ALTERNATE APPROACHES TO VIBRATION AND SHOCK ANALYSIS USING NASTRAN

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ABSTRACT

In analyzing sinusoidal steady-state vibration of structures, the NASTRAN (NASA Structural Analysis) program provides Rigid Formats 8 and 11 for direct and modal frequency and random response solutions. The dynamic solution of the sinusoidal steady state vibration problem usually requires very large memory core allocations and very long computational time. Our experience of analyzing the Proteus system structures revealed an alternate solution set composed of modifying the eigenvector output of normal modes analysis, resulting in significant cost savings. This paper gives a step-by-step approach for the use of this alternate algorithm to the sinusoidal steady-state vibration problem.

The paper then deals with a method that derives an approximate equivalent static load to a base excitation shock analysis. The transient analysis in the current level of NASTRAN, level 16, does not directly provide for either input acceleration forcing functions or enforced boundary displacement. In the suggested alternate analysis format, equivalent force input functions are applied to the constrained locations by using the artifice of placing a large mass, with respect to the total system mass, at the desired acceleration input points. This shortcut static analysis approach is presented to approximate the expensive and time-consuming dynamics analysis approach to the base-excitation shock analysis.

Each of these methods has proved to be a reliable mechanical design guide and has correlated closely with empirical results.

INTRODUCTION

As the Environmental Design Analysis group at IBM's Federal Systems Division (FSD), Owego, NY, facility, our primary function is to guide the mechanical design of FSD hardware during concept and development phases. Vibration and shock requirements associated with these products are often quite severe, as illustrated in figures 1a, 1b, 1c, and 1d.

Structural analysis in support of the mechanical design of electronics equipment is necessary to ensure compliance with the dynamic environmental requirements. Initially, the harmonic and random vibration excitation formats, as well as direct and modal transient shock capability of NASTRAN, have been exercised to validate structural design. As the designs progress, many changes are incurred due to customer request, product improvement, compatibility with

fabrication techniques, and results of analysis, each requiring analytical evaluation. In general, these changes must be assessed quickly and accurately and must result in minimum effect on cost and schedule. Because of long turn-around time and long computation time associated with the rigid formats we have been using, we began a study for an alternate, more efficient algorithm for this solution phase.

The two methods resulting from this investigation for representing structural deformations and stresses under the influence of vibration and shock environments are discussed under the headings "Vibration Stress Analysis" and "Shock Stress Analysis."

<div align="center">VIBRATION STRESS ANALYSIS</div>

The following steps give the structural analyst a simplified shortcut in determining maximum stresses in structural members during sinusoidal steady-state vibration at resonant frequency. This approach foregoes the direct or modal frequency and random response analysis, Rigid Format 8 or 11, respectively, which requires very large memory core allocations and very long computation time, and uses normal modes analysis, Rigid Format 3, and static analysis, Rigid Format 1, with an appropriate ALTER package given in the presentation:

1) First, run a normal modes analysis (Rigid Format 3) to determine fundamental strutural resonances in three principal directions.

    a) Specify MAX in the NORM field of the EIGR continuation card. This normalizes maximum structural displacement for use in conjunction with the ALTER package given below.

    b) Use CHKPNT YES in the Executive Control deck to checkpoint all the necessary data and to recover the data in restart. This step will result in significant savings when used with the ALTER package or to calculate additional vibratory modes.

2) To restart the checkpointed run to determine structural deformation and vibration stresses at resonance, the following items have to be specified:

    a) Specify a maximum structural displacement at the structural resonance, (δ). This can be estimated from the following relationship for a single-degree-of-freedom system.

$$\delta = \frac{386.1 \times G \times Q}{4\pi^2 \times f^2}$$

where

δ = single amplitude of response of structure (inches)

G = input steady state sinusoidal peak acceleration

Q = transmissibility at resonance

f = structural natural frequency

In the above relationship, it is assumed that G is a known quantity, and f has been determined in the NASTRAN analysis using Rigid Format 3. The transmissibility at resonance may be determined from test data of a prototype or similar structure. If this data is not available, however, experience has shown that a range of $0.05 \leq C/Cr \leq 0.10$ is typical of three-dimensional frame structures of standard construction. Figure 2 illustrates the interrelationship between structural damping and amplification factor at resonance.

b) Insert the following ALTER package* in the NASTRAN Executive Control deck, which scales all output, and which includes structural deformations and stresses. (For Level 16)

```
ALTER       108, 108
SDR1        USET,,PHIA,,,GO,GM,,KFS,,/
            PHIGG,QG/C,N,1/C,N,REIG $
ADD         PHIGG,/PHIG/C,Y,ALPHA=(1.Ø.Ø.Ø)/
            C,Y,BETA = (Ø.Ø,Ø.Ø) $
ADD         QGG,/QG/C,Y,ALPHA=(1.Ø.Ø.Ø)/
            C,Y,BETA=)Ø.Ø,Ø.Ø) $
ENDALTER
```

c) In conjuction with the ALTER package, the user would also have to specify the value of ALPHA on a PARAM card in the BULK DATA deck. This value of ALPHA corresponds to the maximum structural response, δ, calculated in the step 2a) of the procedure.

Example of this procedure follows:
Input vibration level = 2 g peak sinusoidal
Natural frequency of structure = 68 Hz
Transmissibility of structure = 10

$$\delta = \frac{386.1 \times G \times Q}{4\pi^2 \times f^2} = \frac{386.1 \times 2 \times 10}{4 \times (3.14)^2 \times (68)^2} = 0.042 \text{ inch}$$

Specifying in the BULK DATA deck

PARAM	ALPHA	Ø.Ø42	Ø.Ø		

will result in linear scaling of all the output data blocks by a factor of Ø.Ø42. Obviously, because of the assumptions used, this method is restricted to linear analysis only.

Note: If the user were interested in a RESTART capability, DMAP statement 109 should also be altered to checkpoint data block PHIGG as well as PHIG and QG in the Rigid Format 1.

The NASTRAN program provides two rigid formats for analyzing shock excitation problems. The transient analysis capability in the current level of NASTRAN, level 16, however, does not directly provide for input acceleration-forcing functions or enforced boundary displacement. To overcome this deficiency in the program, modifications* had to be made to use the program for our specific application of base shock excitation of structures.

The following modifications were necessary to use Rigid Format 9 (Direct Transient):

1) Modify the math model as follows:

   a) Place large seismic masses at all boundary points. These large seismic masses at the support points are necessary to reduce the effects of feedback from the structural responses.

   b) Use multipoint constraint (MPC) equations so that all boundary points will move together, allowing motion only in the direction of the shock.

   c) Calculate a forcing function, f(t), which will produce the desired acceleration function on the overall mass, structural mass plus seismic mass, to satisfy the relationship F=ma at different time intervals.

   d) Input the forcing function, f(t), at the boundary points using the DAREA card in the BULK DATA deck.

2) Cold start Rigid Format 9.

The following modifications were necessary to use the Rigid Format 12 (Transient Modal Analysis):

1) Run a normal modes analysis, Rigid Format 3, (we suggest using the Inverse Power method) to determine the fundamental structural resonance in each principal direction along which shock pulse is to be applied. Be sure to checkpoint this run. In this run, seismic masses should not be attached to the boundary points in the math model.

2) Modify the math model as follows:

   a) Place large seismic masses at all boundary points; approximately 10^5 times the structural mass.

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    b)   Use MPC equations for all the boundary points to allow the boundary points to move only in the direction of the shock.

    c)   Calculate a forcing function in the same manner as in using Rigid Format 9.

    d)   Input the forcing function at the boundary points; these are structural attachment points either at the base or bulkhead of aircraft, shipboard, submarine, or other test fixture frames.

3)   Restart Rigid Format 12 using the structural resonance data obtained in Rigid Format 3,

    a)   Bound the resonance of interest by using the PARAM LFREQ and PARAM HFREQ cards in the BULK DATA deck; the smaller the bandwidth, the more rapid the computation time. To minimize convergence time, specify the same frequency range on the EIGR card as specified on the preceding PARAM LFREQ and PARAM HFREQ cards.

        NOTE: In all rigid formats, it is imperative to use a pre-processor program, such as BANDAID or BANDIT to reduce the semi-bandwidth of structural matrices.

The excessive time associated with model preparation and solution to shock analyses using NASTRAN Rigid Formats 9 and 12 reduced their usefulness for the specific application of mechanical design guidance in the earliest phases of design.

The following method has been developed which approximates the effect of the shock pulse on the system through the use of a single-degree-of-freedom idealization, assuming that the fundamental mode parallel to the direction of the pulse is the sole contributor to maximum deformation and corresponding stresses. This method utilizes a combination of Rigid Formats 3 and 1 in place of Rigid Format 9 or 12. Its implementation is described in the following lists:

1)   Perform a natural frequency analysis, Rigid Format 3, using the Inverse Power method to determine the fundamental structural resonance in each plane in which a shock pulse is to be applied. The use of Inverse Power eigenvalue extraction will prove most efficient since only a few of the resonant modes are of interest.

    Note: One can force the program to search for resonant modes in numerically ascending order by specifying ND = small, NE = large (~100xND) in the EIGR card. This will reduce the computation time required to find the lowest natural frequency. It will significantly reduce the possibility of terminating via termination codes 6 or 7 without determining the fundamental mode.

2)   Calculate the dimensionless parameter t_o/T in which

    t_1 = pulse period (seconds) of the shock to be applied

    T = fundamental period of responding structure = $2\pi/\omega$ (seconds)

3) Using the plotted data in figure 3, extracted in part from reference 4, determine $\ddot{x}/A$ (acceleration amplitude magnification factor)

where

A = peak acceleration of input pulse (g)

$\ddot{x}$ = maximum response acceleration of structure (g)

As shown in figure 3, the solution to the equation of motion and its derivatives for the single-degree-of-freedom idealization are dependent on the degree of viscous damping exhibited by the responding system. This value may be determined from test data by examining the transmissibility (Q) at resonance and correlating Q with the damping factor (C/Cr) through the use of graphs specified in reference 2, repeated in figure 2 for illustration. If test data is not available, experience has shown that a value of damping of $0.05 \le C/Cr \le 0.10$ is typical of most three-dimensional framed structures of standard construction.

4) Cold start in Rigid Format 1 specifying a loading, G, through the use of the NASTRAN GRAV card in which

$$G = A \times \frac{\ddot{x}}{A}$$

where

A = peak acceleration of input shock pulse, g

$\dfrac{\ddot{x}}{A}$ = dynamic load factor determined in step 3

CONCLUSIONS

The two methods discussed previously have proved to be a valuable engineering aid during the developmental phase of mechanical designs. They have proved to be more cost- and time-effective than their counterparts in NASTRAN Rigid Formats 9, 10, 11, and 12. Tables 1 and 2 summarize the time and cost comparisons of the various solutions. In addition, the solutions have proved to yield acceptable accuracy as evidenced in tables 3 and 4.

REFERENCES

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2. Application Selection Guide. Barry division of Barry Wright Corporation.

3. C.M. Harris and C.E. Crede: Shock and Vibration Handbook. New York: McGraw Hill, 1961, pp 23-1 through 23-37.

4. Robert R. Luke: The Impact Response of Single-Degree-of-Freedom System with Viscous Damping. University of Texas, Structural Mechanics Research Laboratory, Austin, Texas.

5. NASTRAN User's Manual, NASA SP-222(03). Scientific and Technical Information Office, National Aeronautics and Space Administration, March, 1976.

6. NASTRAN Theoretical Manual, NASA SP-221-(03). Scientific and Technical Information Office, National Aeronautics and Space Administration, March, 1976.

7. NASTRAN Programmers Manual, NASA SP-223(03). Scientific and Technical Information Office, National Aeronautics and Space Administration, March, 1976.

8. Dr. Gordon C. Everstine: The BANDIT Computer Program for the Reduction of Matrix Bandwidth for NASTRAN. Computation and Mathematics Department, Naval Ship Research and Development Center, Bethesda, MD 20034, March, 1972, Report No. 3827.

TABLE 1 - TIME AND COST COMPARISONS OF ALTERNATE SOLUTION METHODS FOR OBTAINING MAXIMUM VIBRATION DISPLACEMENTS AND STRESSES

Unit analyzed	Math model			Solution Method	RF	Unit $	Total $	Norma-lized $	CPU Time (s)	EXCP (I/O operations)
	Grid points	Finite elements	DOF							
Proteus* Analyzer Unit	44	85	228	Modal/freq. random response	3	167.32			480	28,816
					11 (1 subcase)	188.68	356.00	1.0	328	19,128
					11 (3 subcases)	566.00	733.32	1.0	980	57,000
				Alternate method	3	167.32			480	28,816
					1 (1 subcase)	28.48	195.80	0.55	24	8,755
					1 (3 subcases)	85.44	257.76	0.34	72	25,000
Proteus** STM/TACTAS Electronics Rack	165	750	942	Alternate Method	3	242.71			624	32,662
					1 (1 subcase)	23.04	265.75		31	44,760

Notes:
 *All solutions performed on IBM System/360 Model 85; NASTRAN level 15.0.1, with BANDIT preprocessing
**NASTRAN Level 15.5.2, IBM System/370-158.

DOF - degree of freedom
RF   - rigid format
CPU - central processing unit
EXCP - Execute Channel program

TABLE 2. – TIME AND COST COMPARISONS OF ALTERNATE SOLUTION METHODS FOR
OBTAINING MAXIMUM SHOCK DISPLACEMENTS AND STRESSES

Unit analyzed	Grid points	Finite elements	DOF	Solution method	RF	Unit $	Total $	Normalized $	CPU time(s)	EXCP (I/O operations)	Core size (K bytes)
Proteus Anaylzer Unit	45	85	228	Direct transient (3 subcases)	9	267.00	267.00	0.41	288	69,000	500
				Modal transient (3 subcases)	3 12	167.00 480.00	647.00	1.0	480 1251	28,816 91,000	350
				Alternate solution method	3 1	167.00 54.00	221.00	0.34	480 78	28,816 16,500	300
Proteus STM/ TACTAS	165	750	942	Direct transient (3 subcases)	9	531.00	531.00	1.0	1017	103,000	750
				Alternate solution method (3 subcases)	3 1	242.00 46.00	288.00	0.54	624 78	32,662 16,600	750 350

TABLE 3. - RESULTS COMPARISON OF ALTERNATE SOLUTION METHODS
FOR OBTAINING MAXIMUM VIBRATION DISPLACEMENTS AND STRESSES

Unit analyzed	Solution method	Direction	Fundamental natural frequency (Hz)	Maximum peak axial stress (lbf/in^2)
Proteus Analyzer Unit	Modal frequency & random response	X Y Z	66 188 406	10,400** NA NA
	Alternate solution method	X Y Z	66 188 406	13,710 - -
	Engineering development test	X Y Z	72* 190* 420*	NA NA NA

Notes:
  *Variation in test/analytical results attributed to weight discrepancy (50 lb)
   and modified structural configuration
 **Based on 20% damping; 5% damping yielded 40,100 lbf/in^2 maximum stress

TABLE 4. - RESULTS COMPARISON OF ALTERNATE SOLUTION METHODS
FOR OBTAINING MAXIMUM SHOCK DISPLACEMENTS AND STRESSES

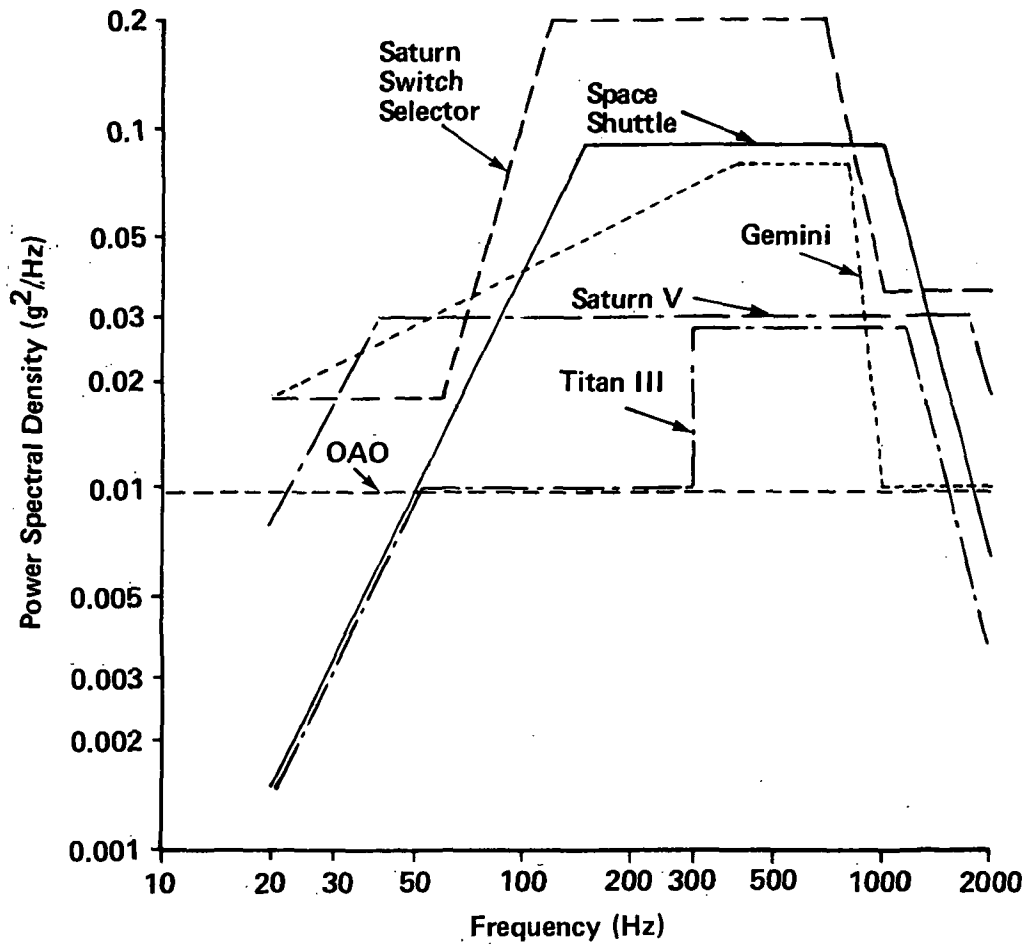| Unit analyzed	Eigenvalue extraction		Shock stress analysis		
	Direction	Natural frequency (Hz)	Loading condition	Solution method	Maximum peak axial stress (lbf/in^2)
Proteus STM/ TACTAS Electronics Rack	- - -	- - -	Navy high impact Medium Weight, inclined, hammer-drop shock test	Direct transient analysis	31,770
	X Y Z	124 70, 125, 146 Not found		Alternate solution method	28,905
	X Y Z	122 70, 124, 146 Not found		Engineering development testing	29,000

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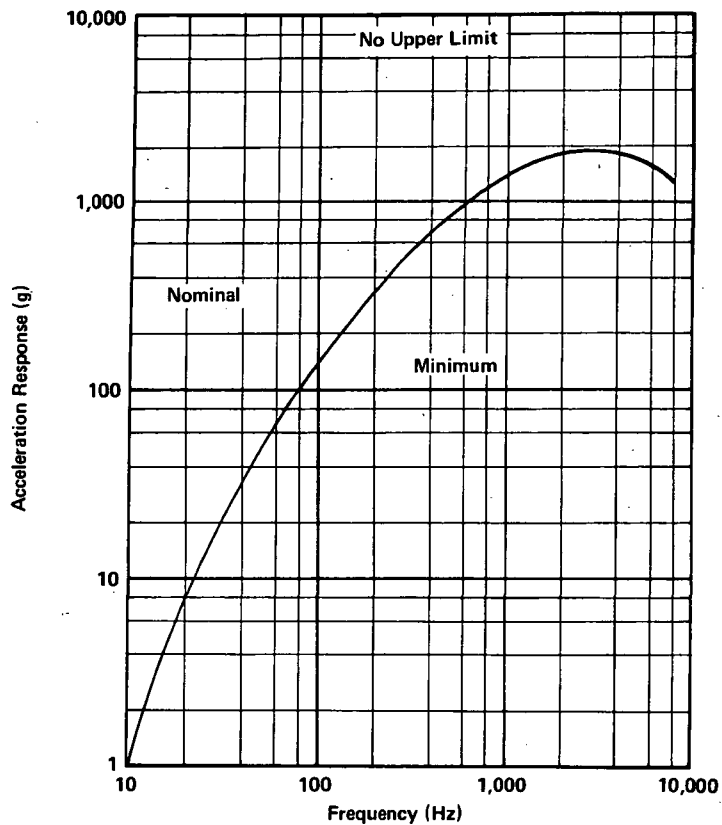Figure 1a. Typical Spacecraft Random Vibration Levels

Figure 1b.   Shock Requirements,
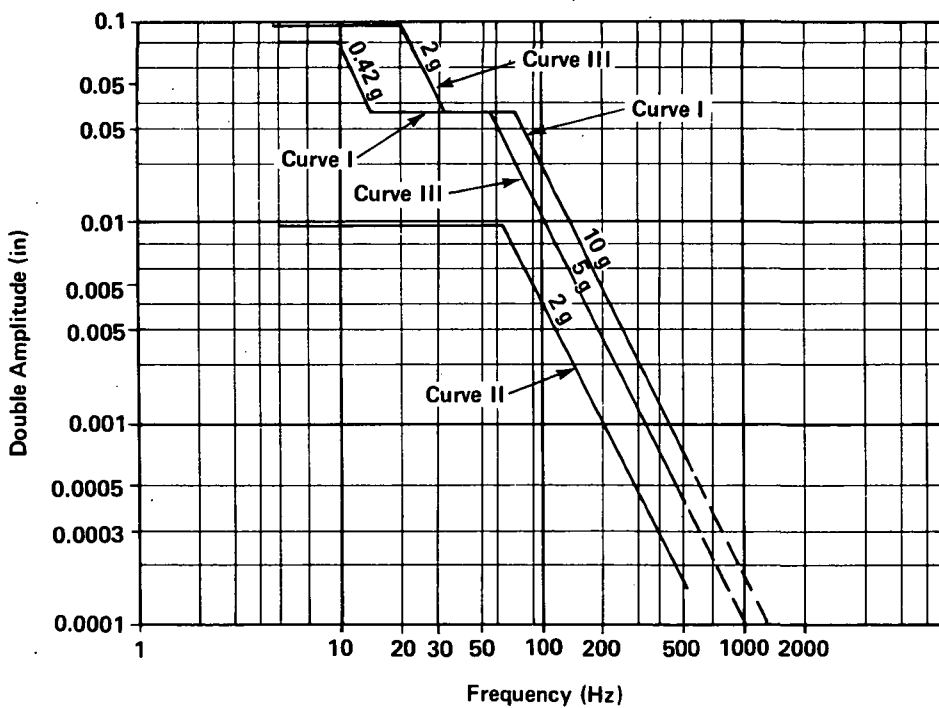Pyrotechnic Shock Spectrum

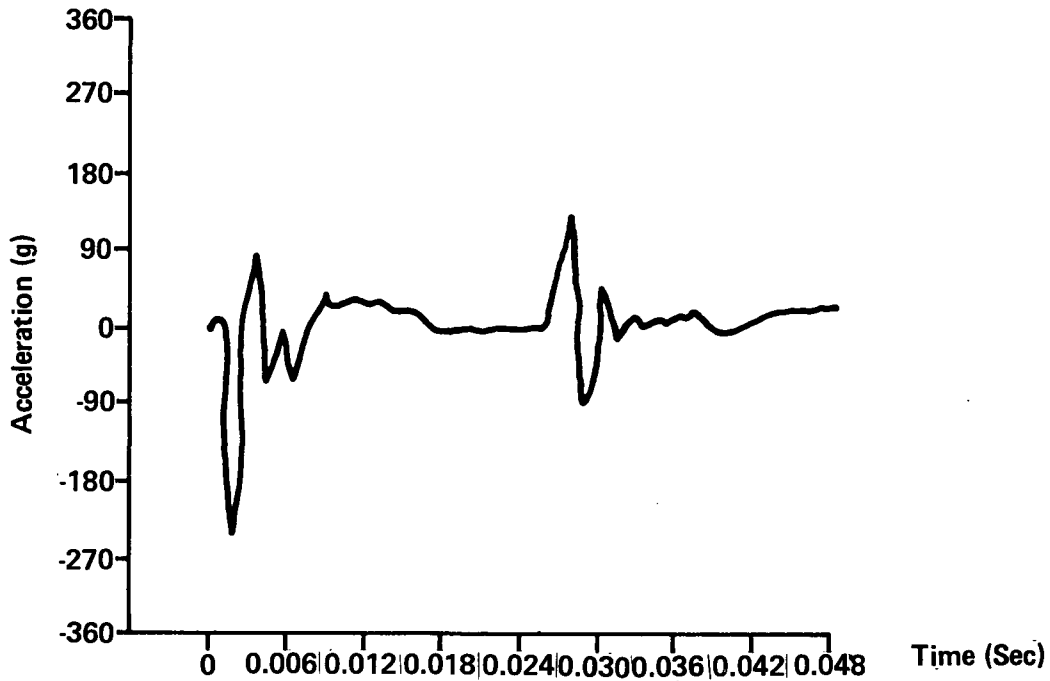Figure 1c.   Typical Aircraft Sinusoidal
Vibration Requirements

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Figure 1d.   Typical Navy Medium-Weight-Hammer-
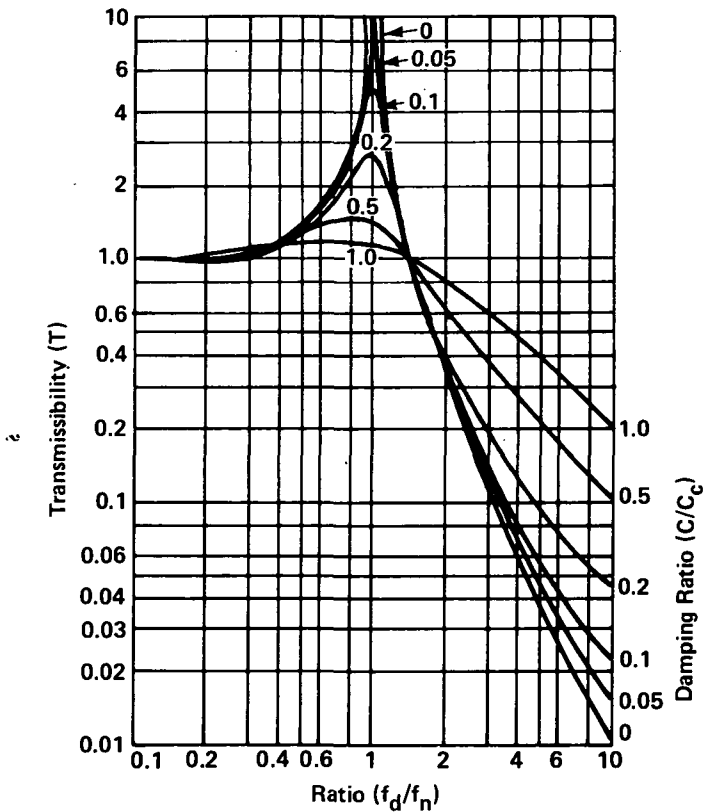Drop Anvil Response

Figure 2.   Family of Transmissibility Curves
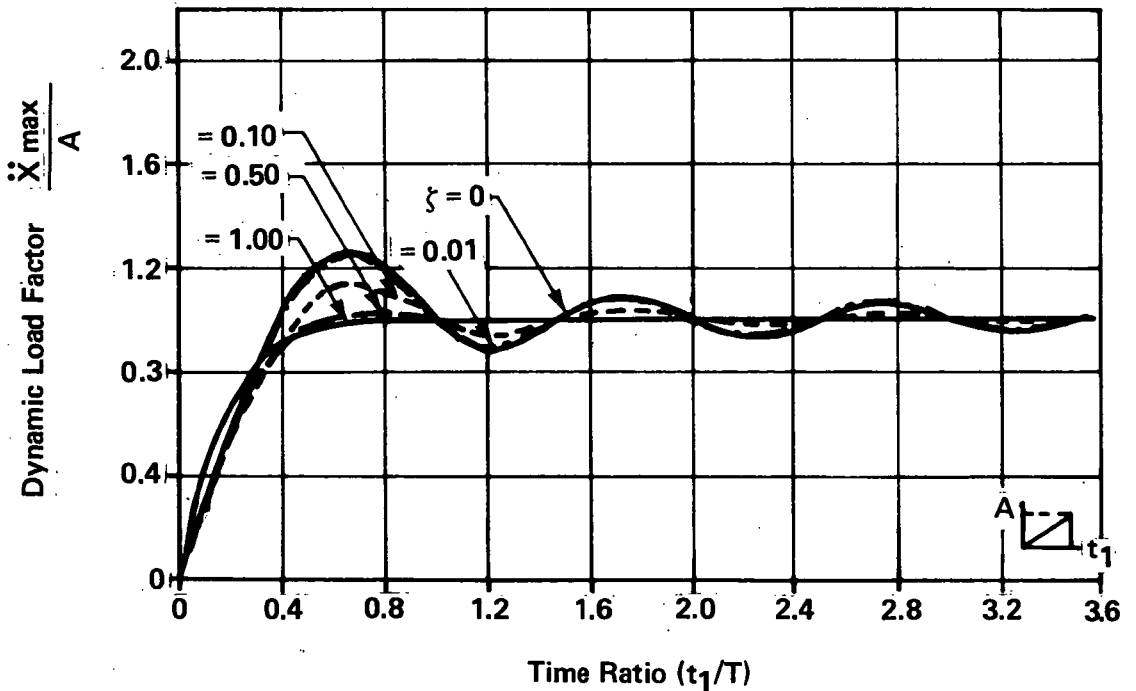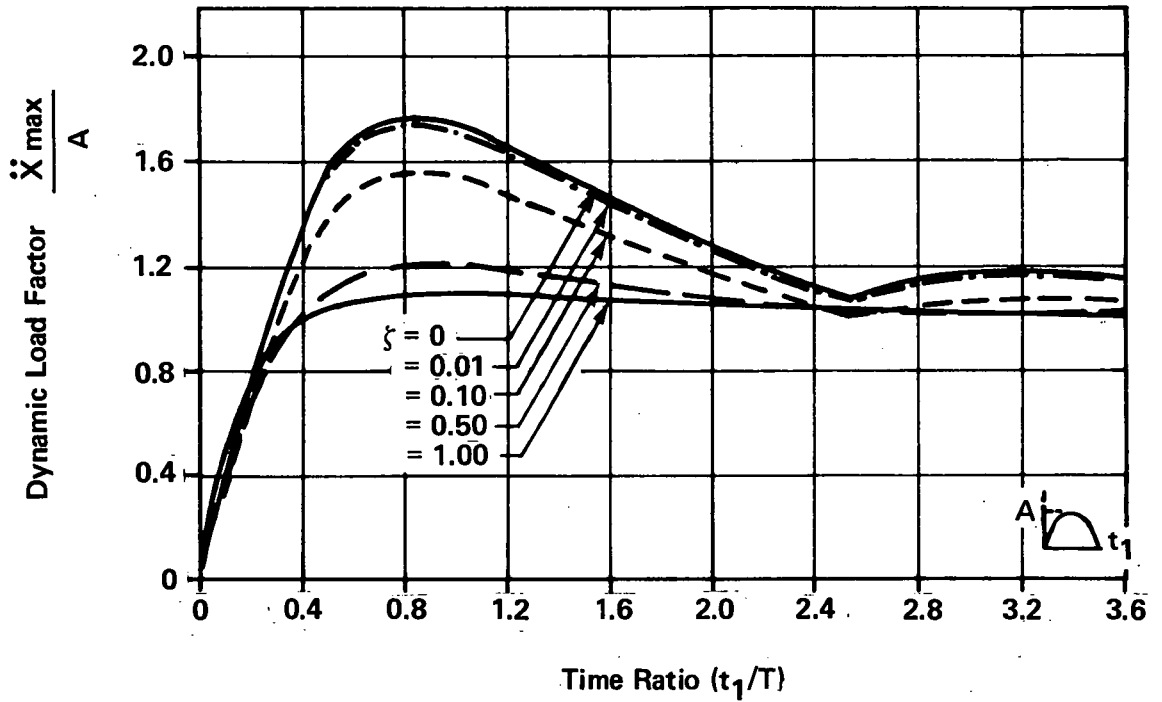for a Single-Degree-of-Freedom System

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Figure 3. Shock Transmissibility Curves for a
Single-Degree-of-Freedom System with Directly Coupled
Viscous Damping Subjected to Sinusoidal and
Terminal-Peak Sawtooth Shock Pulses

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