An Historic View of Shock and Vibration

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This article examines shock and vibration technology as it was more than 60 years ago and makes a broad comparison to our current capabilities in this critical field. We effectively journey through time, pausing along the way to identify some critical developments that provided tools that accelerated advances in shock and vibration technology. These are both analytical and experimental advancements in dynamics as well as peripheral developments, without which we could not have achieved such phenomenal success.

Dr. Elias Klein of the Naval Research Laboratory (NRL), in cooperation with representatives of other naval laboratories, convinced the Office of Naval Research (ONR) of the importance to the Navy of the interchange of technical information on shock and vibration. This resulted in the Naval Research Laboratory's being directed *to act as a center for the collection, correlation, and dissemination of all available information on this subject.*[1] On January 7, 1947, the first Shock and Vibration Symposium was held at NRL for the purpose of planning the steps necessary for NRL to carry out its responsibility. The discussion at this meeting was enthusiastic and the results were fruitful. The information exchange was to be accomplished by a series of shock and vibration symposia hosted alternately at first by interested Navy laboratories. A parallel series of shock and vibration bulletins were to be published and would contain the proceedings of the symposia along with other useful related technical information. Klein[1] originally described the contents of the bulletins as follows.

> *An unclassified bulletin will be issued bimonthly to participating Naval activities. It will contain minutes and scientific notes on the symposia; notes on the facilities of various activities; reports on recent work; some papers on theory or experiment or on both; articles on work recently done, work in progress, or proposed projects.*

It is instructive to note that the participants in the first symposium listed Suggested Topics for Future Symposia in the form of questions:

- What is the nature of shocks caused by (a) noncontact underwater explosions, (b) gun blasts or air blasts from bombs, (c) rocket exhaust, and (d) impacts?
- What relation exists between shock experienced by equipment mounted in superstructures of ships and that attached to hull members?
- How closely do the characteristics of existing machines simulate present service conditions?
- How much dependence should be placed on resilient mounts for the protection of equipment?
- What intensity limits of steady-state vibrations can be tolerated by (a) instruments, (b) beings?

These are very important Navy-related questions. Many other general shock and vibration questions have been raised over the past 60 years; whenever possible, the symposia have been planned to provide answers.

In the sections that follow, our shock and vibration capabilities will be examined as they were 62 years ago and how they evolved. The greatest emphasis will be on measurement and testing. Some special developments that contributed greatly to the advancement of our technology will be highlighted. These include not only developments within our field, but also other technological developments that provided new tools that increased our capabilities beyond our wildest dreams. Shock and vibration is a critical and enduring technology as evidenced by the fact that the 79th Symposium was held 62 years after the first.

Early Years

Among the early measurement devices were peak-reading accelerometers.[2] These were mechanical gages designed to indicate the maximum acceleration of a shock motion. These were: (a) the putty gage; (b) the Buchanan gage (a weighted-end cantilever of the same type as the putty gage); (c) the indenter gage; and (d) the ball-crusher gage. Blake[2] discusses the principle of operation of each gage. Sources of error are discussed, particularly those due to the duration of the acceleration. The necessary conditions for minimizing these errors are pointed out, and the work yet to be done is indicated. Velocity shock was measured on ships by a very heavy British velocity meter. A smaller velocity transducer was manufactured at the time by the MB Corporation.

One of the most useful developments for measuring naval shock was the multifrequency reed gage, otherwise known as a mechanical shock spectrum analyzer. Reed gages were designed and constructed for measuring shock motion on ships. The gages consist of a set of reeds of different natural frequencies rigidly attached as cantilevers in a heavy frame that is fastened rigidly to the structure subjected to the shock motion. The reeds have masses at their extremities to which styli are fastened. These styli scribe a record of the motion of the reed on waxed paper. For measurements, the gage is installed so that the longitudinal axis of the reeds is normal to the direction of the applied motion. One of the outstanding features of the gages is that their operation requires no power supply. They may be installed in many places where other available instruments would prove impracticable. The reeds with masses attached are single degree of freedom systems of different natural frequencies. A plot of the excursions of the reeds during a shock event is the shock spectrum of that event. References 3 and 4 provide informative discussions of reed gages.

Vigness[5] very astutely stated that the general objectives of mechanical shock measurements are threefold:

- *First and most fundamentally, to make measurements which give the shock motions in quantitative units as functions of time, the results of which can be studied to determine proper steps for their elimination or isolation.*
- *Second, to make limited measurements that provide information concerning important features of the shock motions. These include maximum accelerations or displacements within a given frequency range and comparisons of intensities of similar shocks by measurements of one or more components of the shock motion.*
- *Third, to directly measure what the shock motion does to certain idealized mechanical systems, and to directly obtain damage probability, design criteria, and a comparison of the damage potentialities of shock motions without much concern about what the shock motions are.*

He obviously had a clear understanding of our needs for shock measurements. They did well with the instruments of the day, but the real measurement capability was yet to come.

Testing and Measurement

The status of testing (simulation) had advanced significantly by the mid-1950s. Crede[6] stated that vibration testing procedures had undergone a pronounced evolution since 1947. His paper presented a review of vibration testing procedures leading to the present concept of the continuous spectrum or random excitation. Means used to define the vibration existing in an environment were discussed, and there is a comparison of scanning at discrete

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frequencies versus testing with random excitation. Crede not only presents a clear description of the vibration test trends of 50 years ago, but discusses factors that influence simulation choices that are still valid today. His closing remarks were probably written because at that time random vibration was still quite controversial:

> *Finally, the simulation of vibration environments is currently in a very tentative state. Much more information is needed, not only on the nature of environments but on the strength of equipment when subjected to vibration, before it will be possible to state with some degree of certainty that a particular testing procedure is adequate to qualify equipment for use in any designated environment.*

In 1956, random vibration was still a new concept. To become better acquainted with the problems with this concept, McIntosh and Granick[7] conducted a study of the response of simple beams to this form of vibration. The work in their preliminary investigation is described in their paper. The authors intended to continue and extend this investigation to determine the value of random vibration testing. The final paragraph in this paper is quoted to give the reader an understanding of the status of random vibration at that time:

> *The real value of random vibration test techniques actually cannot be appraised until more is known about the true service environment. Investigations must be conducted on the structural conditions in widely scattered regions of missiles. These investigations ought to be of a thorough, comprehensive nature similar to those conducted on aircraft. It is essential that the highest priority be given to these assignments, because from these studies and from laboratory experiments, we shall be looking for the answer to the question: Is it necessary to adopt random vibration testing as a general requirement?*

Noonan[8] reviewed the requirements for vibration testing of shipboard equipment specified under Type I - Environmental Vibration, in MIL-STD-167(SHIPS). Information was given to provide a better understanding of the importance of environmental testing. He describes some of the reasoning behind the development of the MIL-STD-167 specification that after a few revisions is still the specification required for equipment to meet Navy vibration requirements. This paper provides excellent guidance on the application of the specification, the types of equipment to be tested and on designing to meet test requirements.

A milestone development that advanced our vibration test capability probably more than any other single event is described in a paper by Hansen.[9] He developed the first horizontal oil slip table for horizontal vibration testing by using a horizontal test fixture that could technically be called a "flat hydrostatic bearing." It consists of a flat, fixed plate upon which a movable specimen table in the form of a similar flat plate is suspended on a film of oil. The specimen table is free to slide horizontally but resists with almost infinite force any vertical motion either as a complete entity or as a spurious, resonant, standing wave such as those to which most other tables are prone. (The forces are similar to those that hold together optical flats or Johansson blocks.)

The lower plate is fixed solidly to the foundation or to a large mass such as a concrete-filled steel box. The height and level of the whole fixture is adjusted by four jack screws located in the bottom corners. The movable specimen table is driven by a drive rod in the conventional manner. There was extensive discussion following Hansen's presentation, all of which is published with the paper in the proceedings. It is believed that within two years, most all of the vibration test laboratories had a horizontal slip table.

At the 27th symposium, there were a number of papers on fixture design, with special emphasis on horizontal testing. Hansen was an innovative test engineer just doing his job. He very likely had no idea that his work would have such a great impact on vibration test technology.

To give a better understanding of the status of shock and vibration activities 50 years ago, a few examples are given from papers describing the effort at that time. For example, Armstrong[10] was concerned with evaluating the validity of shock tests. The purpose of his paper was to explore the usefulness of some of the simplest dynamic and static relationships in pointing the way toward testing that can result in correct design and evaluation decisions in cases where the state of knowledge of field condition or specimen response is incomplete and where also the capabilities of testing equipment falls short of the mark in various respects. In other words, the essence of valid shock simulation is that the tests reveal in the test specimen the effects that would result from the service condition being simulated.

Morrow[11] discusses a number of considerations in shock and vibration, the philosophy of smooth specifications, the test of components versus parts, force versus acceleration for amplitude excitation and the single frequency equivalent. His discussion relates mostly to vibration test specifications.

It was noted previously[7] that random vibration in the 1950s was a relatively new and controversial concept. Booth[12] presented a paper describing the nature of random motion and how it is generated. He said that the properties of random motion most useful to the vibration engineer are stated in simple terms. The method used to create these motions in the laboratory and operation of the major components of the required equipment is briefly described in his paper.

Wimpey[13] presented a method of applying the continuous-spectrum concept to vibration analysis of electronic components. The acceleration spectral density spectrum concept is defined by the author, and the mechanizing of this concept and its subsequent evaluation are discussed. Modifications of conventional vibration equipment are described and instrumentation methods for measuring the statistical variables with this technique are defined. In the 1950s, vacuum tubes (electron tubes) were still widely used. Robbins[14] described a white-noise vibration test developed for the vibration evaluation of vacuum tubes over a wide range of frequencies. White-noise, random vibration with all frequencies present is explained theoretically and compared with sinusoidal vibration. The author describes a practical test method and presents details on the white-noise generator, vibration test equipment and methods of reading the tube noise output.

Five decades ago, we were already in the age of jets and guided missiles; this resulted in an increase in the severity and variety of mechanical environments for equipment in military applications. Among the more important resulting changes was the extension of the frequency range of mechanical excitation to which electronic components were subjected. Researchers realized that much of this excitation is transient and aperiodic in nature. This is why Wohl and Schnee[15] discussed the relative effectiveness of impulse versus steady-state excitation in the field of resonance and compared vibration testing of vacuum tubes using a precision impulse exciter. Optimum excitation, representative of the broadest range and field environment, is considered.

Fuses were important in the warheads of guided missiles. For this reason, two independent approaches were followed by Warren[16] to obtain information for designing reliable fuses. One approach determines the vibration environment of the fuse in flight and attempts to simulate it in the laboratory. The other approach is to construct the fuse to function reliably under the full output of a vibration exciter while being swept through the available frequency range. At the time the paper was written, the first approach had not been successful. As a secondary objective, however, production of an *equivalent damaging effect* was satisfactory.

Relating to vibration testing, Yorgiadis[17] collected and published experimental acceleration-time records of various types of mechanical vibration tables. He showed that in addition to the fundamental sine wave of vibration, there are superimposed high-frequency random harmonics that are of substantial magnitude. These undesirable harmonics were found to originate in gears, ball and roller bearings, or other regions of repeated localized impact.

A vibration testing machine for very heavy loads was described by Brown and McClintock.[18] Large airborne cryogenic equipment weighing up to 10 tons was subjected to sinusoidal vibration testing on the NBS-60,000 mechanical shaker. The experience gained was used to design a second machine capable of testing units weighing up to 20 tons.

Barnes and Mock[19] described two vibrators for testing small electronic components. One is a magnetostrictive unit with a flat response (20%) between 1 and 10 Hz. The second is a liquid jet vibrator producing a nearly uniform acceleration spectral density between 1 and 10 Hz.

Edelman, *et al.*,[20] described a special vibrator for testing items up to 10 lb to accelerations of 10 g from 1,500 to 15,000 Hz. Greater acceleration can be reached at the many axial resonances of each vibrator.

A lot of attention was and still is paid to shock testing devices and techniques. Blake[21] presented a good argument that machines for simulating shock (as well as sinusoidal and random vibration) cannot afford to neglect the mechanical impedance of the item under test. Unfortunately, machines of that era were usually designed to duplicate the envelope of typical field motions without considering the impedance. Blake acknowledges the difficulties of dealing with this problem, but points out that finding solutions would enhance the validity of the tests.

There were several other diverse papers on shock testing in the same proceedings. At the Naval Ordnance Laboratory, there was a need for a shock testing machine to validate the design of submarine weapons and equipment. Mead[22] describes a program to develop a shock test machine called the UWX (underwater explosion). This machine may well be the predecessor of a machine developed at Naval Ordnance Laboratory at White Oak and designated as the WOX (White Oak experiment). The WOX machine still exists, and tests are being run at its present location in NSWC Dahlgren, Virginia.

Before the current design of the Navy's Floating Shock Platform (FSP), now the Navy's official heavyweight shock test facility, there was a program to develop a mechanical heavyweight machine described by Gareau[23] in a 1956 paper. At the end of the paper, a schematic drawing of this complex machine was included. Of course, the machine was never constructed.

Westgate[24] described an unusual drop-test facility to test materials and instruments at high impact levels under controlled conditions. The facility was a 300-ft, universal, drop-test tower that was installed at Sandia Corp. (now Sandia National Laboratories) and used a then-new type of gas-energized, hydraulically controlled accelerating device known as the HYGE actuator.[25] In machine operation, stored energy in the form of compressed air is released instantaneously, and the waveform is then controlled by means of hydraulic flow through an orifice controlled by a metering pin.

Sanders[26] describes the design, operation and performance of the pneumatic impactors used to generate the boost phase of the flight of the Talos missile. The simulation covers the high acceleration at the start of the boost phase and moderate deceleration between the booster burn-out and the missile's combustor ignition.

Finally, an inexpensive shock machine developed for testing lightweight items was described by Schatz.[27] The shock pulse obtained is approximately a square wave, and a somewhat novel arresting media of lead and plastic was employed.

Four papers in the area of measurement in the 1950s provide interesting information. Jones, *et al.*,[28] published a paper describing a number of small pick-ups designed to meet special requirements in a number of different applications. Essentially small pick-ups are required to avoid loading the equipment under test significantly. This way the weight of the pick-up does not affect the equipment response during the test and ensures that the measurements are accurate.

Meyer[29] describes the development and use of a statistical amplitude probability meter. It was a device that would provide a measurement of the statistical amplitude probability distribution of a forcing function. By this means, randomness is proven or, if the function is not random, will give insight to the amount of periodicity present.

Upham and Dranetz[30] describe development of a miniature recording accelerometer that can be mounted directly on a test structure. At that time, it had already been used to monitor simulated water-entry impact of torpedoes. A playback device reduces pulse-coded information to analog form for further recording, analysis or control.

Transducers must be calibrated. Christensen[31] reviewed sensors as well as calibration techniques employed in the laboratory. He discussed the virtues and vices of commonly used calibration techniques. He then described a system of optical calibration that had been developed.

It is obvious that the references discussed in this section are mostly from the 23rd Symposium. This symposium had the greatest number of attendees ever. It is viewed as a milestone symposium at a time when enthusiasm for advancing the technology was at a peak. It provides a reference point to compare today's capabilities in the same technical areas. Of course, there have been many landmark papers published in the many symposia since then, but it is not possible to reference and discuss each of these in this brief article. Instead, I refer you to a DVD containing all unclassified symposium papers through the 78th Symposium. The DVD is available for purchase from SAVIAC.

There is no question that our current capabilities in shock and vibration testing, measurement and analysis are indeed remarkable. In the remainder of this article, some of the developments that accelerated this advancement are discussed.

Advances in Shock and Vibration Technology

Probably the most significant development that contributed to the technological advancement was the development and evolution of the computer. Most "old timers" will remember that we were still doing computations using the slide rule. Development of the electronic calculator was a huge step forward at the time. But by far the greatest increase in our computational capability is the evolution of the computer. The early computers were slow and had little memory and, in fact, were used mostly for word processing. Over the years, with development of hard drives and the rapid increase in the amount of memory available, our computational capability rapidly increased. Today the average personal computer has many times the memory capability of the early mainframe computer and is faster and easier to use.

Software development kept pace with the hardware, and today the response of the equipment and structures to shock and vibration loads can be rapidly calculated. This is possible due to the development of methods like finite-element modeling. (FEM) Using FEM on complex structures produces models having 100 degrees of freedom or more. Computer programs like NASTRAN can calculate the response of such structures without the burden of extensive computer time. Equations of motion in matrix form have become the usual approach to conduct dynamic analyses in both the time and frequency domain.

In the area of testing, measurement and data analysis computers are also the tool responsible for our increased capability. Both shock and vibration tests are more often than not programmed and controlled by computers resulting in more precise and accurate simulation of the field environment. We are in a digital age. Using a personal computer with several gigabytes of memory, an engineer can analyze field or test data and present the results very quickly in the format of his choice. For example, from a transient acceleration time history record he can calculate velocity or displacement, plot a shock spectrum and much more.

In the area of shock data analysis, the digital age essentially began in 1965 with the development of *An Algorithm for the Machine Calculation of Complex Fourier Series* developed by Cooley and Tukey. This is better known as fast-Fourier transform (FFT). In the late 1960s, several papers covered the digital calculation of response spectra from earthquake records, studies of selected shock analysis methods and digital shock spectrum analysis by recursive filtering. In addition, a monograph was published by SAVIAC in 1969 on the principles and techniques of shock data analysis. In this digital age, publications like these have resulted in an ever-growing list of vendors offering analyzers and other equipment for special purposes like machine monitoring for fault detection, response of structures to earthquakes and other applications.

There has also been a rapid development of new transducers to measure almost any parameter that might be related in some way to shock and vibration. Most recently, there has been a surge in the development of MEMS devices, some of which are miniature transducers such as accelerometers. Despite all these advancements, many research efforts are underway to develop new approaches and equipment to help solve some problems that still exist. One wonders what the shock and vibration world will be like 50 years from now.

Summary

We have examined shock and vibration technology over the past 60 years and offered some hints to the reasons for our present enhanced capability. We recognize that a number of cutting-edge papers in our technology could not be included in the references. As the technology moves, remember that the study of dynamics began not just 60 years ago but more than 300 years earlier.[32]

In 1579, a young medical student at Pisa was worshipping in the Cathedral. Save for an annoying rattle of a chain, there was silence in the Auditory. A Sacristan had just filled a hanging oil lamp and left it swinging. The noise of the oscillating chain interfered with the student's meditation and started him on a train of thought that was far removed from his devotion. He observed the rhythm of the swinging lamp, it seemed to him that its beat was regular, that the swinging lamp was taking exactly the same time in each of its oscillations, although the amplitude was continuously diminishing. Was his observation correct? If so, he had come upon a fundamental fact.

When he got home, he took two threads of the same length and attached them to two pieces of lead of the same weight. He then tied the other ends to separate nails and was ready for detailed observations. He took the two pendulums, drew one of them to a distance of two hands' breadth from the perpendicular, the other to four hands' breadth and then released them simultaneously. With an assistant, he counted and compared the oscillations of the two threads. The total was exactly the same – 100 counts in each case. The two threads, in spite of the great difference in their starting points, ended their swinging at the same time. In the swinging motion of a cathedral lamp, therefore, this young man discovered the rhythmic principle of nature, which today is applied in the counting of the human pulse, the measurement of time on the clock, the eclipses of the sun and the movement of the planets.

The young man was Galileo (1564-1642) the founder of the science of kinematics and the one who first realized that the theory of sound and the theory of oscillation are essentially one and the same. Without going into detail, Galileo discovered the principle of the pendulum. This was the beginning of the study of dynamics. One wonders what Galileo would think of what we can do today.

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