response. However, the limited core storage prohibited its implementation. The desired response can be characterized as follows

$$\underbrace{\begin{Bmatrix} YDA \\ YDB \end{Bmatrix}_{j\omega}}_{\text{Desired Response}} = \underbrace{\begin{Bmatrix} YA \\ YB \end{Bmatrix}_{j\omega}}_{\text{Actual Response}} + \underbrace{\begin{Bmatrix} EA \\ EB \end{Bmatrix}_{j\omega}}_{\text{Error Term}} \qquad (11)$$

To compensate for the error in response, the input to the structure (XRA, XRB) must be adjusted as follows

$$\underbrace{\begin{Bmatrix} XRA \\ XRB \end{Bmatrix}_{j\omega}}_{\text{New}} = \underbrace{\begin{Bmatrix} XRA \\ XRB \end{Bmatrix}_{j\omega}}_{\text{Old}} - \left[TF\right]^{-1}_{j\omega} \begin{Bmatrix} EA \\ EB \end{Bmatrix}_{j\omega} \qquad (12)$$

It is believed that this technique can be applied iteratively to achieve a high degree of accuracy.

Application to Large Payloads

The Space Shuttle System (STS) will accommodate a large variety of payload configurations. To evaluate the feasibility of applying this technique to large payloads, particularly with regard to costs, it is necessary to establish some ground rules and assumptions. The technique will be applied to a typical cradle-mounted payload (Figure 16) requiring nine channels of shaker systems and control. Two shakers at each of four orbiter attachment points will provide vertical and longitudinal excitation; a single shaker at the keel fitting is required to produce side loads.

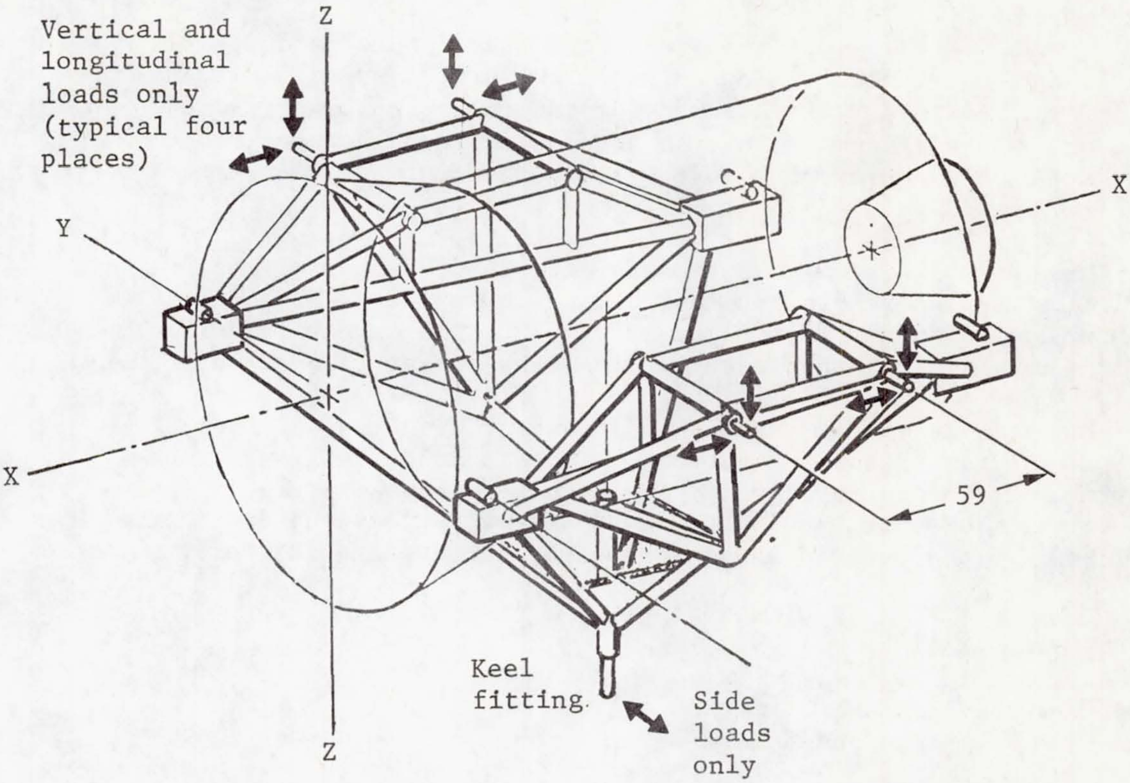

Figure 16.-Sketch of typical cradle-mounted payload.

The computer choice and software development will require provision for establishing and inverting a 9x9 transfer function matrix to calculate the required output waveforms.

The control system hardware requirements have been based on modifications to current systems employing minicomputers to control vibration exciters in the laboratory. The system requires a minimum of two input channels and nine output channels, and both disk and digital magnetic tape for storage of data required for transfer function calculations and synthesis of forcing functions.

Facility requirements include the vibration exciters, power amplifiers, and fixture/suspension system. Under the ground rules and assumption stated, either electrodynamic or hydraulic shakers could be used. The cost estimate is based on the use of electrodynamic exciter systems.

The major cost elements of developing and implementing the technique on large payloads are shown on the next page.

Development and checkout of software	$30 000
Control system hardware	$150 000
Design and fabrication of fixture and suspension system	$20 000
Electrodynamic shakers and power amplifiers (nine at approximately $100 000 each)	$900 000
	$1 100 000

The major cost item is the shaker systems. The cost could be: (1) significantly reduced by using electrohydraulic systems, or (2) eliminated by a laboratory already equipped with adequate shaker systems.

CONCLUSIONS

A computer program has been developed that provides the capability to control multiple vibration exciters to specified waveforms simulating mission events. A series of tests was also conducted to demonstrate the technique on a complex truss structure. It should be recognized that the response of a structure to a given transient event is a function of the dynamic characteristics of the structure; therefore, not every analytically generated desired response is necessarily attainable. The results of this study indicate that "physically realizable" transients can be achieved with the methods presented here.

The technique can be applied to large payloads provided the control syst em includes sufficient computer memory and data storage capability to handle the large matrix inversion routines and provide sufficient resolution to accurately define the transfer functions and synthesized waveforms. An iterative technique has been described that could provide a significant improvement in accuracy compared to the results of the demonstration tests presented. Currently available control systems, which include disc and magnetic tape data storage capability, provide the capability to implement the technique for large payloads.

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