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Summary Report

Pulse Applications and Parameter Identification for U.S. Navy Medium-Weight Shock Machine

Prepared for

Department of the Navy
Naval Research Laboratory
Washington, D.C.

by

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El Segundo, California

November 1977

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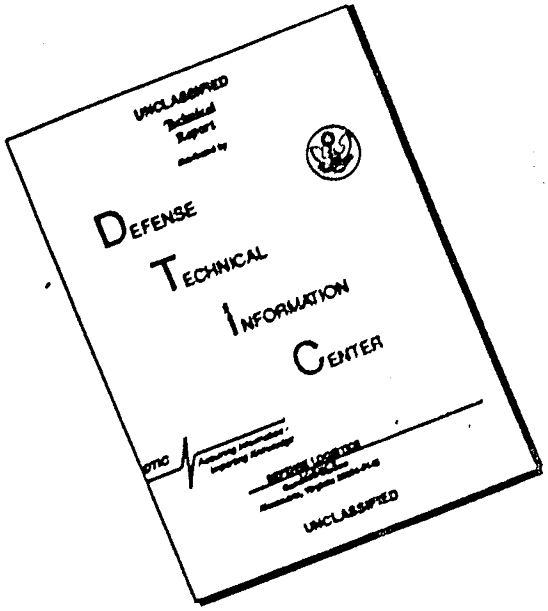

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This report summarizes the results of a study on pulse applications and parameter identification for the U.S. Navy medium-weight shock machine.

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PREFACE

This report presents the results of a study on pulse applications and parameter identification for the U.S. Navy medium-weight shock machine. G.J. O'Hara was project manager for the Naval Research Laboratory. F.B. Safford was principal investigator for Agbabian Associates and was author of this report.

R.O. Belsheim, NRL (now with NKF Engineering) furnished technical information in the loading effects of equipment on structural motions. Professor S.F. Masri, University of Southern California, performed the investigations on parameter identification.

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CONTENTS

ILLUSTRATIONS

ILLUSTRATIONS (CONTINUED)

TABLES

PULSE APPLICATIONS AND PARAMETER IDENTIFICATION FOR U.S. NAVY MEDIUM-WEIGHT SHOCK MACHINE

SECTION 1

INTRODUCTION

1.1 BACKGROUND

The U.S. Navy medium-weight shock machine has played a paramount role over the past 30 years in the hardening of shipboard equipment to shock loads. Shock loading of shipboard equipment originates from depth charges, conventional and nuclear bombs, torpedoes, and missiles. Supplementing the shock machines, shock barges were subsequently placed into service by which equipment mounted in the barges were subjected to underwater detonations.

The combination of the shock test machines and the shock barge has proved singularly effective in the upgrading and qualification of equipment to specified hardness levels in a broad sense. However, rapid changes in naval warfare require more refined test/analyses and continuous improvements thereof. These improvements are necessary to meet the ever-increasing threats caused by technical change, particularly those due to the improving detection and accuracy of offensive weapons systems. Balanced hardness in a naval weapons system is becoming a more critical requirement to enhance survivability and operability, both during and after an attack.

Failures and malfunctions of both equipment and structure closely correlate to threat time-histories. This correlation motivates the continuing need for test simulation ever more closely approximating threat environments. The invention and development of a high-force output mechanical pulse generator (Refs. 1, 2) showed considerable promise in inducing structural motions simulating those motions induced by threats. The use of a mechanical-force pulse generator with the U.S. Navy medium-weight shock machine should extend test machine applications and provide for a more flexible transient shock capability.

Another critical area in need of development is an accurate description of the structural load paths between input threat and the mounting locations of operational and weapons-system equipment. With an adequate

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structural description, the motions at equipment mounting generated by an attack may be predicted and the structural path can be analyzed for methods mitigating shock transmission. Obtaining the appropriate transmitted shock time-histories at the mounting points of equipment permits hardening of the equipment. One of the better and more practical descriptions of the structural load paths is impedance and mobility. The severity of postulated attacks will range from linear into varying degrees of the nonlinear regions such that high-force-level impedance measurements are required. The high-force levels are required for impedance measurements in a quasi-linear sense or for the formation of nonlinear functionals. Electrodynamic shakers are available with high-force outputs, and the mechanical force pulse generator discussed in the previous paragraph may also be used.

Impedance measurements may be used to extract the normal modes, damping, and resonant frequencies of a structure. Another approach to handling impedance measurements is the conversion from their nonparametric form to parametric form. In this latter procedure, parameters are identified for each structural path measured, and represent a coupled and distributed system. Representation of impedance in parametric form provides additional opportunities for design changes or modifications for shock transmission mitigation.

1.2 SCOPE

The scope of this study covers the following two objectives:

- Provide the design for a mechanical-force pulse generator, specify associated hydraulic power unit and controls, and provide pulse-train profiles and mandrels; and The force-pulse system will be designed for use with the U.S. Navy medium-weight shock machines and for use in measurements of impedance.

- Perform an exploratory parametric identification study of U.S. Navy medium-weight shock machine, test article, and impact loads using NRL-furnished data. Determine equivalent system model and associated parameters.

SECTION 2

MECHANICAL FORCE-PULSE GENERATOR

2.1 REQUIREMENTS

Transient shock tests on equipment and systems to simulate the motions induced by a conventional explosive or nuclear attack are largely limited to single-axis test machines. Further limitations exist in the size and weight of equipment that can be tested. Simulating multiaxis loading on large equipment with many degrees of freedom represents a difficult problem, as it is impractical to generate continuously varying forces of sufficient magnitude. This problem becomes extremely difficult or impossible where in-place or field tests are required. On the other hand, short duration forces of large magnitudes over a wide frequency range can be generated by mechanical pulse generators. Since a discrete number of pulses superficially presents an appearance quite different from a continuous excitation signal, it becomes necessary to select the pulses in such a way that the resulting vibration of the structure matches as closely as possible the response (e.g., displacement, velocity, or acceleration) produced by the continuous force, as determined by an appropriate error criterion. This approach is shown in Figure 1.

It is important to note that the method of Figure 1 requires that the criterion response to the continuous input be known, which generally would not be true in practice. To accomplish this objective, the approach proposed here assumes that: (1) a mathematical model or impedance measurements of the system under study are known and (2) the inputs of interest (e.g., explosive or nuclear blast) are given. Under these conditions the "criterion response" can be calculated and used to obtain the pulse train for the simulated test.

In general, the response-time history of a test article under simulated test should show a reasonable approximation to the expected environmental phenomena for meaningful hardness/vulnerability evaluation. To accomplish

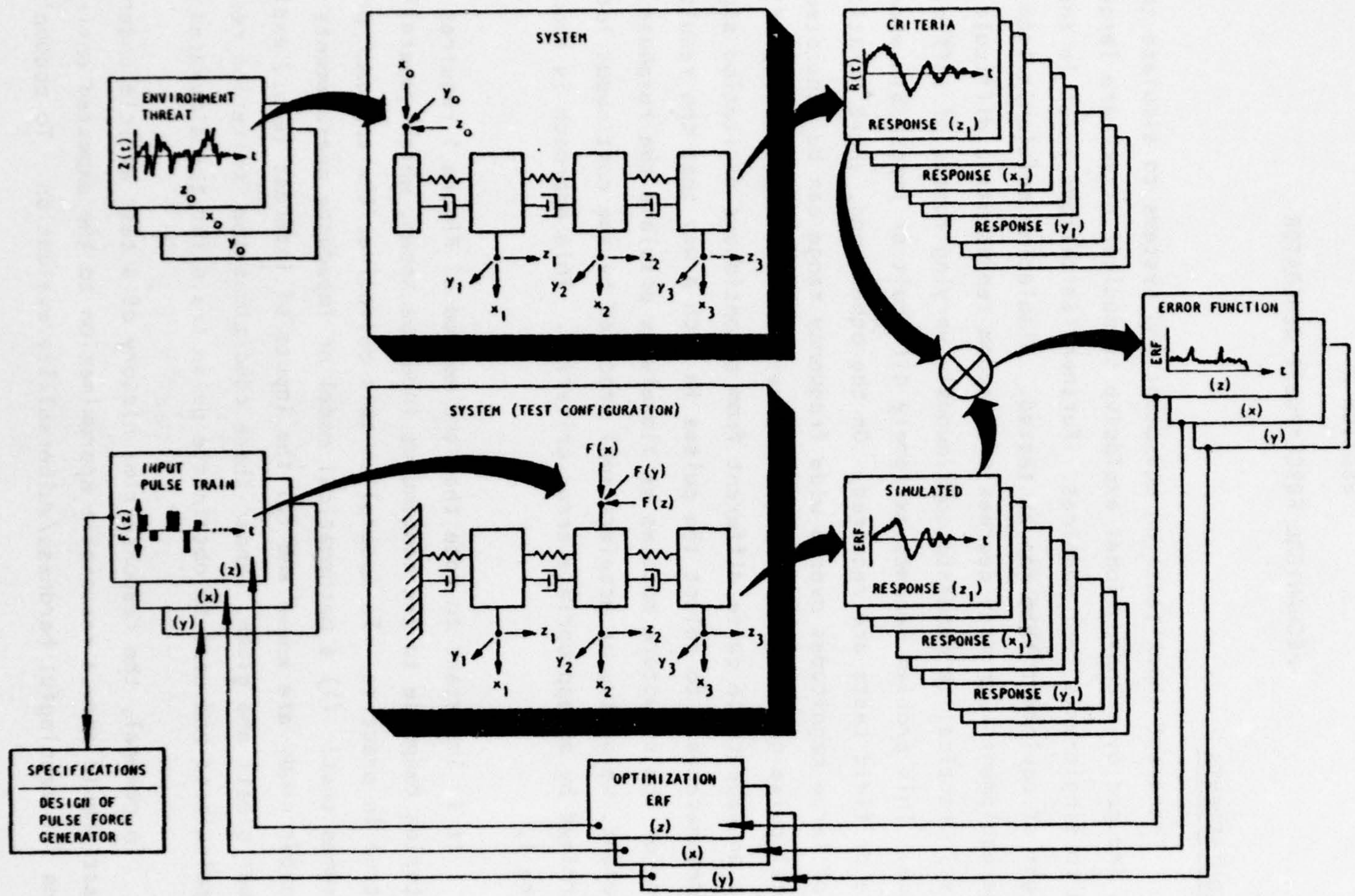


Fig. 1 — Optimum response simulation of multidegree systems by pulse excitation

the desired response motion, a computer algorithm is used for the optimum selection of a finite number of pulse heights, duration, and onset times to accomplish this objective.

The basic criterion used is the integral squared error between the reference and simulated response, evaluated at a sufficient number of points within the system under test to characterize it as completely as possible. Given the error criterion, the pulse occurrence times, pulse widths, and the pulse amplitudes are selected by a systematic search algorithm such that the error is minimized.

Application of the pulse generator for impedance measurements requires a different form of the pulse train. Use of the pulse generator in this manner requires a sufficiently long pulse train duration (T) to provide the required frequency resolution ($f = \frac{1}{T}$) and force levels sufficient to provide favorable signal-to-noise ratios over the frequency range of interest. Generally, configuration of the pulse train is optimized to generate an approximately flat Fourier magnitude spectrum. Studies have also shown that diagnostic pulse trains can be generated that approximate (in a transient sense) sine wave bursts, chirp, and random effects. Both chirp and random are particularly useful in developing functionals for nonlinear systems.

The pulse generator inherently possesses several desirable features for transient load application with large systems when tested in place and/or in the field. These features include:

- High force output
- Wide frequency band from static
- Portability
- Ganged operations
- Design simplicity
- Reliability

2.2 PRINCIPLE OF OPERATION

The concept of a mechanical pulse generator simply turns a device for energy absorption around to obtain the desired force profiles as a useful output (Ref. 3). By drawing a metal bar or mandrel through a cutting tool (or vice versa) with suitable motive power (air pressure, hydraulic pressure, explosive force, electric, mechanical), a series or a set of force-time histories may be generated. Reaction at the attach point of the device transmits a force output to a test article. Figure 2 illustrates the device with motive power for operation supplied by the stored energy in a pneumatic cylinder. Figure 3 is an example of a force-pulse time history as output from the device. The device may be started or stopped by a variety of devices.

Forces may be generated singly and in series as for one cutting head or in parallel with multiple cutting heads. A single large cutting tool may be used if economic. Cutting of metal may be groove cuts, i.e., the work is wider than the tool width; or single cut, i.e., the tool is wider than the work. The cutting tool may have a wide variety of shapes to suit the force waveform output requirement needed. Large forces may be generated from this device and the force required to cut metal is largely independent of rate (velocity). The force is a function of volume of chips cut (depth, width, and length of cut) and the specific energy of cutting. The energy absorbed in metal cutting is given by (Ref. 3)

$$Fl = lwt\mu \qquad (1)$$

where

F = Force of cutting, lb
l = Length of cut, in.
w = Width of cut, in.
t = Depth of cut, in.
μ = Specific energy of cutting, in-lb/cu in.

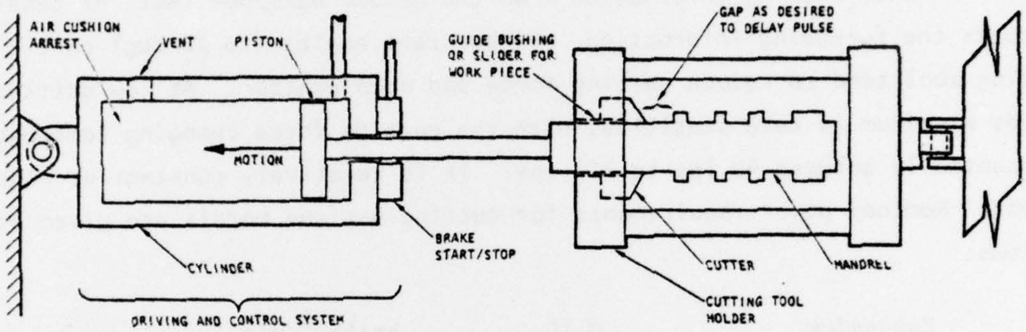


Fig. 2 — Pulse-forming device with driving and control system

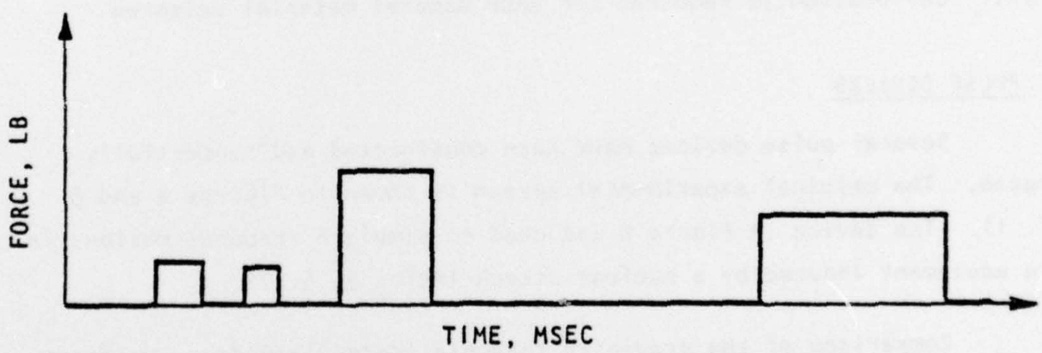


Fig. 3 — Force time-history output of device (typical)

The values of specific energy of cutting for mild steel and aluminum are 3×10^5 in.-lb/cu in. and 1.5×10^5 in.-lb/cu in., respectively. A load cell or strain gage may be incorporated in series with the device to provide force-time history readout as the device is operated.

Metal-cutting information from the *Metals Handbook* (Ref. 4) generally supports the foregoing information. Higher rake angles (to 20 deg) on the cutting tool tend to reduce cutting force and data scatter. At low cutting speeds aluminum is rate sensitive, with the cutting force changing somewhat exponentially between 40 ips to 100 ips. It is relatively constant at higher speeds. Nominal power requirements for cutting various metals are given as follows:

Magnesium	0.10	hp/in.^{3}/min
Aluminum	0.15	hp/in.^{3}/min
Copper alloys	0.25	hp/in.^{3}/min
Steels	0.80	hp/in.^{3}/min

These values may change considerably with hardness and alloy content. Calibration is required for each mandrel material selected.

2.3 PULSE DEVICES

Several pulse devices have been constructed and successfully operated. The original experimental system is shown in Figures 4 and 5 (Ref. 1). The device in Figure 6 was used to simulate response motions in large equipment induced by a nuclear attack (Refs. 5, 6, 7).

Comparison of the predicted response (determined from impedance measurements), pulse-simulated response, and measured response are provided in Figure 7. This same pulse generator, which was also used to measure transfer impedances (Ref. 8), has a nominal output force capacity to 10,000 lb. Another version in the form of drop shock tower is pictured in Figure 8 and output data is given in Figure 9. Figure 9 data are from a reinforced-concrete protective structure, flush buried to ground surface

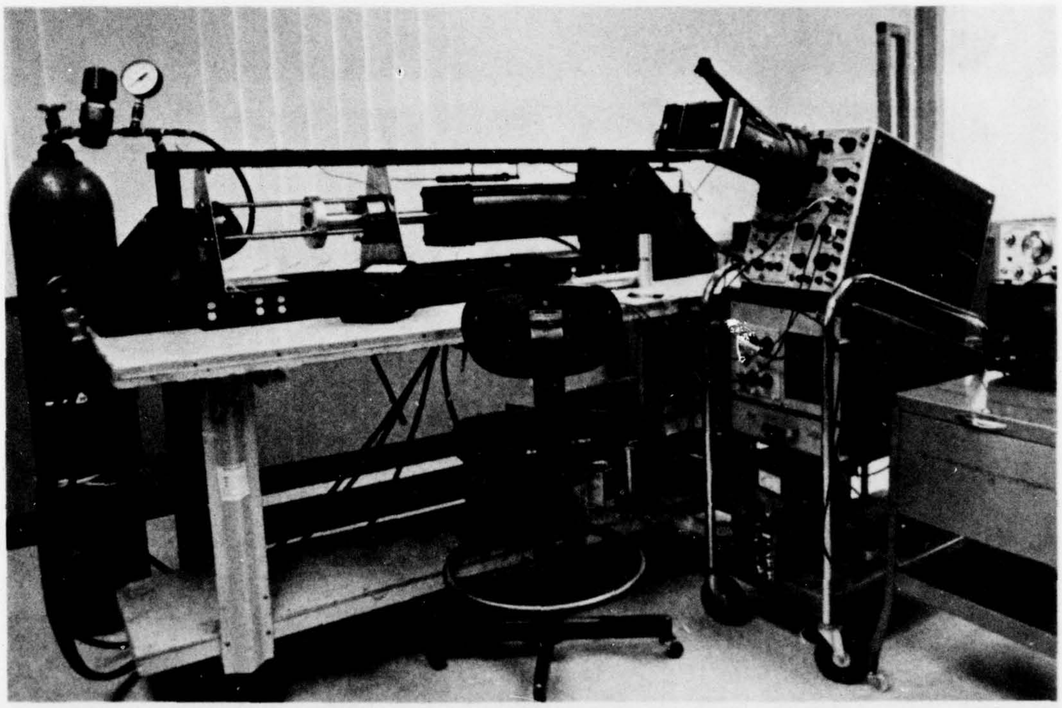


Fig. 4 — Experimental test for mechanical pulse generator

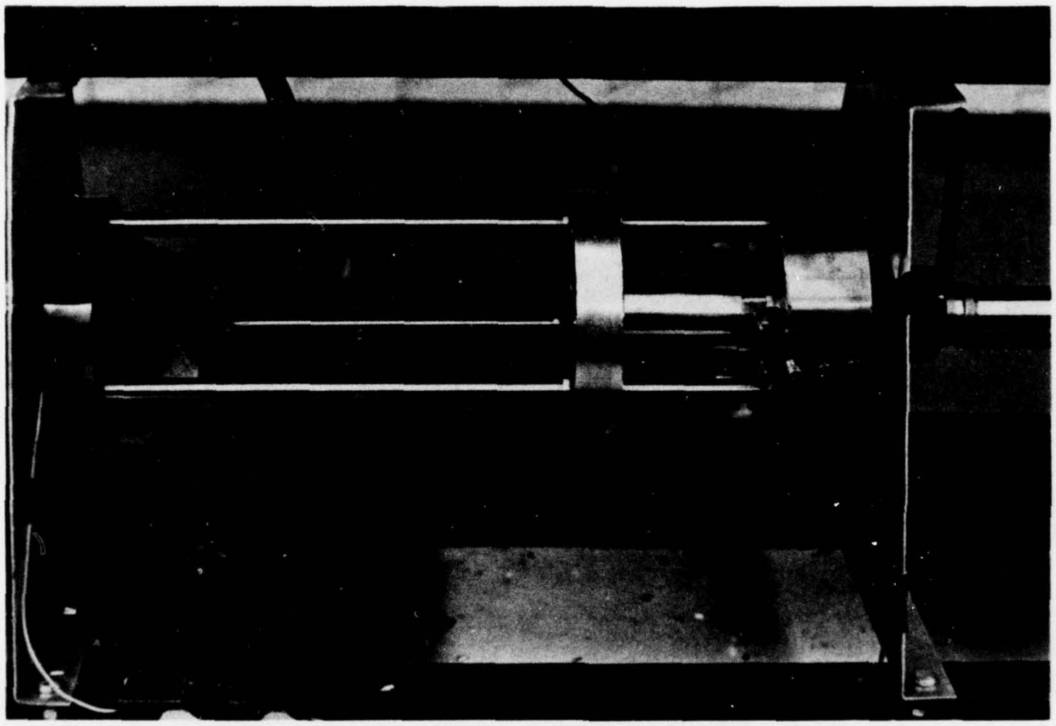


Fig. 5 — Cutting fixture with mandrel tool holder, right; bearing guide plate on mandrel, center; and output plate, left

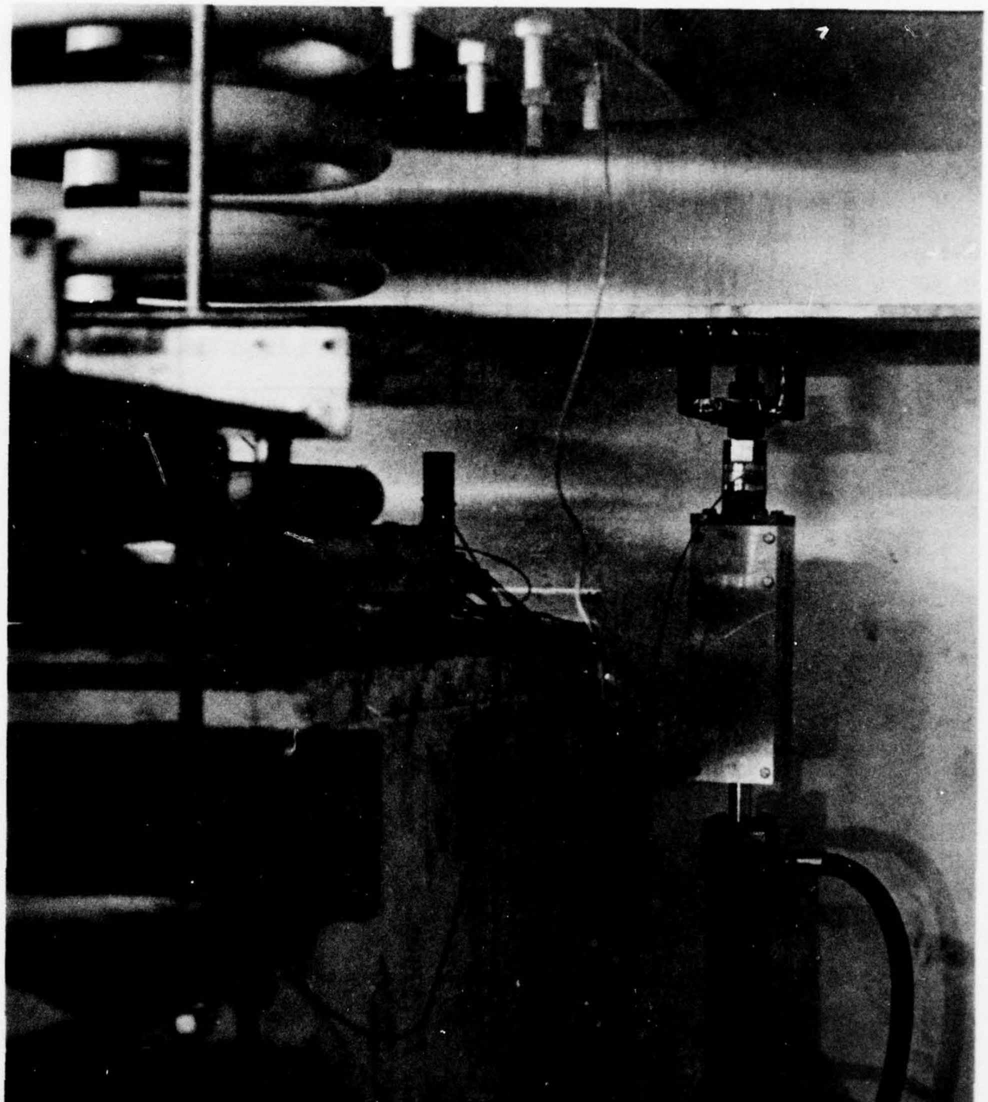


Fig. 6 — Pulse-test configuration for control room platform showing one of four units required

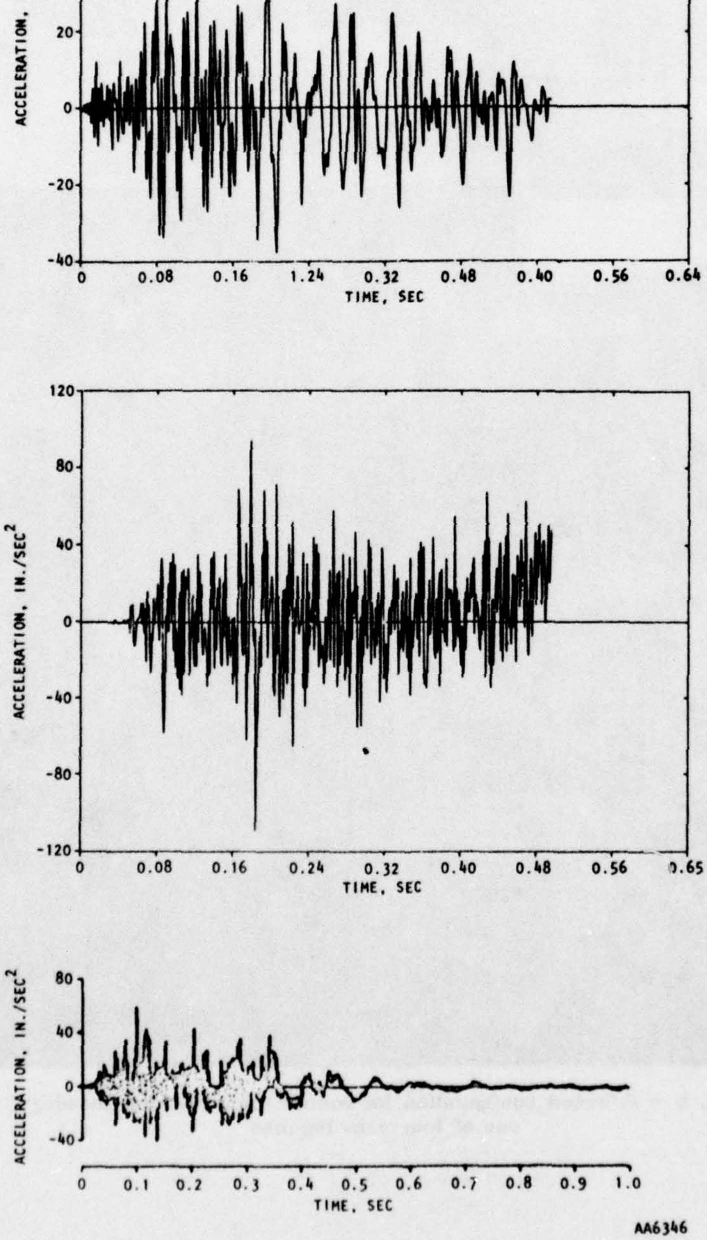


Fig. 7 — Control room platform: acceleration-time histories of predicted, pulse-simulated, and pulse-tested motions

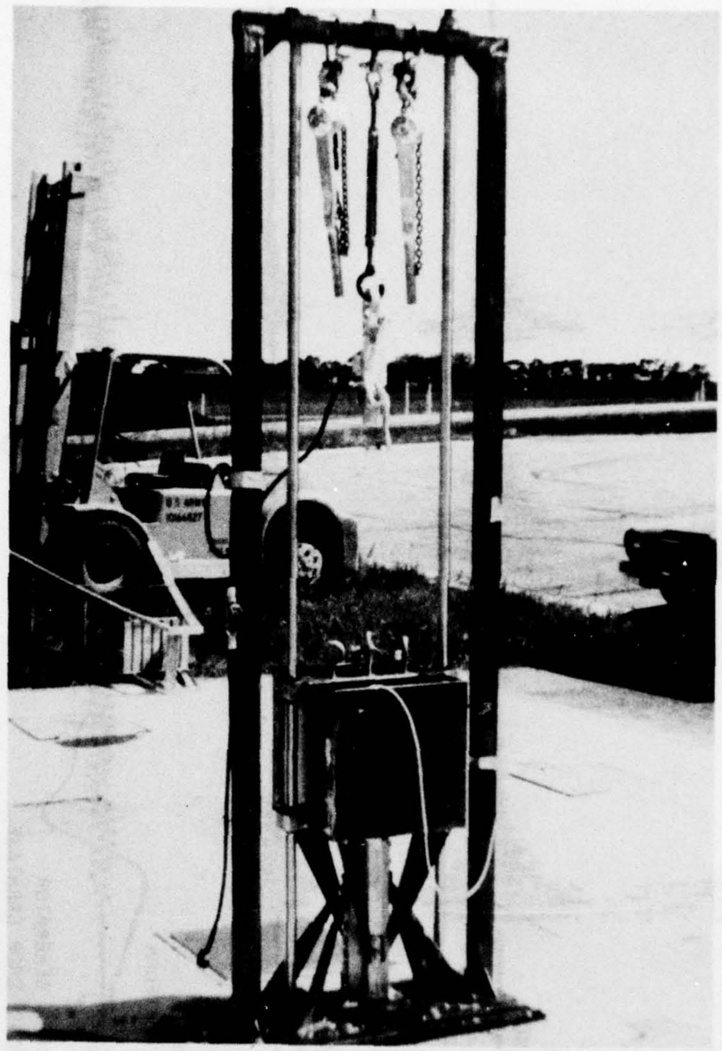


Fig. 8 — Medium-force pulse generator mounted on EDC structure

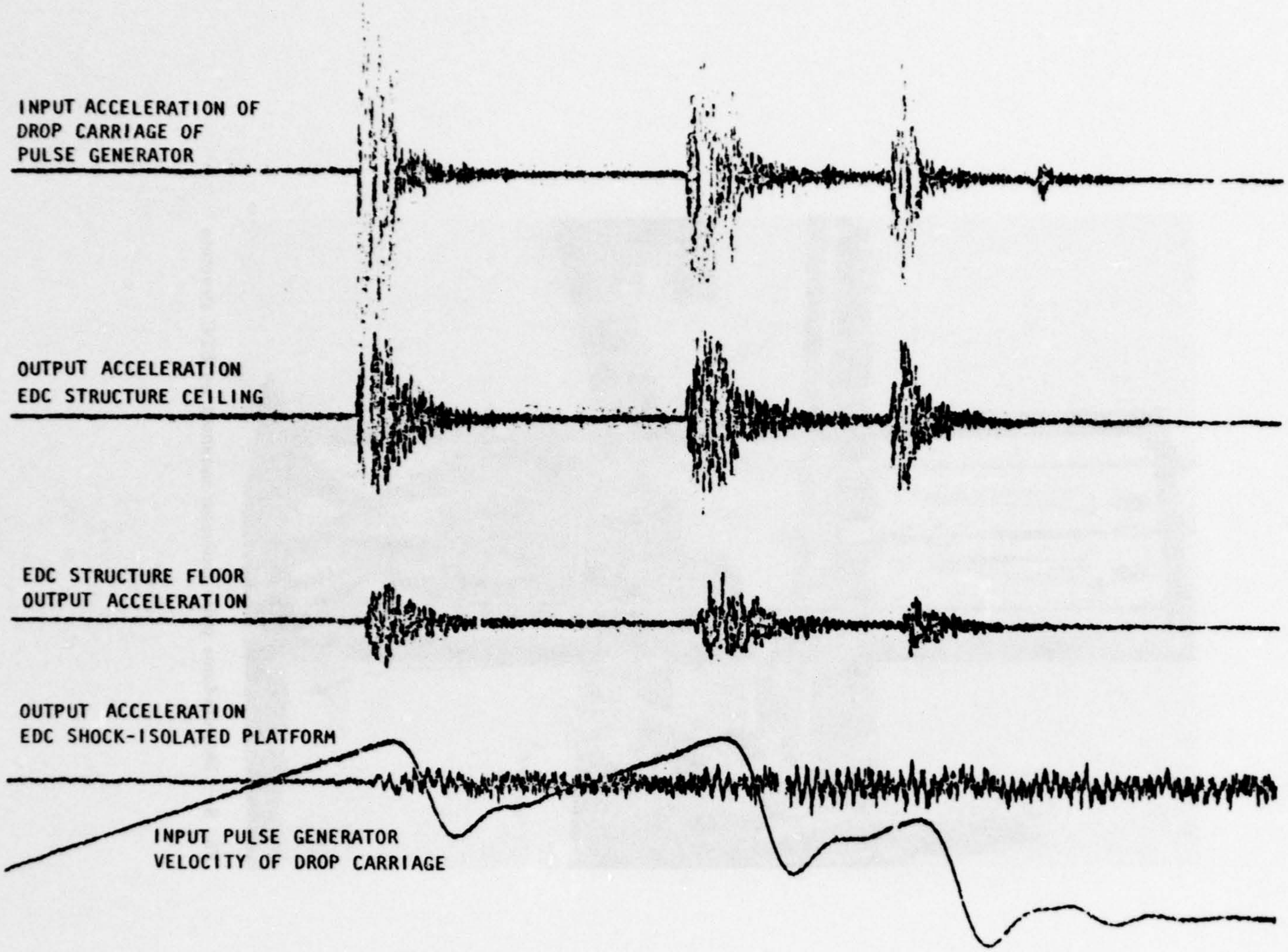


Fig. 9 — Oscillograph records amplitude histories of drop carriage and EDC structure response

where the generator was configured for three 5000-lb pulses of 25 msec durations each. This drop shock tower has the potential capacity to produce pulse amplitudes up to 150,000 lb.

2.4 NRL PULSE GENERATING SYSTEM

The NRL Pulse Generating System, Figure 10, was primarily designed for laboratory use in conjunction with the medium-weight shock machine. However, this system is inherently flexible and may be used in remote locations and on shipboard. A full technical and engineering description of this system was provided to NRL in Report R-7710-3-4333, "Specification for Evaluation of Impedance Analysis Techniques for Naval Applications," December 1976 by Agbabian Associates, El Segundo, Calif. Major design change over previous versions was in reconfiguration so as to reduce the weight below gage (load cell). Maximum capacity of this unit is 10,000 lb force. To obtain maximum capacity, a dual cutter would be required, and bottled compressed air would be needed in place of plant air.

The calibration mandrel for the system is drawn in Figure 11, and its Fourier magnitude spectrum is given by Figure 12. A three-pulse mandrel Fourier spectrum is shown in Figure 13 only to present the wide spectrum that may be obtained.

The pulse-generator system is depicted in Figure 14. This system operates from plant air to an air/hydraulic multiplier, thence to a hydraulic drive to operate the pulser. Orifice flow control gives cutting velocities from 20 in./sec to 136 in./sec.

Initial applications for this device are planned for the U.S. Navy medium-weight shock machine, illustrated in Figure 15 with its impact hammer. Single-pulse impact of this hammer is in the order of 1 msec. Whereas, for example, the mandrel in Figure 11 generates 12 pulses of 0.8 msec each for a total test record length of 76 msec at 120 in./sec cutter velocity or 12 pulses of 4.8 msec each for a test record of 456 msec at a 20 in./sec cutter speed. This latter application is schematically shown in Figure 16.

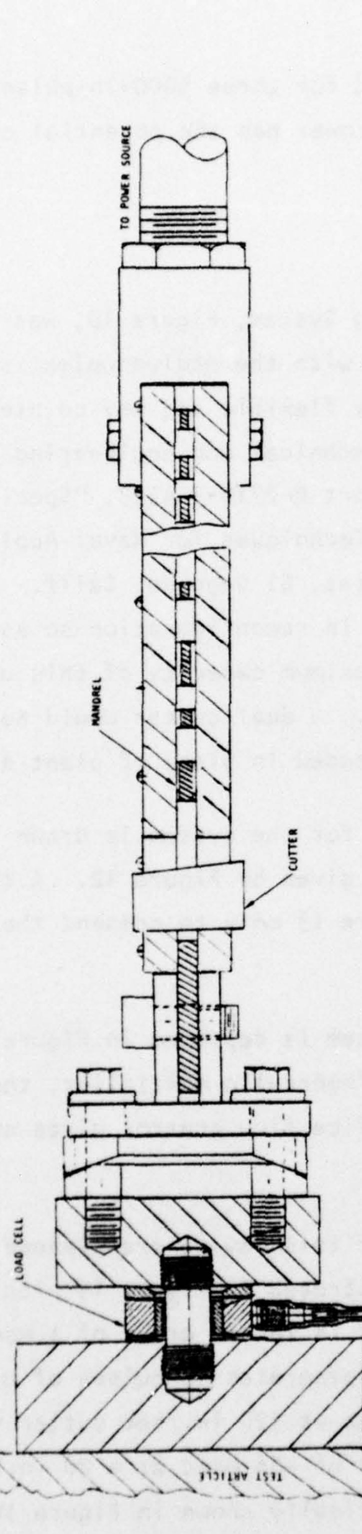
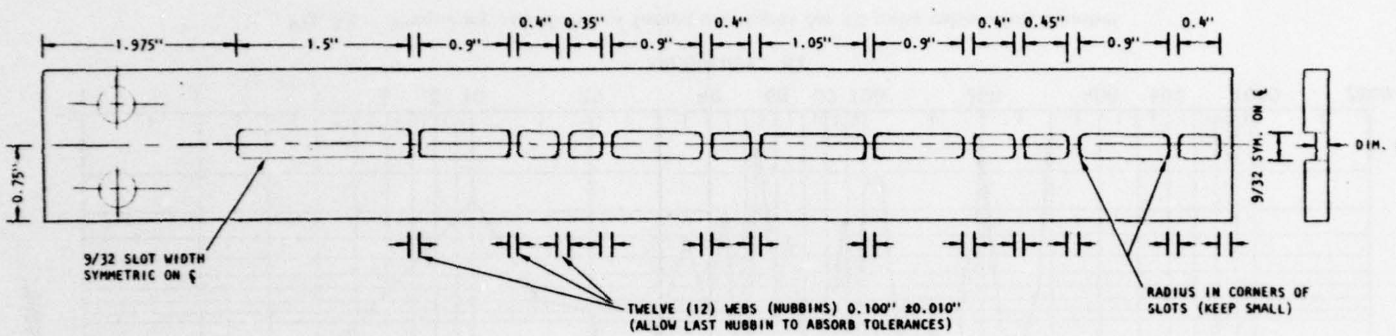


Fig. 10 — Outline drawing of NRL pulse generator



DET NO.	DIM. A
7710-13A	0.25"
7710-13B	0.170"
7710-13C	0.085"

Fig. 11 — Calibration mandrel for NRL pulse generator

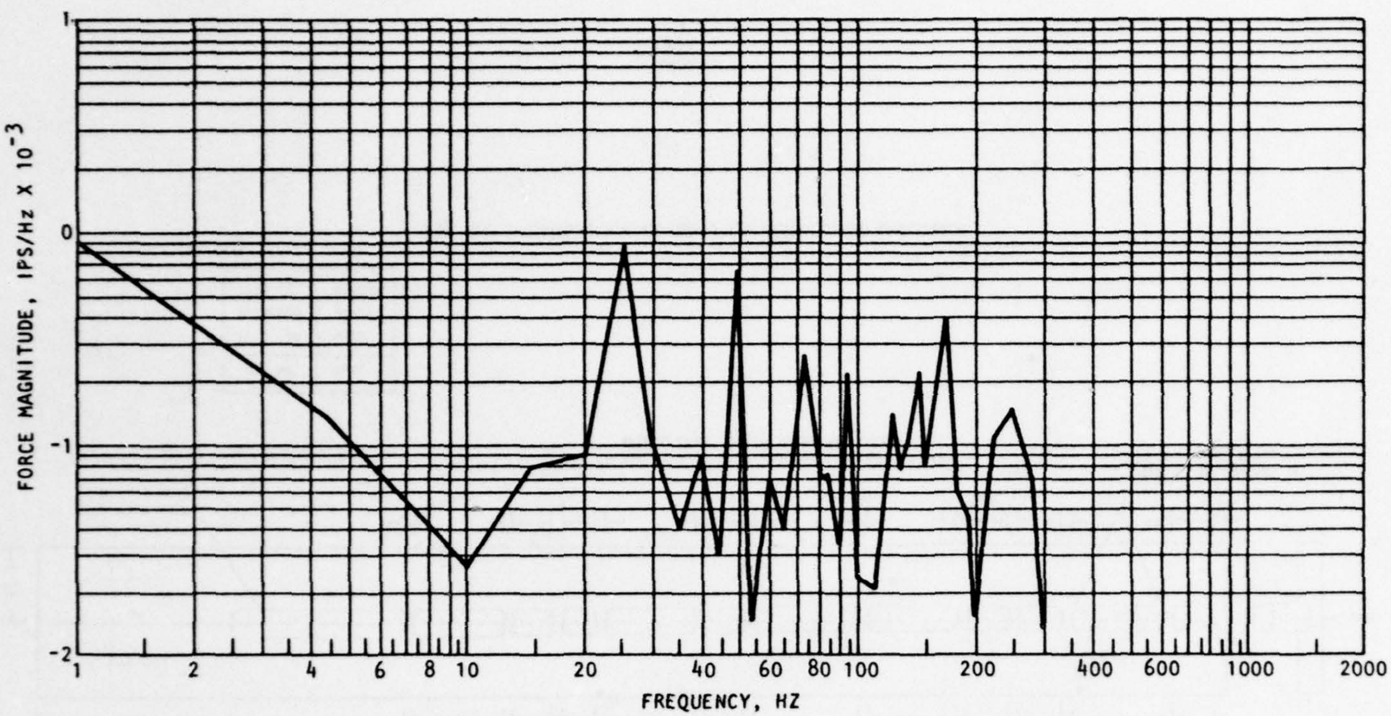
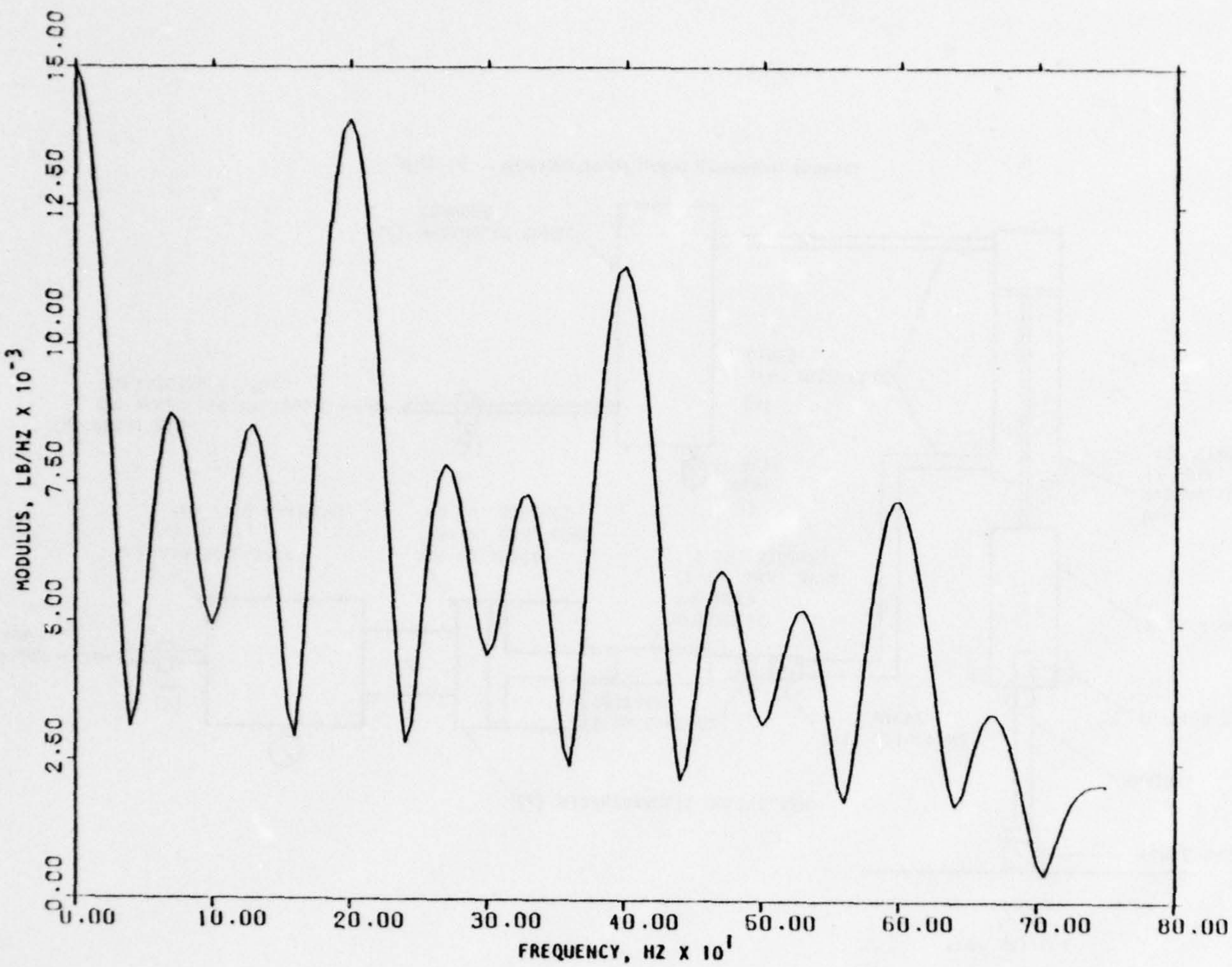


Fig. 12 — Frequency transform of force-pulse input for 12-pulse calibration mandrel



(a) Fourier magnitude

Fig. 13 — Frequency transform of force-pulse input for 3-pulse train

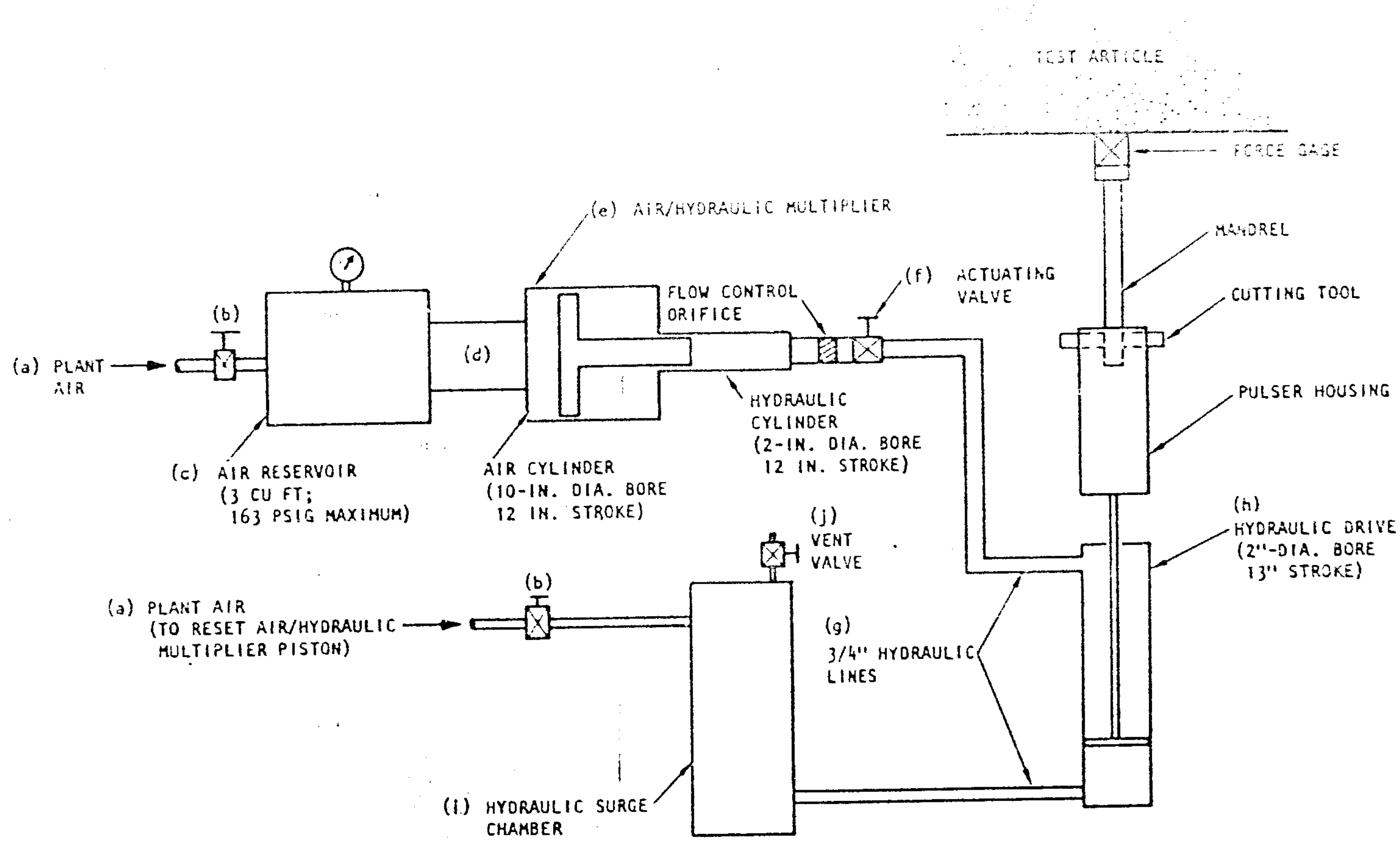


Fig. 14 — Schematic of pulse generator system

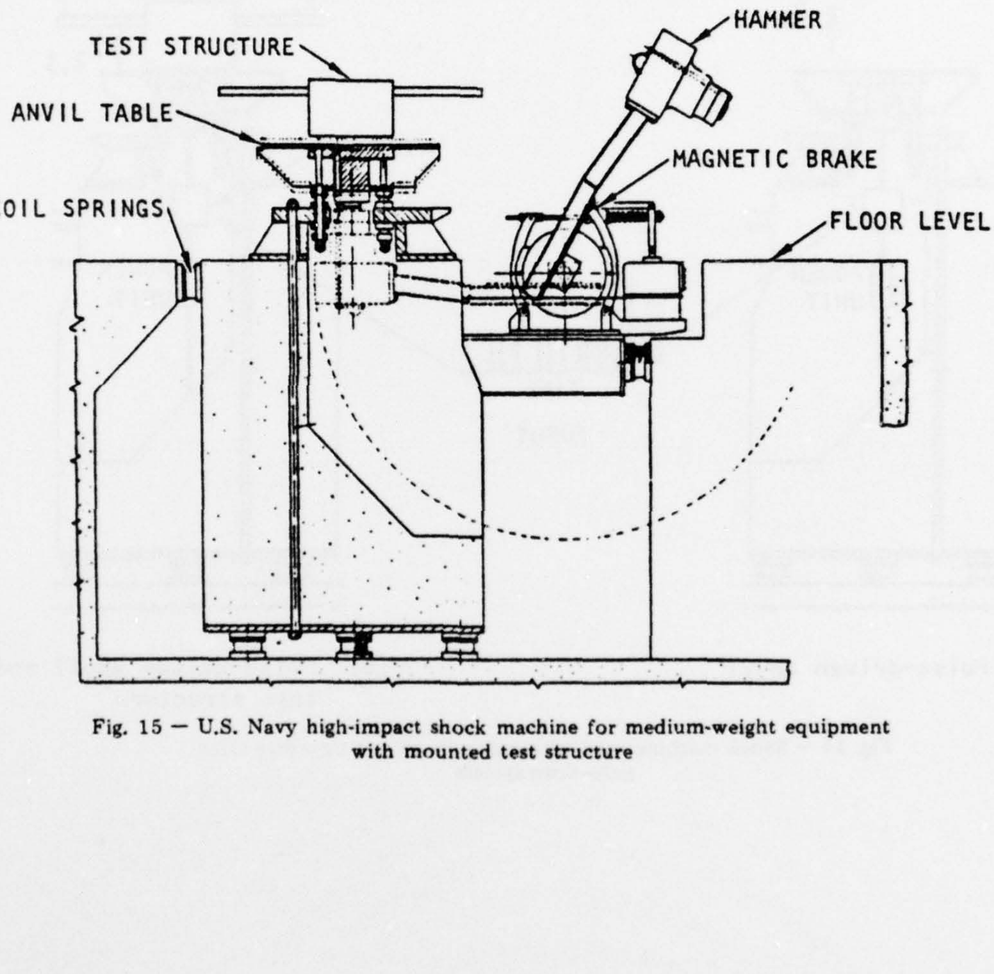


Fig. 15 — U.S. Navy high-impact shock machine for medium-weight equipment with mounted test structure

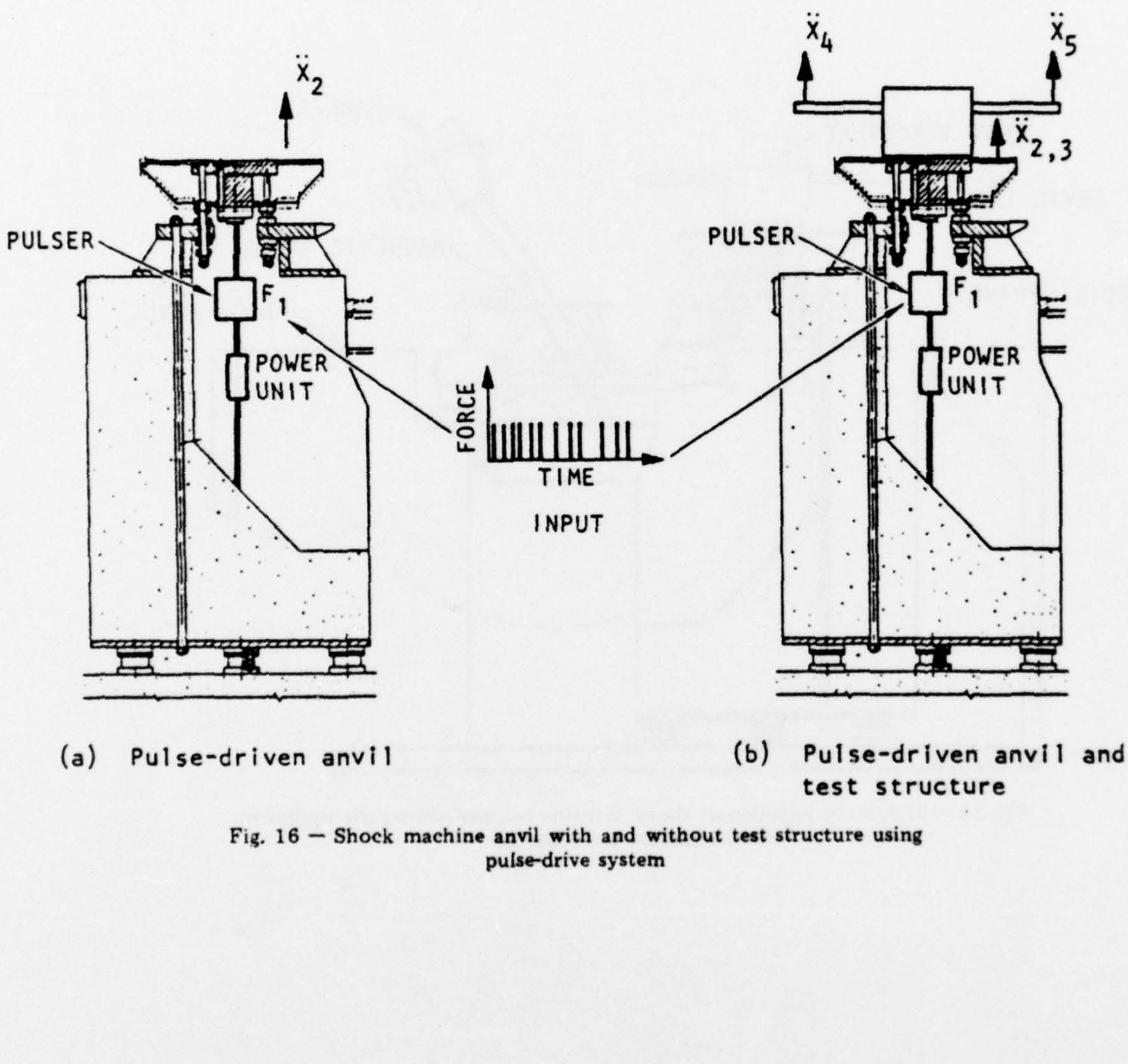


Fig. 16 — Shock machine anvil with and without test structure using pulse-drive system

SECTION 3

U.S. NAVY MEDIUM-WEIGHT SHOCK MACHINE PARAMETER IDENTIFICATION

3.1 SHOCK MACHINE AND TEST ARTICLE

The vibration of a mounting base or element of structure is altered when another structure is mounted thereto or a previously mounted structure is replaced with a different component. Knowledge of the shock and vibration environments at mounting locations within a naval vessel is a necessity for the determination of hardness and survivability of equipment. This is a continuing problem due to the continued changes in the state-of-the-art resulting in the upgrade and substitution of equipment.

The environment at mounting points of equipment is given by the following expression (Ref. 9):

$$V'(\omega) = V(\omega)\left[\frac{Z_{22}}{Z_{22} + Z_{33}}\right] \tag{2}$$

where

$V(\omega)$ = Complex velocity of mounting point without equipment

$V'(\omega)$ = Complex velocity of mounting point with equipment attached

Z_{22} = Driving point impedance of mounting point

Z_{33} = Driving point impedance of equipment

When one equipment is to be exchanged for another equipment and the original velocity at the equipment mounting interface is known, the response with the substituted equipment may be predicted by (Ref. 9):

$$V'(\omega) = V(\omega)\left[\frac{Z_{22} + Z_{33}}{Z_{22} + Z'_{33}}\right] \tag{3}$$

where the parameters of Equation 3 are the same as in Equation 2, except Z'_{33} is the driving point impedance of the substituted equipment.

Other forms of Equations 2 and 3 may be used and these basically include the transfer impedance term from the input load points to the equipment mounting locations.

A practical application of the above was conducted in 1960 (Ref. 10) using the medium-weight shock machine. Impedance measurements were made on the anvil and upon a test structure as sketched in Figure 17. The output impedance of the anvil for both magnitude and phase is in Figure 18 and the input impedance for the test article is given in Figure 19. The anvil and test article were struck with the hammer as shown in the configuration of Figure 15. The velocity response from this test is plotted in Figure 20 in the form of a velocity shock spectrum. A similar test was conducted upon the anvil only and the resulting data was modified by Equation 2 to predict the motion of the anvil if the test article was attached thereto. This prediction is also plotted in Figure 20. While the shapes of the two curves are in general conformity, the predicted amplitudes exceed actual up to a factor of nearly 2. Several areas have been considered to account for the above difference and the most probable one is the extremely low level of force used to measure the impedance of the components. As discussed in Section 1 of this report, a sufficient measurement force is required in a quasi-linear sense to obtain suitable values of damping (material, joints, aerodynamic).

An alternative means of measurement of a system is with and without load. Complex subtraction of these measurements using Equation 2 yields the input impedance of the load. An example of this procedure is given in Figure 21. This example is particularly interesting due to the extremely large impedance mismatch between the base structure and the spring isolator-supported load that was detected by the impedance measurements.

The foregoing tests on the shock machine are planned to be repeated using updated techniques of measurement and data processing. Recent experience indicates that very useful results will be obtained by which accurate

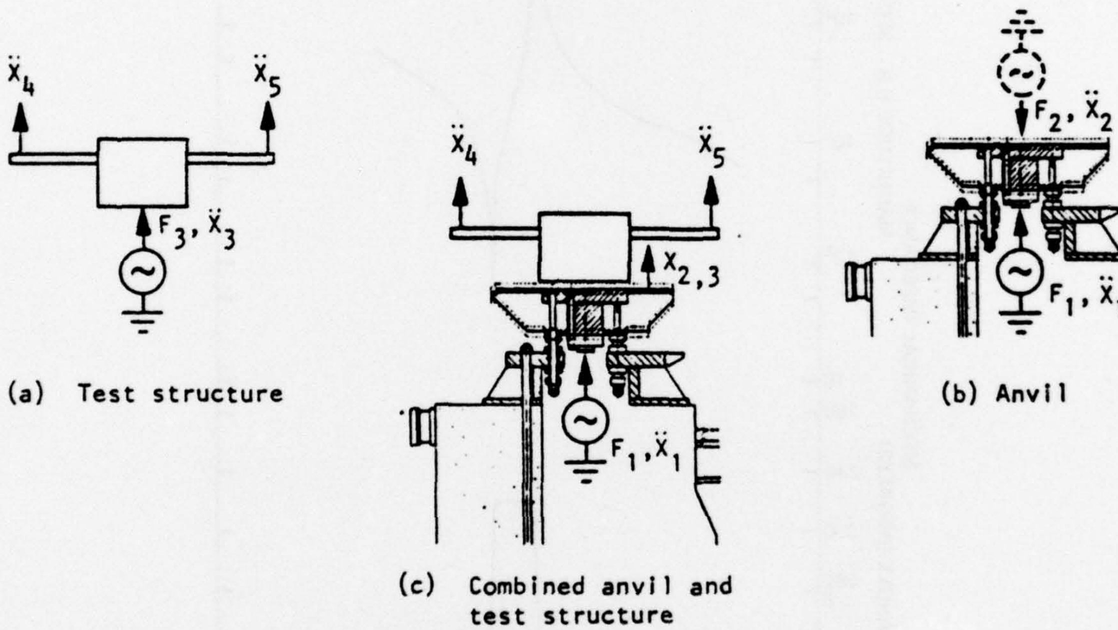


Fig. 17 — Impedance measurements of shock machine and test structure

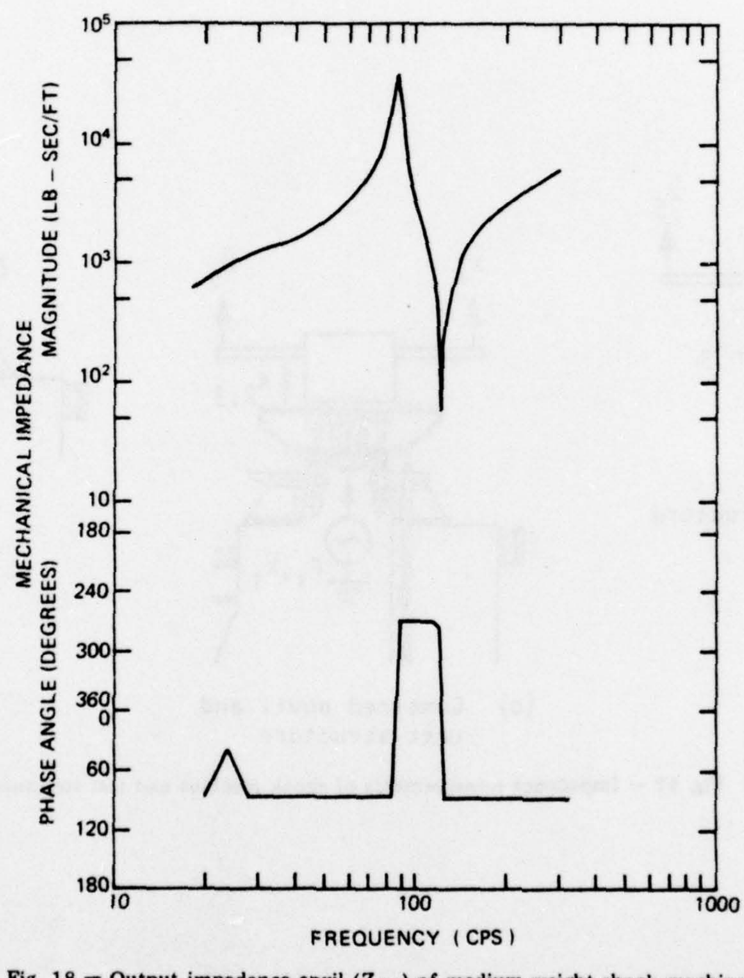


Fig. 18 — Output impedance anvil (Z_{22}) of medium-weight shock machine

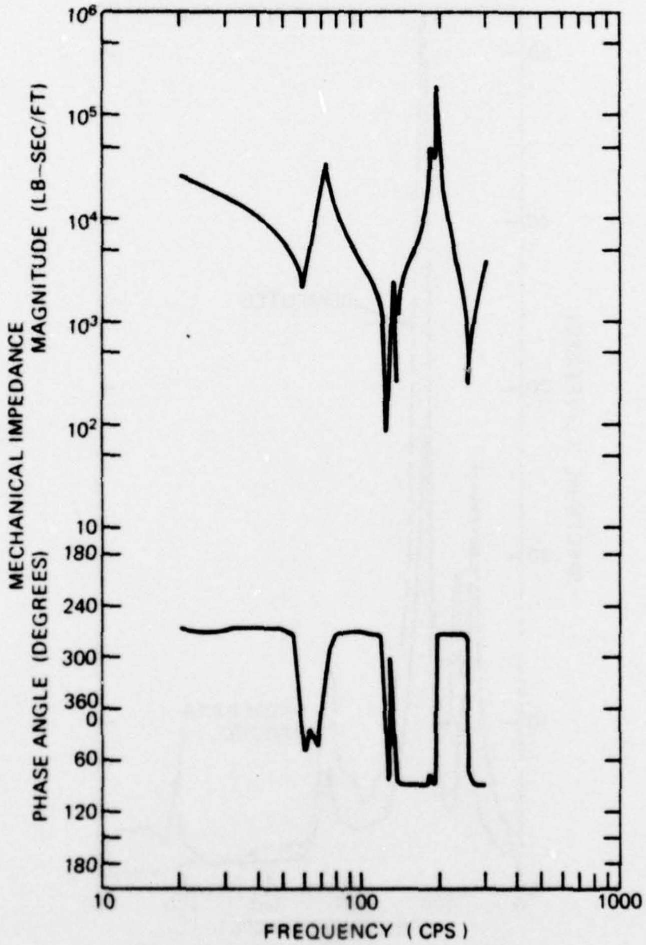


Fig. 19 — Input impedance test article (Z_{33})

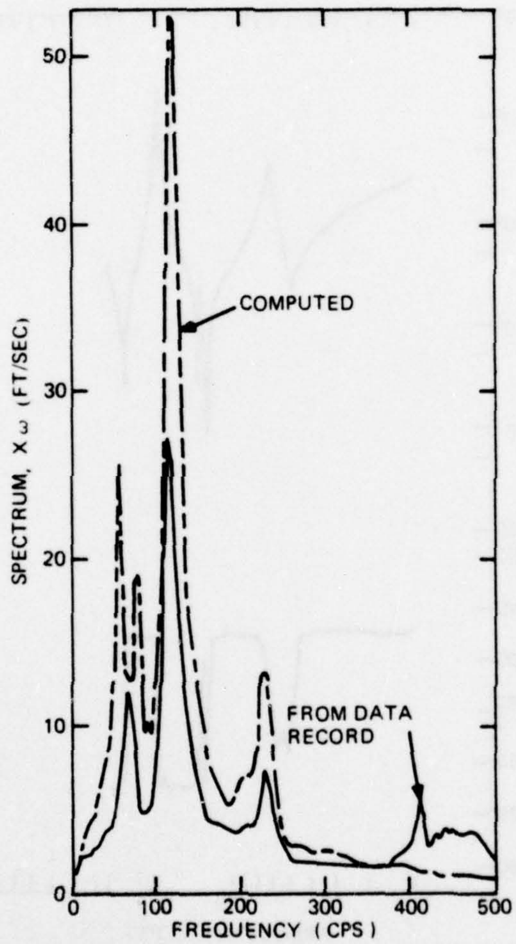


Fig. 20 — Shock spectra velocity of anvil and test article (data record and computed)

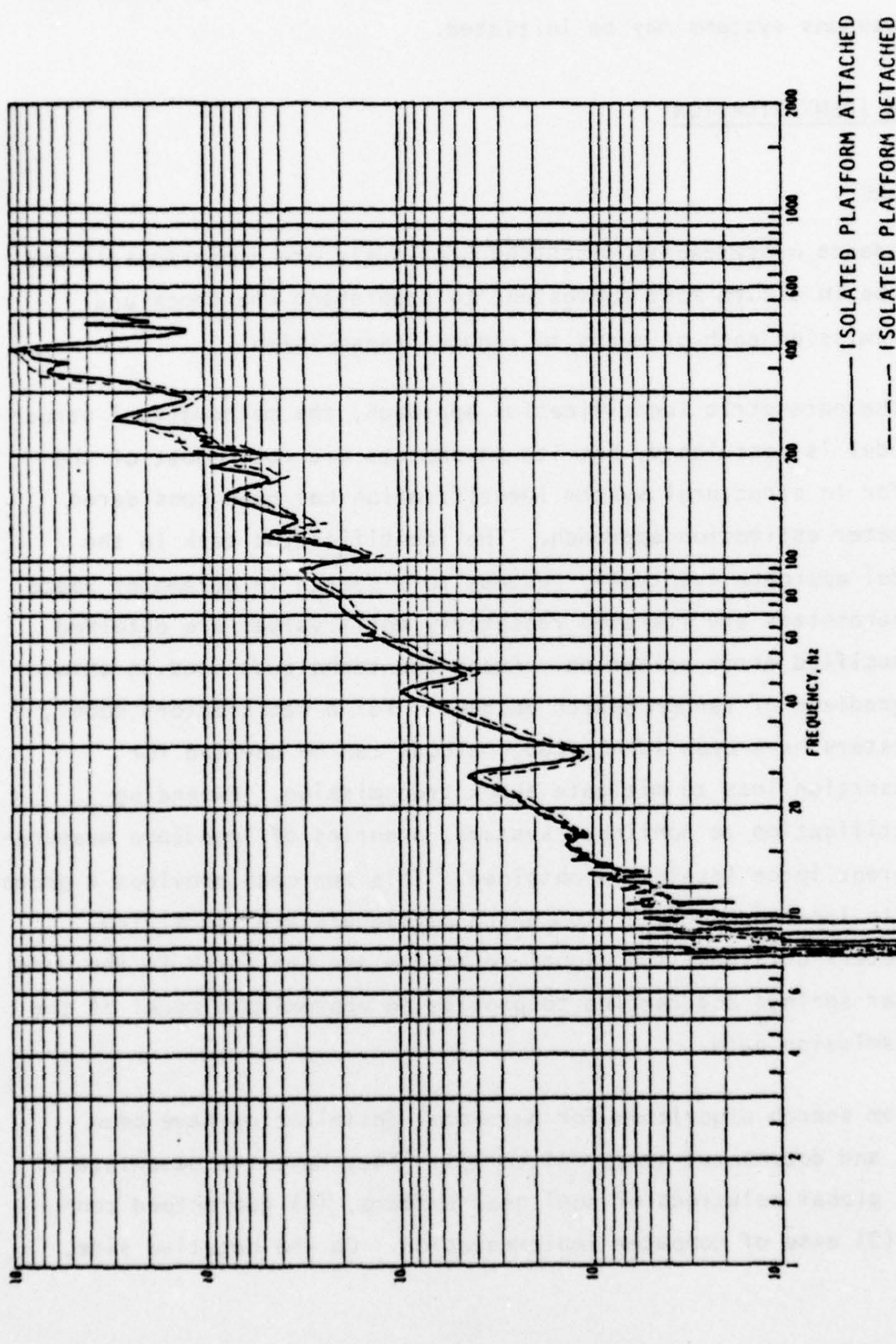


Fig. 21 — Driving point impedance tests of a reinforced-concrete structure at attachment location of a shock isolator

predictions can be made on the velocity effects of loading a structure with new and changed equipment. Once this procedure is established, application to operating weapons systems may be initiated.

3.2 PARAMETER IDENTIFICATION

3.2.1 PROCEDURE

Impedance measurements discussed previously are nonparametric and may not often be in a form most convenient to understand the shock and vibration transmission path or means to reduce transmissions.

In the parametric identification approach, the mathematical structure of the model is postulated, but its parameters are not. Most of the work done so far in structural system identification has been considered from the parameter estimation approach. The identification task in the parametric model approach eventually reduces to a search in parameter space where system parameters are iterated repeatedly until values are obtained that meet a specified error criterion. Among the techniques used in this approach are gradient or random search methods. For a satisfactory model, once the parameters have been identified, methods can be devised for appropriate insertion loss to mitigate shock transmission. Extending parameter identification to nonlinear systems, a series of impedance measurements at different force levels are obtained. This approach provides a group of nonparametric impedance curves from which parameters are identified. From the parameters obtained, functional relations are set forth in the model as for nonlinear springs and damping to provide an approximate model of the nonlinear transmission path.

Random search algorithms for parameter optimization have been widely applied and documented (Refs. 11 to 17). They have the advantage of (1) leading to global solutions of nonlinear systems, (b) guaranteed convergence, and (3) ease of computer implementation. On the negative side, random search algorithms may converge very slowly, particularly in criterion surfaces of high dimensionality. The basic algorithm for minimization of a criterion function $J(\alpha)$, where $\underset{\sim}{\alpha} = (\alpha_1, \alpha_2, \ldots, \alpha_m)^T$ is a vector of unknown parameters, proceeds as follows: (1) An initial parameter value $\underset{\sim}{\alpha}^o$ is estimated and $J(\underset{\sim}{\alpha}^o)$ is evaluated; (2) trial points $\alpha^i \epsilon \Omega_\alpha$, where Ω_α is the given permissible region in the m-dimensional parameter space, are selected from an appropriate probability density function defined over Ω_α; (3) a successful point α^{i+1} is one for which $J(\underset{\sim}{\alpha}^{i+1}) < J(\underset{\sim}{\alpha}^i)$. The sequence $J(\underset{\sim}{\alpha}^i)$ thus converges to a local minimum. Rather than using "pure random search," most algorithms are based on a "random creep" procedure in which exploratory steps are confined to a hypersphere centered about the latest successful point α^i. However, convergence by such procedures may be extremely slow, since no allowance is made for variations in the nature of the criterion function surface as the search progresses towards a minimum.

Several procedures have been tried in the past to circumvent slow convergence. The addition of a bias vector to each iteration causes the search to favor successful directions (Ref. 14). Restriction of the search to a directed hypercone has also been proposed (Ref. 16). However, such schemes are highly directional and lose some of the flexibility of the random search procedure, as in the case of narrow "canyons" or "ridges" in the criterion function surface. Rastrigin (Ref. 11) has compared a random search where each step is random in direction but fixed in length (fixed-step-size random search), with a fixed-step-size gradient search, and showed that under certain conditions the random search is superior. It is intuitively evident, however, that one would obtain even better performance if the step size of the random search procedure were optimized at each step of the iteration. If the steps are too small, the average improvement per step will also be small and convergence time will be lengthened. If the steps are too large, they may overshoot the minimum; and the probability of improvement will again be too small. Hence, some method of adapting the step size to the local behavior of $J(\alpha^i)$ is indicated.

Schumer and Steiglitz (Ref. 15) have tested one approach to adaptive step size random search. They use a fixed-step-size algorithm, where the trial vector $\Delta\alpha^i$ is of length ℓ and distributed uniformly over the hypersphere of radius ℓ whose center is at the latest successful parameter value α^i. A random step of size ℓ and an incremental step of size $\ell(1 + a)$, where $0 < a < 1$ are taken in the same direction. The step size that produces the larger improvement is used as the nominal length ℓ for the next iteration. If no improvement occurs, ℓ is incrementally reduced. Thus, the algorithm is capable of adapting its step size as a function of the search.

The algorithm used for the medium-weight shock machine is another approach to the determination of the optimal step size (Ref. 18). Rather than a fixed-length step, steps used are random in both length and direction. Hence, the adaptation described below is based on the selection of the optimal variance of the step-size distribution as the search progresses. Large variances are desirable in the early, exploratory portions of a search. However, in the vicinity of a local optimum, a smaller value of the standard deviation, σ, will decrease the probability of overshoot.

The algorithm for the adaptive random search consists of alternating sequences of a global random search with a fixed value for the step size variance followed by searches for the locally optimal σ.

Figure 22 illustrates the adaptive algorithm whereby a very wide-range search selects the standard deviation best step size (σ) for the coarseness of the increments used, followed by a sequential precision search of finer increments. As the rate of convergence decreases, a new precision search is made, but directed towards a smaller step size. At selected iteration intervals, the wide-range search is reintroduced to prevent convergence to local minima.

The adaptive random search method was used to determine a pulse train (composed of 8 pulses) whose response spectrum matches a criterion

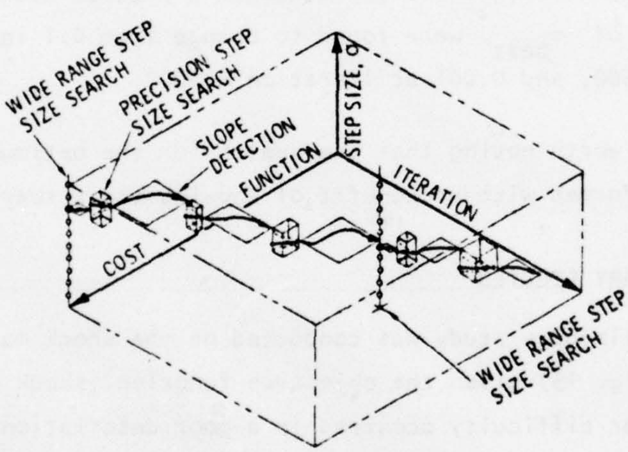


Fig. 22 — Adaptive step size search, both wide range and precision, for rapid convergence of cost function

response spectrum as closely as possible over a given frequency range ω_{min} to ω_{max}. Since each individual pulse in the train is characterized by 3 independent parameters (amplitude, a_i; duration, d_i; initiation time, t_i), a total of 24 parameters are needed to define the 8 pulses of the desired train. Note that the response spectrum of a pulse train is a nonlinear function of the pulse parameters.

Figure 23 shows that superior results are obtained by using the adaptive features of the random search method. While both cases (a) and (b) started with the same standard deviation, $\sigma_{best} = 0.1$, in the case (a) the search was conducted for 2000 steps with fixed σ. When the search for the best standard deviation, σ is conducted at a rate of iteration frequency = 500, the values of σ_{best} were found to change from 0.1 initially to 0.01 at iteration = 500, and 0.001 at iteration = 1000.

It is worth noting that the search for the optimum solution of this problem was performed without benefit of knowing the answer in advance.

3.2.2 PRELIMINARY STUDIES

A preliminary study was conducted on the shock machine anvil and test article (Fig. 15) given the objective function (shock spectrum) of Figure 20. Major difficulty occurred in a poor description of the pulse input from the hammer. A 1 msec rectangular pulse was finally specified and held fixed during all subsequent computations. Shock spectrum objective functions also pose costly computer operations as each parameter iteration involves conversion of trial model time-histories into shock spectra until convergence is obtained.

The results of the preliminary parametric study showed (for the four-degree-of-freedom model chosen to represent the distributed system) reasonable results. Parameters for the model are listed in Table 1 and the shock response spectrum is given in Figure 24. Results of the spectrum may be compared to Figure 20.

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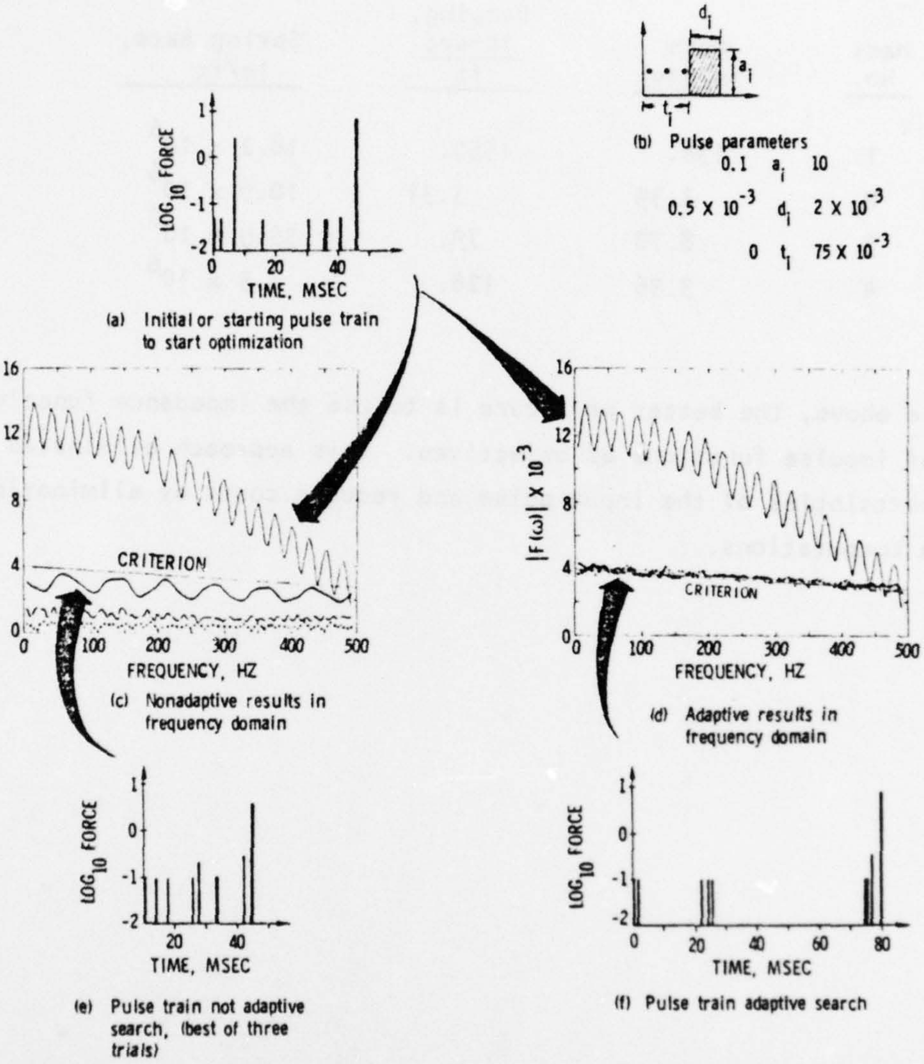

Fig. 23 — An 8-pulse train (parameters of amplitude, duration, and occurrence time) is given initial values and then optimized by adaptive and nonadaptive random search methods to match a criterion frequency spectrum

TABLE 1. MODEL PARAMETERS OF ANVIL AND TEST ARTICLE
(Input impulse of 1 msec duration)

Mass No.	Mass (slugs)	Damping, lb-sec/ft	Spring Rate, lb/ft
1	136.	1550.	18.2×10^6
2	3.39	3.31	10.9×10^6
3	8.78	79.	35.9×10^6
4	3.96	128.	6.9×10^6

In view of the above, the better procedure is to use the impedance functions in the form of impulse functions as objectives. This approach eliminates the large uncertainties of the input pulse and reduces costs by eliminating shock spectra computations.

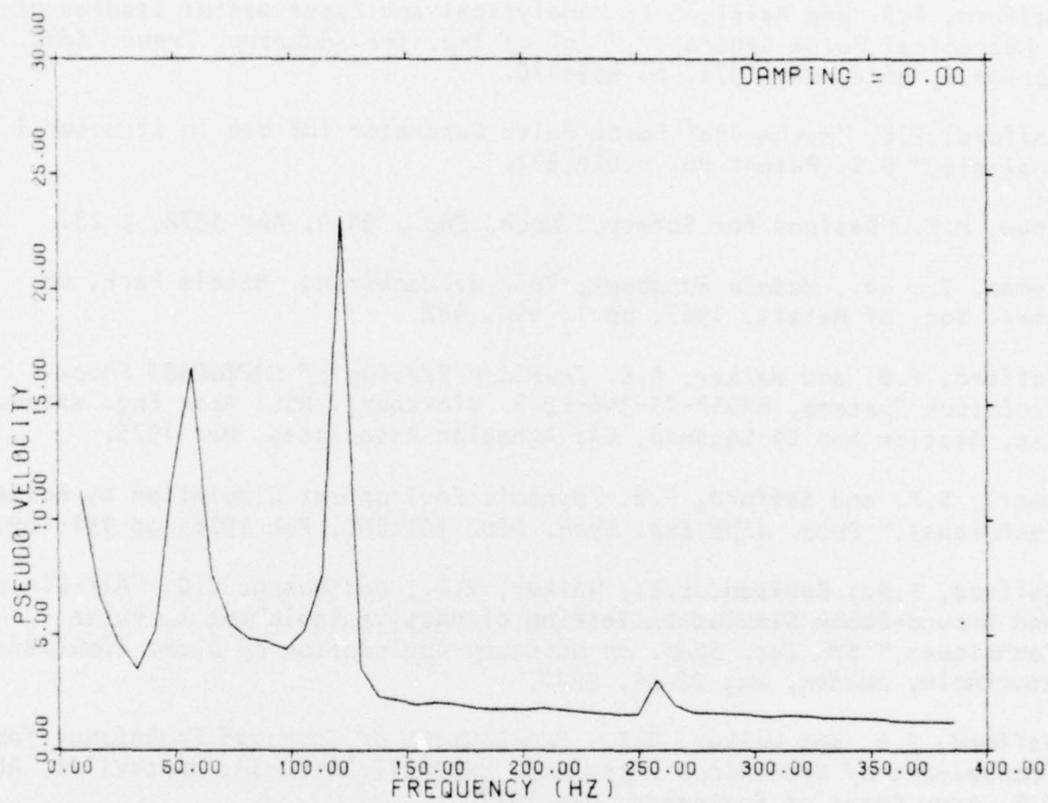

Fig. 24 — Shock spectrum response of anvil and test article using identified parameters

SECTION 4

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