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ABSTRACT

This report has been prepared to describe some of the progress made since World War II in the several areas related to the complex set of problems encountered in shock design and analysis of shipboard systems. It discusses: requirements for shock protection, selection of failure criteria, determination of shock environment, development of analysis and design procedures, results from past research and engineering, and the needs for future research and engineering. Essentially it sketches the evolution from the simple shock design number concept, which is limited, to a more rational approach which can allow the shock design-analysis of unprecedented equipment.

PROBLEM STATUS

This is an interim report on a continuing problem.

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BACKGROUND FOR MECHANICAL SHOCK DESIGN OF SHIPS SYSTEMS

INTRODUCTION

This report has been prepared to describe some of the progress made since World War II in the several areas related to the complex set of problems encountered in shock design and analysis.

It is the purpose of any program of shock analysis, design, and testing to insure that the equipment or structures under consideration be capable of performing their intended functions before, during (if necessary), and after, encountering severe environmental conditions. As Navy engineers it is our duty and responsibility to provide the fleet and/or its supporting groups with the knowledge, techniques, guidance, and help needed to attain this goal. The problems of general interest are the shockproofness of items on ships subjected to attack by enemy forces who have a wide range of weapons and delivery systems at their disposal. The particular problem at hand is to assume that defensive countermeasures will fail and an enemy will succeed in making an attack upon a ship; thus it is necessary that the target be capable of withstanding the attack and still perform its intended function. It is obvious that a direct hit by a weapon will do significant damage in the immediate region of the explosion; this becomes the problem of the armorers. The problem which we have devoted effort to is that of the near miss, when the hull is not lethally damaged, but when a severe mechanical shock loading is transmitted to the machinery, equipments, and other structures of interest on the ships.

The subject has been subdivided into several parts for convenience.

I. Requirements for Shock Protection
II. Selection of Failure Criteria
III. Determination of Shock Environment
IV. Development of Analysis and Design Procedures
V. Results from Past Research and Engineering
VI. Needs for Future Research and Engineering

There is no special effort herein to present a historical or policy document. However, background information will be presented under some parts to provide a more complete presentation. Perhaps the main portion of this paper can be considered to be closely allied with the current BuShips' Shock Design Analysis Procedure as developed at NRL, but other pertinent topics will also be discussed.

I. REQUIREMENTS FOR SHOCK PROTECTION

Certain decisions must be made by management—with the advice and cooperation of their specialists in structural dynamics—regarding the degree of protection required, including a definitive statement as to how effective a ship and its systems should be after a severe shock caused by some "reference" attack situation. There must be several levels of shock protection which can be supplied and/or required for equipments, depending upon the importance of the equipment. For example, a missile in a launch mechanism might be considered to be "expendable" under severe shock conditions and consequently heaved over the side to make way for one which is undamaged. This of course requires that the stowed missiles, the transport and launch mechanism, the fire control systems, etc., be capable of withstanding the severe shock and remaining operational. For another example, consider the difference between propulsion machinery and the refrigeration machinery for comfort or the fresh meat locker. If the refrigeration machinery is knocked out by shock, the effect is not as serious as having the ship stop dead in the water. To summarize, the problem is to retain a fighting ship.

In the distant past the goal was to have "shockproofness" up to intensities corresponding to attacks which produce lethal hull damage. This goal may be unrealistically severe for most shipboard items, and for other items of prime importance it has not been achieved, because routine shock tests (1-16) have vividly demonstrated failures often occur at only a small fraction of this severity.

The continued usage of Mil-Std 901 by BuShips has in a sense recognized this, since shock resistance of hulls has been significantly improved over the years, whereas laboratory test levels have been essentially unchanged. Also, for items which are shock designed, rather than shock tested (because of their physical size or weight), the design criteria are associated with an interim set of shock intensities (17-20).

Operational analyses—while they cannot solve the fundamental problem—can and should be made to study this problem of realistic goals for shockproofness. Because of the many varieties of ships, weapons, and equipments the value of such analyses may be low at first, but as experience and improved data become available the value should markedly increase. An example of the type of question which operation analysis can help to answer is, "Is it more efficient, from a standpoint of war capability and economics, to produce a larger number of weaker vessels and systems than to build maximum shock survivability in each unit?" However this study should recognize that much can be done at little extra cost to improve the shockproofness of current systems, and that this can and should be done anyway. It should be recognized, however, that operational analyses are merely another useful tool and are not a panacea for all our ills.

One type of operational analysis which has been performed is that in 1958 NRL published (21) a study of the probabilities of shock damage associated with equipment systems aboard submarines when subjected to nuclear explosion attack. This study was among the first to apply statistical reliability concepts to weapons and propulsion systems. Probability distribution functions were derived describing various functional submarine capabilities after nuclear attack.

In order to proceed to other parts of this report it will be assumed that the goals of shockproofness can be realistically stated in terms of interim and future needs. Once these goals have been stated they should be the basis for both design and evaluation.

II. SELECTION OF FAILURE CRITERIA

One of the most perplexing problems which faces any engineer dealing with structural dynamics is the basic question, "What constitutes failure?" Unfortunately this simple, direct question rarely has a simple, direct answer. The environment of an equipment is a function not only of the attack situation but of the equipment itself. The mathematical model of the real structure (required for analysis) may be quite complex and difficult to obtain; and the analysis can be quite time consuming. Even so, the environment, the model, and the analysis are only a means for obtaining some numbers upon which engineering judgment must be based. The problem is compounded because shock is normally an environmental (or secondary) design requirement, since the equipment is intended to perform some function which governs its design.

The meaning of failure is relatively simple in an actual shock test, since it is possible to find out if the equipment did, and can still, perform its useful function. In a shock analysis the failure must be associated with some calculable quantity. It is of the utmost importance that the shock analyst completely define his failure criteria before beginning the analysis because the type of analysis, the complexity required, and even the type of environmental description which is needed are dependent upon the failure criteria. A good analysis will also point out areas of overdesign, where improvements in this or future equipments are possible.

Shock-induced failures can be arbitrarily (for convenience) classified as "mechanical," "functional," or "secondary." Mechanical failures of structural components can normally be associated with excessive flexibility (excluding cases of frequency coincidence or unforeseen brittle fracture), in that strains or distortions have become too large. Functional failures are interruptions of functions which are intermittent while the shock environment is present or can be quickly corrected after the shock is over. Secondary failures are those caused by the failure of some other piece of equipment which causes failure of the equipment under consideration. For example, a fire extinguisher breaks loose from a bulkhead, impacts, and causes failure of an electronic chassis which survived the original shock.

A particular shock analysis can be arranged to yield one or more of the several failure "indicators," including the following: (a) allowable stresses or strains, (b) allowable forces, moments, etc., (c) allowable displacements, relative and absolute, (d) allowable energy absorption, (e) allowable absolute accelerations, and (f) allowable bearing loads. The analyst thus needs a clear understanding of his particular failure criteria before starting an analysis to insure that the needed information can be obtained.

It should be noted that shock design analysis alone is rarely practicable if an assemblage of items is so complex that a reasonable analysis of each component is impossible or prohibitively expensive. A reasonable limitation seems to be that the grosser type of failure, excessive deflection, unreasonable bearing loads, internal impact, etc., can be computed, but many things cannot be. An attempt at a design analysis should not be an excuse to overlook quality control, good fabrication techniques, possible distributions of unwanted stress raisers, and, particularly, component shock testing!

III. DETERMINATION OF SHOCK ENVIRONMENT

The realistic determination of shock environment requires not only good measuring equipment and sufficient manpower to perform the task, but it is of prime importance that the engineers, whose responsibility it is to make such measurements, understand what they are doing and why they are doing it. Reed gages, accelerometers, velocity meters, strain gages and all the other measuring devices can only record (within their own limitations) the environment at their locations. If instruments are scattered indiscriminately about a ship, without long and serious thought as to how the data will be used, the resultant data may cause more harm than good. For example a velocity meter placed in the middle of a deck plate will give some idea of the motion of the plate when loaded with a velocity meter but the data has little other value. Suppose a 150 pound man, attending a 250-pound part of a weapons system was to be located on that plate. Does the data have real value? Can extrapolations and interpolations be made? Could a better measurement be made the next time? The response of a reed gage at the top of a mast can have academic value, but if it were replaced by a real equipment what environment should be designed for? Consider a reed gage properly positioned at the base of an equipment whose response we wish to study. Does the gage contain the specially tuned reeds that correspond to the frequencies of concern? If it doesn't, more harm than good can come from attempting to use the data.

It is mandatory that every shock measurement made have a specific requirement, stated before the test, so that the correct instrument in the correct location will be used.

A research type of requirement should be equally valid with a requirement which helps to understand or detect a potential failure. Experience during several full-scale "routine" shock tests has shown previous instrumentation was inadequate both because of excessive size and weight needs, and because of inherent instrument limitations. A continuing research program at NRL has resulted in several very promising instrumentation developments (22-25).

A meaningful description of the shock environment is a prerequisite to a shock-design analysis. The first step on the road to this description is intelligently chosen data skillfully obtained. One such piece of data is usually worth more than a file cabinet full of reports of shock motion records where the data was indiscriminately taken. Intelligent planning of data collection at shock tests is a must.

IV. DEVELOPMENT OF ANALYSIS AND DESIGN PROCEDURES

Theory and research must produce usable design information in order to be of any help to the designer of shipboard equipment. This means that the techniques must be both practical and easy to use by engineers familiar with the other common design and analysis techniques for other shipboard features and must provide good answers to all pertinent questions. A usable shock design method must make use of standard engineering and mathematical techniques. It certainly would not be helpful to evolve a shock design method which could only be used by a very limited number of specialists. The concept of shockproofness goals enters here also, as it rapidly becomes impossible and/or impractical to attempt useful designs if the environment is specified so that unrealistic and unattainable goals are set for the present state of the design art. A balance, with a gradual upgrading of requirements, seems to be a practical approach here.

Any practical shock design method will have several easily recognizable requirements or characteristics:

1. The goals should be established so that several levels of shock protection are available for design of equipments, depending upon the importance of such equipment.

2. There must be a description of the shock environment which the item must survive. This should be in the simplest possible form. Of course a balance between simplicity and precision must be maintained.

3. There must be some means of describing the item to be analyzed in a mathematical form.

4. There must exist "standard" engineering and mathematical techniques (which the method uses) so that a design may be analyzed quickly and with some degree of uniformity by the various hardware suppliers.

5. There must be an explicit performance or failure criterion which can be determined—by analysis—from the description of the item and the environmental conditions.

6. A shock design method should produce information such that a second analysis of a particular type of equipment can be performed more quickly than the first.

7. The technique should be a learning tool also so that future designs of similar equipment can be designed more efficiently with certain revisions which appear to be useful.

8. Finally, it must be recognized that all design, whether for shock or not, is an iterative procedure utilizing past experience as well as the design rules. Stresses,

deflections, bearing loads, etc., cannot be determined until a design has been assumed. If certain stresses, etc., are too high, then the design must be modified.

When specified, design for shock sets performance criteria in the truest sense. Unlike many other performance criteria, however, its adequacy often cannot be judged by a go/no-go test because of the physical size of the items involved. The true acceptance test would occur if the warship were attacked, but then the equipment had better pass the "test." In the absence of this or a reasonable substitute, acceptance or rejection of a unit as meeting shock design requirements must be based on predicted performance under such requirements. It is not enough, with the present state of the art, to merely specify the environment and allowable stresses or deflections. Because of the vital importance of the problem the intervening stages (contrary to present-day practice) must be jointly reviewed by the naval engineers responsible and the vendors' cognizant personnel. Decisions must be made during this review stage to ensure that the final product is acceptable from all standpoints, without expensive "reinvestigations" or delays in delivery.

Before discussing the background to, and use of, the present BuShips-NRL Design-Analysis Method, it will be helpful to recall other techniques which have been used in the past and which may be in use now. It will be well to remember that the proper comparison of the several design procedures requires that they be evaluated both for the same "attack situation" (even though the design input may be specified in different fashions), and for the same kinds of failures (even though the performance standard may be specified differently). The proper assessment of design procedures would require that each of them be applied to several identical design situations, and the results compared on a "damage basis."

Shock Design Number Methods

The procedure previously used by BuShips for design of "sub-bases, hold-down bolts, feet, and main structural members" of items weighing more than 4500 lb is of the shock design number type. The design input is specified by a shock design number which varies with the gross weight of the item, with the type of ship, and with the direction of attack. The item weight times the appropriate design number gives a static force to be applied at the c.g. of the item, prior to a static analysis; loads in three orthogonal directions are applied individually, with no superposition of any other stresses. The performance standard is the yield strength of the material.

This method has been very popular because of its simplicity; however it is of limited usefulness and realism. In various studies (26-30) it was shown that the BuShips curves were unrealistically low. Various proposals were made (26,28-30) to increase the shock design numbers, but these were never implemented because it was demonstrated (27) to BuShips that the shock design number approach is basically incorrect since it completely ignored variations in flexibility (or stiffness) for different installations. It also is incomplete because it offers no design check procedure for internal parts of the item or for the foundation supporting the item.

A variation of the basic shock design number procedure has been proposed (7,26) for surface ship installations. These reports propose shock design numbers larger than those of the BuShips curve, based on short-duration accelerations measured from velocity-time records, and also adds a "resiliency factor," based on peak shock spectra, which modifies the shock design number in accord with the ratio of the dominant frequency of the item to the shock disturbing frequency of the general input motion. The proposed curves of shock design numbers and resiliency factors were obtained from "envelope-type" analyses of available test information on surface ships. The yield strength is the performance standard. To the authors' knowledge, the accuracy of the proposed procedure has not been investigated, although Ref. 26 recommends this.

This proposal was made prior to work which showed the "spectrum-dip" effect (31-35); the use of peak spectra envelope-type analyses to obtain shock design numbers is therefore suspect, unless an extremely conservative design method is desired. This variation, with some changes for the modified ship design, has been used in the past as a design specification (36) for certain components of the nuclear power plant on a modern destroyer.

Iteration

The iteration approach gives a dynamic design analysis procedure which is completely numerical, and utilizes iterative convergent solutions of the equations of motion, with particular inputs as a function of time. Although a number of numerical methods are given in the literature, a leading proponent of this approach has been Newmark (37). Of interest here is the proposed procedure for design-analyzing equipment foundations on submarines. An early report in this investigation contained a comprehensive literature survey, with coverage through 1956 (38). Later reports describe the analysis procedure (39) and discuss design inputs (40). The procedure is for design analysis of foundations only and assumes that large inelastic action (yielding) is often desirable. The equipment item is assumed to be a "rigid" mass, and the foundation is idealized as a yieldable spring between it and an "effective" mass of a part of the hull. The design input is the pressure-time description of the free-water shock wave which acts as a forcing function on the hull mass. The spring is assumed to have an idealized elasto-plastic load-deflection curve, and analysis of this nonlinear two-mass system determines the foundation design. A very significant decision required during the analysis procedure is the magnitude of the "ductility factor," which is the ratio of the total elastic-plus-plastic spring deflection to the total elastic deflection. With this model, a variety of design conditions can be analyzed, and the results presented in graphical form. If this simple model is not considered adequate for a particular design situation, a more complex model can be used.

The design approach has the advantage of explicitly including plastic action, but since the dynamic interaction (spectrum-dip) effect between equipment and hull is a proven fact (at the University of Illinois, also) (41,41a) the interrelation between the general input at the hull and the real ductility factor of the foundation is complicated. The procedure is not directly useful for the design of equipment or machinery, since this was not the intent. As Newmark states (39) "In many respects the procedure described herein may be considered to be one that is suitable for a preliminary design. Further analysis by more elaborate procedures can be made to investigate the adequacy of the preliminary design after it is completed. In general, this is not necessary for the design of the foundations, but it may be desirable for the purpose of investigating the behavior of the equipment supported by the foundations."

A recent BuShips design data sheet (42) "is applicable to a foundation, supporting equipment which is to be treated as a rigid mass, when criteria are stated in terms of accelerations or loads and energies or velocities." For simple systems this method applies some of the limit analysis techniques, while for more complex systems it more closely follows the present shock design-analysis method of NavShips 250-423-30.

Present Shock Design-Analysis Method

NavShips 250-423-30 and NavShips 250-423-31, with their respective amendments (19), form the basis of the present shock design-analysis method in current use by

BuShips. In essence the procedure specifies design inputs as design shock spectra (derived from shock test data) which, when used as inputs to equipment systems described by their respective normal-mode parameters, produce estimates of meaningful performance standard parameters such as strain and deflection. While it is based on theory which assumes linear and elastic systems, the procedure has been shown to give reasonably correct results when applied to actual shipboard systems (43-47). This procedure is discussed quite completely in a later section. A number of variations of this basic procedure have been used, particularly for reactor design analyses (48,49). For submarine machinery, one variation from the standard method, which considers the input to the equipment-foundation system from an assumed-rigid hull, is to consider inputs from "fixed" bulkheads, with the hull flexibility added to the foundation flexibility. While this has certain attractive features, it immediately raises several added problems: (a) since hull flexibility cannot be computed accurately, plastic models of the compartments and/or experimentally determined flexibilities are required, (b) further investigations would be required to establish rational design inputs at this new location, especially with respect to the dynamic interaction (spectrum-dip) effects, and (c) the shock wave impinging on the hull would introduce force loadings on part of the dynamic model (in addition to the basic design input at the bulkhead), with the inherent complications in analysis. Several other variations, some of which use both shock design number procedure and normal-mode procedure, have been proposed (50). BuShips, in addition to the shock design-analysis procedure, specifies certain basic ship motions (20) which are design inputs for special design problems where a dynamic design analysis is needed.

V. RESULTS FROM PAST RESEARCH AND ENGINEERING

Development of Theory and Analysis Procedures

Since theory and research provide the basis of any rational shock design-analysis method, a summary of the pertinent research accomplished at NRL—which has directly influenced the present BuShips Dynamic-Design-Analysis Method (DDAM)—seems to be in order.

In 1948, NRL Report 3302, "The Equivalent Static Acceleration of Shock Motions," was published (51) in which the concept of earthquake spectrum, proposed by Biot (52) was extended to cover the case of mechanical shock.

A sequence of reports (53-57) unified and clarified normal mode theory (which is used in the DDAM) and presented it in a fashion that most practicing engineers can understand, i.e., by using only the mathematical methods which are familiar to most engineering graduates.

In 1952 and 1953 NRL participated in a series of underwater explosion tests designed to help in shockproofing nuclear powered submarines. Parts I through V of a series of reports (58) describe the components and damage, present the data obtained, review the background shock theory, derive scaling relations for the models, and discuss deviations from theory. Part VI examines the former design criteria as given by the specification curves in terms of strain gage data recorded during these shock tests. "Computed design accelerations," which are the ratios of the maximum recorded strains to the strain computed due to a load equal to the static weight acting in the direction of the shock, were calculated. Most of these computed design accelerations were found to be considerably higher than the shock design numbers which would have been read from the former specification curves. It was therefore concluded that a curve of design acceleration (or shock design number) as a function of weight alone cannot predict elastic shock stresses in submarine equipment with satisfactory precision. Part VII showed, in plots of measured shock parameters versus shock factor, that these shock parameters increased at a smaller rate after the hull structure had yielded than before it yielded (than when it remained elastic).

In 1954 an interim shock design method (59) based on normal mode theory was proposed for submarine equipment and machinery. The shock-spectra obtained from previous tests were divided into classes of shock, and those classes were subdivided into groups according to weight and location. (The rational selection of these classes and groups was a difficult and time-consuming task, simply because of the significant variations observed among data one would expect to be very similar.) These spectral classes formed loosely correlated groups which were analyzed statistically for fiducial limit curves. The 90% fiducial limit shock spectra obtained in this fashion were recommended as design inputs to be used in connection with normal mode theory. Provision was made for considering plastic behavior and for using energy methods of analysis. Included were various charts and graphs to aid in the design procedure.

In 1955 a draft report (60) was prepared on the design criteria for a heavy-weight shock machine. The approach followed the fiducial limit type of thinking. The report was never issued because the fallacies and penalties inherent in "envelope" spectra were shown by concurrent research.

It became apparent from application of the interim design method (59) that few structures could survive the intensity of shock described by the fiducial limit curves. However, structures which were in place during the shock trials from which the input data was obtained did survive. Design analyses using the fiducial limit curves predicted they should have failed rather spectacularly, so obviously something was wrong with either the theory or the combinatorial analysis which produced the fiducial limit shock spectra. Attention was immediately focused on this problem, and normal mode theory was reviewed. Since normal mode theory only demands that shock spectrum values which correspond to the "fixed-base" natural frequencies be used, an inverse application of the theory immediately showed that the shock spectra for those equipments in place during field trials exhibited valleys in the region of their fixed-base frequencies. This was labeled "shock spectrum dip," and in 1956 two papers (31,32) reported it.

Since the problem of shock spectrum dip was so important, work was carried on in three general directions: (a) a review of the existing data, (b) experimental verification of the shock spectrum dip, and (c) theoretical and analytical studies to explain the phenomenon.

In 1957, a report (33) was published discussing this problem. This report presented experimental evidence (the data from the 1952 and 1953 series of tests) concerning the effect of equipment dynamic reactions on the shock motions of support structures. Since shock spectra are important measures of shock intensity for use in equipment design, some of the effects on these spectra were reported here. For the analyzed data the spectrum velocity of interest was plotted as a function of effective mass. A derivation of the mathematical description of this effective mass was presented. This important report made the following points:

1. The spectrum values which apply to the computation of stress in an equipment structure are only those which coincide with the fixed-base natural frequencies of the structure in place during the shock motion, and the dynamic reaction of the structure upon its foundation acts in such a way to make its applicable spectrum values near the lowest point of the spectrum valleys.

2. Unless one knows the fixed-base natural frequencies of the structure before a test, and has specially-tuned reeds at these frequencies, the reed gage records obtained at the foundation of the equipment will yield information of slight value and definitely not

the information required for design; a shock motion record must be measured and analyzed to obtain design data.

Work continued on the problem, and in 1958 a paper and a report dealing with shock-spectrum dip were published. The paper (34) emphasized the potential errors resulting from the neglect of impedance effects during field measurement. It pointed out fallacies in the assumption that shock and vibration machines have impedances like actual equipment foundations. A related error results from the tacit assumption, in making measurements, that foundation impedance is large compared with equipment impedance. It pointed out that using specifications with this unacknowledged assumption may result in overdesign by factors of five or more.

The report (35) presented laboratory experimental evidence of the shock spectrum dip. This report discussed a series of tests performed at NRL on a model structure whose stiffness and mass parameters could be varied. Shock spectra (from numerical integration of velocity meter records) for twelve different combinations of stiffness and mass were presented. It was demonstrated that, even for the same shock-generating system and weight of test structure, the shock spectra obtained are extremely sensitive to the frequencies of the test structure being considered. It was shown that the peaks in the shock spectra occur at the natural frequencies of the system as a whole, and that these frequencies do not, in general, correspond to the fixed-base natural frequencies of the equipment. It was shown that valleys in the spectra appear in the vicinity of equipment fixed-base natural frequencies, and that spectra levels in these valleys (rather than those of the peaks) control the stresses in a structure. The extreme overconservatism in design resulting from incorrect usage of shock spectra was pointed out. It was also stated that the type of fiducial limit analyses attempted before could not hope to produce rational design inputs.

Concerning this phenomenon of shock-spectrum dip a paper and a report were published in 1959, giving a theoretical approach to the problem. The theoretical papers (61), using mechanical impedance and Fourier integral techniques, demonstrated that the undamped "after-shock spectrum" is in reality the Fourier spectrum of the shock motion. As a result of this, a theorem was presented which states that the undamped shock spectrum is always greater than, or equal to, the Fourier spectrum of the input. Additional studies showed that the shock spectrum peak values coincided with natural frequencies of the combined systems, whereas the values useful for design lie in the intervening valleys. It was also noted that the shock spectra tend to be unique for each shock, because each shock spectrum has associated with it a Fourier spectrum.

The theoretical report (62) used three simple examples to illustrate the large difference between ordinary shock spectra measured during tests and the "design shock spectra" which are really needed as design inputs. It also pointed out that, even when the equipment fixed-base natural frequency coincided with a natural frequency of the system as a whole, the resulting shock spectrum value at this frequency did not lie on a large peak in the spectrum.

The data from field tests were reviewed with this new information, and significant parameters such as effective modal weight and limiting design accelerations were formulated and checked. This knowledge led to the original BuShips interim shock design values which were used with the DDAM. In essence the recognition of dynamic structural interaction effects made a rational determination of design values possible.

Recent theoretical studies and exploratory research have emphasized work on impedance (63-70); for example, a state-of-the-art survey of impedance (67-70) has been conducted. The most obvious conclusion of this investigation is that reliable mechanical impedance measurements are rare. Before impedance techniques, using measured data, can be of any help in research, engineering, or dynamic design analysis, much must be accomplished.

To aid in calculating the response of linear and nonlinear structures to time dependent inputs—of the type recommended in NavShips 250-423-29—several NRL reports (71-74) have been published and are an aid which is available if the system to be analyzed is such that this is necessary. Work has progressed on the solution of certain classes of linear and nonlinear differential equations, algebraic equations, matrix eigenvalue and eigenvector problems, and Fourier series and Fourier integral transforms, as well as many other problems which arise in structural dynamics.

Two of the most recent examples of research which has had immediate influence on the state of the art are (a) a memorandum report (75), dealing with velocity meter corrections, which corrects some mistaken notions in previously used techniques and (b) an elementary study (76-78) of the theory of resonance testing which points out that the generally accepted engineering methods of experimentally determining certain natural frequencies are theoretically incorrect.

In this brief description of the need for theory and research in developing any rational procedure many items have been glossed over or left out entirely. In any quick treatment such as this it is impossible to cover everything, so only the main points directly related to the design of structures have been discussed.

Experimental Check of the Method's Validity

The current DDAM has been "field tested" several times.

As part of the "SS 428 Insert" testing program a memorandum report (44) was published describing a stress and flexibility study of an SS 567 class submarine motor-foundation system. Mockups of the main motor were installed in the insert section of the submarine ULUA (SS 428) and shock tests were performed. Estimates were made from construction drawings of the flexibilities and natural frequencies of the system. Experimental jacking tests were conducted to check the computed flexibilities. Damage to this system was then predicted, and this damage was observed during the tests. These predictions were made using the first realistic design shock spectrum, which was based on results shown in Ref. 33 and thus considered the spectrum-dip effect. The relatively good experimental verification of the predictions would not have occurred if the fiducial limit spectra had been used as design inputs.

At a Shock and Vibration Symposium in 1960 a paper (45) was presented showing actual results of applying a rational design method to the CGN model cruiser. The purpose of the tests on the CGN was twofold, namely (a) to study the design procedure, as applied to real equipment systems, and (b) to provide information as to the inputs to be expected for this type of ship. Calculations, using information from construction drawings, jacking tests, and vibration surveys, were made to obtain the desired information for application of the design-analysis method.

A recent series of tests on the DD 474 (FULLAM) provided another evaluation of the design-analysis procedure. Here again, the objective was to study and evaluate the design procedure and to obtain design input information. A letter report giving the predicted responses was made (79) and an analysis report is in progress.

For some years before general acceptance of the DDAM was made by BuShips, the Nuclear Reactor Code (1500) at BuShips used this technique in its previous interim forms, and in its present form. It was recognized very early that the shock hardness and general safety considerations of nuclear components within submarines would have to be of very high quality and reliability. As a result, their experience has proven invaluable in gaining acceptance for the more rational shock design analysis procedure.

Two memorandum reports on the routine SKATE (SSN 578) shock tests have been published (80,81). One report shows the use of the DDAM to predict shock responses; the second report gives preliminary results from the tests. Preliminary reports of NRL results from routine shock tests on the SKIPJACK (SSN 585) and the THRESHER (SSN 593) were included in overall test reports (12,82). This test data has been used in developing current DDAM inputs and will be reported on more fully.

The Electric Boat Division of General Dynamics has compared pretest and post-test predictions of the DDAM with measured values obtained during the THRESHER and SKIPJACK shock tests (46,47). Agreement was found to be good.

As with any new advance in the state of the art there has been some disagreement among various groups and individuals concerning the complexity, value, cost, correctness, etc., of this method. Years of effort and thousands of dollars of government money have been spent to improve on the gross oversimplifications demanded by the empirical static design approach. Except in special limited situations shock design numbers, peak velocities of essentially similar motions, peak accelerations, etc., are inadequate and dangerous descriptions of a complex environment. On the other hand, experience has shown the usefulness and validity of the DDAM. Further research can bring improvements, but a major gain is already in hand.

We cannot agree that costs must rise sharply if the method is routinely applied. We do not believe that the weight penalty, if any, will be great, since it will become possible to make more rational strength distributions. The "beefing-up-of-the-weak-points" stage should disappear as second and third generation designs evolve, and less material will be wasted in unproductive regions. An auxiliary benefit, derived from a requirement that equipment either pass a shock test or be shock designed, is that the vendors and Navy engineers will improve shock-resistance tremendously, merely by being forced to think of the environment. Warships with their equipments and weapons systems can be built which are capable of fighting on after receiving a severe attack.

VI. NEEDS FOR FUTURE RESEARCH AND ENGINEERING

It has been demonstrated in this report that theory, research, and engineering development of procedures and processes can pay off with better engineering tools to produce better equipment. Basically we need more of this process.

The presently constituted shock design values will have to be revised to fit different situations. Since this is a classified subject, and this paper is not, detailed discussion of this must be postponed. However, it is possible to say that theory, supported by controlled experimentation, can supply most of the needed answers; these answers cannot be obtained as efficiently—if at all—without continuing research to guide the needed measurement program.

The effect upon shock transmittal of antinoise mounts is not sufficiently well understood. The ability to measure mechanical impedance, both inside the laboratory and outside, needs to be upgraded if this powerful tool is to ever have much practical value. The wide range of nonlinear shock design problems and the effect upon the environment of nonlinear structural feedback needs to be investigated.

The results of research and development need to be made available to the practicing engineer. This is an education problem. A recent great stride in the right direction was made by BuShips, who sponsored a series of six-week courses in structural dynamics for Navy civilian engineering personnel. More should be done.

The equipment "shockproof" testing requirements should be reviewed and efforts made to have a clearer understanding of the relationship between the tests and the real environment.

This list of needs in shock could be continued, but these are largely self-evident.

The recognition that shock is an essentially dynamic problem, not a static one, has been a long time in coming. There now exists an excellent opportunity to perform a valuable service by extending both our capabilities for protecting our ship systems and our knowledge. The persistent pursuit of a rational understanding of shock phenomena has in the past paid dividends and will continue to do so in the future.

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13 ABSTRACT

This report has been prepared to describe some of the progress made since World War II in the several areas related to the complex set of problems encountered in shock design and analysis of shipboard systems. It discusses: requirements for shock protection, selection of failure criteria, determination of shock environment, development of analysis and design procedures, results from past research and engineering, and the needs for future research and engineering. Essentially it sketches the evolution from the simple shock design number concept, which is limited, to a more rational approach which can allow the shock design-analysis of unprecedented equipment.

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