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Limitations of Instrumentation for Mechanical Shock Measurement

M. W. OLESON

Structures Branch
Mechanics Division

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U.S. NAVAL RESEARCH LABORATORY
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FOREWORD

There is a frequently quoted remark attributed to one of our scientific predecessors, Sir William Thompson (Lord Kelvin, 1824-1907), which goes, "When you can measure what you are speaking about and express it in numbers, you know something about it, but when you cannot measure it, when you cannot express it in numbers, your knowledge is of a meagre and unsatisfying kind." Perhaps it would not be unreasonable to paraphrase this statement in a more modern context by saying that "Experimental justification is the essential and final test of any scientific generalization." The distinction here is a subtle but real one; in Lord Kelvin's day, "you," as a singular pronoun, could address both the theorist and the experimentalist. In today's compartmentalized technology, "experimental justification," and "scientific generalization," more frequently address separate people, if not actually separate organizations. In Lord Kelvin's day, one man could encompass the theory and the practice; today, with scientific boundaries greatly expanded, and with the intermixture of disciplines involved in pursuit of further scientific knowledge, it is usual to find the parts of what Kelvin's age called a "philosophical" study–particularly the theoretical and the experimental parts–in the hands of individual specialists. Such specialization is useful when it brings a higher order of total talent to bear on a mutual scientific objective. It is inhibiting when the functional parts become uncoordinated; when measurement and theory become their own self-sufficient ends lacking in mutual understanding, appreciation, and goal. Perhaps mutual understanding is the key phrase. Without this, the mutual goal, the "experimental justification...of a scientific generalization," remains mysteriously difficult to attain.

The report which follows was originally prepared as a lecture to be presented at a Pennsylvania State College Seminar on "Transient Vibrations." Basically, it is a review of contemporary mechanical shock measurement practice, the applicable instruments, and their range of use. It was prepared for an audience of structural analysts–the theoretical specialists of shock studies–in the hope of augmenting an understanding of the problems incident in making pertinent experimental measurements.

It seems likely that there are a greater number of experienced structural analysts than there are experienced structural measurement specialists. For these analysts, and for the less experienced instrumentalists, a review of this nature might be useful, especially so since most contemporary instrumentation articles or papers seem to concentrate on a specific device, or class of device, giving somewhat incidental attention to the broader context of application in an instrumentation system.

Before closing this foreword, the reader's attention is directed toward two particular points which are made in the following text; first, close and effective liaison between the theoretician and the instrumentalist is an essential prerequisite of good data production, and second, the effective application of an instrument system to a measurement problem is contingent on all of the problem circumstances. As a corollary to the second remark, one might observe that too much effort to "standardize" instruments and measurement techniques may, in practice, inhibit that flexibility which would otherwise allow consideration of all of the problem circumstances.

ABSTRACT

This report is basically a review of contemporary mechanical shock measurement practice, the applicable instruments, and their range of use. It includes discussion of the problem factors which condition selection of a measurement system, most of the commonly employed transducers, a representative shock measurement application, and elementary accuracy considerations. In selecting a shock measurement system, if the shock data are intended to support a theoretical thesis, then specific measurement conditions are established, whereas a primarily experimental investigation involves less anticipatable response and more complex instrumentation. When the data are intended to complement or extend existing data, continued use of even inadequate instrumentation may be desirable. Single point data are inexpensive compared to time-dependent data. The choice of instrumentation is interrelated with the choice of recording an acceleration, velocity, or displacement parameter–in either an inertial or a relative reference space. Simpler signal reproduction is required for a waveshape analysis than for a frequency analysis. The instrumentation selection also depends on whether field tests or laboratory tests are conducted, on whether a single test or repeated tests are made, on size and weight compatibility between the structure being tested and the attached measuring components, and on the number and qualifications of operating personnel. Although most electromechanical transducers employ only a few electrical and mechanical principles, in embodying these principles they have competing limitations, accounting for a multiplicity of somewhat interchangeable transducers. A recent program carried out at the San Francisco Naval Shipyard involving 1500 shock records provides useful examples of shock measurement applications of a variety of transducers. Sometimes it is useful to make accuracy determinations rather than depend on an intuitive understanding of the accuracy. (In such determinations, accuracy must be distinguished from precision.) No specific conclusions or recommendations are presented in this report, since the purpose is to outline the capabilities and limitations of instrumentation suited for use in a variety of measurement problems.

PROBLEM STATUS

This is a report on one phase of a continuing problem.

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LIMITATIONS OF INSTRUMENTATION FOR MECHANICAL SHOCK MEASUREMENT

INTRODUCTION

Studies of structural shock response are directed toward increasingly sophisticated, technically precise methods for the design of shock resistant devices. As is the situation in most fields of modern technology, advancements result from the interplay of imaginative theorizing with empirical experimentation. The association is vital. Just as the most precise physical data are merely numbers without intelligent interpretation, so also the most inspired theoretical conclusion remains only a hypothesis until verified by accurate experimentation. But accurate experimentation is dependent upon the availability of instruments which are capable of producing accurate and pertinent measurements. It follows that fidelity limitations imposed by "state of the art" instruments are, at least potentially, reflected as limitations in the technology.

However, it would be a mistake to assume that imperfect instruments are the only deterrent to perfect data. Under any circumstances, an instrument can do no better than perform within its intrinsic capability. Those of us who use it must understand its capabilities and limitations, for in the end the quality of data produced is largely dependent on the appropriateness with which we can select and employ the instrument.

It would be impossible to present, in one short report, all the conditions and criteria involved in the selection of instruments for each problem that may come to mind. Instead, we will take the easier path of outlining several elements common to many problems; of suggesting the problem circumstances which warrant attention and describing several commonly used instruments from which a selection can be made; of outlining representative examples of actual instrumentation installation and expressing some thoughts regarding the accuracy which may be expected.

Actually, one may remark that there is, in general, no a priori solution to the instrumentation problems encountered in the forefront of a technology. By the very nature of its advance, it is in a state of change, and the instrumentation attending its experimental side must be adapted to the same change.

PROBLEM FACTORS AFFECTING INSTRUMENT SELECTION

In practice there is no one transducer or instrumentation system which is superior in all applications or, for that matter, even suitable in all applications. The best system is that which satisfies a particular measurement problem with a minimum of complexity, cost, and effort. Although we must admit that the requirements of a research measurement are seldom straightforward and unambiguous, it is nevertheless true that these requirements, as we understand them, are the initial criteria by means of which a measurement system is selected. The function of the data, the form in which it is to be obtained, and the conditions under which the measurement must be conducted are all problem factors to be considered. The outline at the top of the next page and the remarks following delineate in a rather broad fashion, some of these common problem factors.

Function of Data:

- Support Theoretical Thesis
- Experimental Investigation
- Accumulate "Representative" Numbers
- Complement Indirectly Related Measurement

Presentation or Form of Data:

- Time-Dependent Variable vs Single Point
- Parameter
- Presentation as Related to Analysis Technique
- Accuracy

Operating Conditions:

- Field vs Laboratory
- Single Test vs Repeated Tests
- Nature of Tests
- Nature of Structure to be Studied
- Number and Qualification of Operating Personnel

Function of Data

If we wish to investigate the validity of an analytically derived thesis, we can usually depend on the prior calculations to establish measurement conditions, such as the expected range of the variable, and the point of instrument attachment on a test structure, with some precision. Also, a special test structure is frequently employed for this purpose, and if so, its design can be adjusted to accommodate particular instrumentation. On the other hand, a primarily experimental investigation generally involves operating equipments which are structurally of greater mechanical complexity and of less anticipatable response.

Sometimes the problem is to supplement or extend existing data as part of a continued effort to obtain a set of representative values. Much shipboard shock data falls into such a category. Here it may be desirable to continue the use of a particular instrument, or type of instrument, even under circumstances where its intrinsic shortcomings may degrade the data. That is, consistent data comparability may be of greater importance than absolute accuracy.

Complementing data is that obtained to complete a measurement pattern. It is frequently a nonproportional measurement, such as an event indication, which imposes correspondingly simplified instrumentation requirements. (One is sometimes tempted to employ a more sophisticated technique here than is required, degrading the calibration or interpretation of its result to meet the simpler data need. An analog of "Parkinson's Law" applies–when the test is completed, the demand for data will meet or exceed that actually procured. There will surely be someone who wanted <u>all</u> of the data from that gage.)

Presentation or Form of Data

Shock response data can be acquired and reproduced in several forms, some involving simple easily operated devices and some being quite complex. We can usually expect that the more sophisticated our data requirement, the more complex and costly it will be both in terms of equipment and in terms of time. Often the cost factor imposes as much of a restriction on our endeavors as does the prevailing instrument technology. Perhaps this is well, however, since it does force us to examine our data needs somewhat critically.

Single point data can be obtained inexpensively in a variety of ways, usually involving some kind of passive transducer which trips at a preset parameter level, or retains evidence of a peak parameter level. Accessory equipment and operator experience required are minimal. However, by the same token possible malfunction of the transducer may go undetected for lack of trained scrutiny.

More commonly, research measurements are obtained as time-dependent variables, providing waveshape, frequency, and amplitude information.

Depending on the nature of the problem, one may wish to record an acceleration, a velocity, or a displacement parameter–in either an inertial or a relative reference space. In principle the three major parameters are related and any two can be obtained from the third. In practice the transformation is not always possible without prohibitively large error. Choice of a measurement parameter is interrelated with the characteristic limitations of the various available transducers–particularly in the frequency domain–and with the type of data analysis to be performed. For example, waveshape analysis of a ship shock response is not usually feasible from an acceleration record because of prominent high-frequency content; a velocity record under the same conditions will de-emphasize the high-frequency components and can frequently be studied with more profit. As a matter of fact, it is interesting to view the initial choice of measurement parameter as a means of signal frequency filtering which is not attended by phase distortion.

Most of the transducers which we will be interested in are electromechanical devices; the mechanical parameter being converted to a proportional electrical signal. In addition to those electrical accessories which are specifically required for operation of the transducer itself, some device must be provided for reconstituting the electrical signal in a form suitable for analysis. Magnetic tape recorders, oscillographs, oscilloscopes, and indicating instruments are all used. Of these, the magnetic tape recorder-reproducer is certainly the most adaptable, since a recorded signal may be easily reproduced as many times and in as many ways as desired, thus accommodating a variety of analyses. The version suited to data recording is, however, a comparatively expensive device.

Various types of analysis are performed on measured shock signals, perhaps the two most common being an interpretive study of the signal waveshape (peak values, time to peak, prominent frequencies, etc.), and a frequency decomposition of the signal expressed as shock spectra or as power-spectral-density values over some specified frequency range. For waveshape analysis, the signal is presented graphically as a time function; for frequency analysis, the signal is usually reproduced electrically and applied directly to either an analog or a digital computer. It is worth noting that these two methods of analysis complement each other, in that each produces information not readily obtained from the other. By virtue of its simpler signal reproduction requirements, interpretive waveshape analysis usually precedes frequency analysis, and is consequently sometimes referred to depreciatively as a "preliminary" analysis. Such an inference is unfortunate. It tends to obscure the fact that careful study of the displacement, velocity, or acceleration waveshape may be of considerable importance in understanding the mechanical causes and effects associated with the measurement.

Our attitude toward accuracy in measurement–like a politician's attitude toward motherhood–is that we are all in favor of it. However, a little objective consideration quickly demonstrates that we must reckon with the consequences as well as the objectives; if we demand very high accuracy, we must be prepared to pay the cost. In a measurement system this generally means careful attention to the calibration and stability of all of the system elements, the use of precision components, and a sufficient number of qualified people to operate the equipment. Good quality contemporary shock measuring systems have accuracy capabilities of the order of 2% to 15%. In most situations this accuracy is quite commensurate with the mechanical repeatability of the instrumented structure, and with the function of the data.

Operating Conditions

Shock and vibration measurements are made on real mechanical structures; they may be simple, as a specially designed cantilever beam, or complicated, as a locomotive diesel engine, and they may weigh only a few ounces or many tons. In any event, it is obvious that our instrumentation must be chosen to be compatible with the structure, the type of mechanical excitation to which it is subjected, and the conditions under which a measurement is to be procured.

A "field" measurement usually implies that the measuring equipment is to be disassembled, transported, and reassembled at some remote location. Clearly, a prime requirement on equipment for such use is that it be portable and be rugged enough to withstand the repeated physical abuse of such handling without deterioration. Repair of equipment in the field is always costly and frequently not possible. Equipment for field use must also be insensitive to the ambient surroundings, which usually include temperature and humidity extremes and many times include shock and vibration conditions apart from those under study. We may observe that equipment suited to field use is usually also suited for use under the more beneficent conditions of the laboratory but that the converse does not always hold.

The distinctive difference between a single test and repeated tests is that the initial cost of preparation can be prorated in the latter case. Failure of a vital measurement component–a tape recorder for example–during a one-shot test is catastrophic. Similar loss of one set of measurements out of several may be discomfiting but is not as serious. Sometimes, in the single test situation, the added cost of using redundant measuring systems is warranted. To be effective, such redundancy should be complete, including the transducer, electronics, recording system, and even the source of operating power. Our manned rocket flights are one example of a single test situation and, indeed, one in which redundant instrumentation systems are employed at some length. Though the flights are repeated with succeeding vehicles, the singular costs of each flight are so great as to make it stand alone in importance.

Shock measurements are frequently made on rocket structures, but they are also made on submarines. Clearly, a rocket in flight and a submarine under simulated shock attack impose different requirements on a measuring system. In comparison, those components installed aboard the rocket must be small in volume, light in weight, and economical in power consumption. Except in the case of a recoverable rocket section, signals are transmitted via a radio link to a ground receiving station, a complication not usually present during submarine shock studies. The point here is that in our choice of a measuring system we must select components which are compatible with the nature of the test and the type of structure involved. A 10-pound velocity meter installed in a submarine may be quite satisfactory; the same instrument, even if it would fit within a small satellite, would itself alter the measuring conditions excessively.

Any consideration of a shock measuring system would be incomplete without attention to the number and qualification of people who will operate it. There are several aspects involved; the location, orientation, and method of installing a transducer on the test structure requires specialized knowledge of the function of the test and of the mechanics of the structure itself; operation and maintenance of electronic system components, recorders, etc., requires a different but still special knowledge; and interpretation of the records produced must frequently be made in the light of both the expected structural behavior and the measuring system characteristics. Interpretation is sometimes particularly difficult, since the character of shock response signals and the character of anomalous signals produced by many electronic system deficiencies are closely akin. In most sustained experimental programs, records are studied concurrently with the program, partly to acquire early data results but partly also to provide for the early detection of instrument malfunction.

As data demands grow in quantity and sophistication, so the number and qualifications of the operating personnel must also increase. In particular, individuals of complementing backgrounds must be in a position to work closely together, each in appreciation of the broader objectives but particularly qualified to cope with the inevitable problems of his specialty.

TRANSDUCERS

Anyone who sets out to study the advertising literature with a view toward purchasing a shock measurement transducer, must be impressed, if not actually intimidated, by the number of devices available. Even more confusing, organizations and individuals with experience in the field have found it necessary to produce their own instruments in the midst of such commercial competition. The fact is, most of the electromechanical transducers in common use basically employ only a few well-known electrical and mechanical principles–the behavior of a linear single-degree-of-freedom system, the piezoelectric effect in certain crystalline materials, the strain-resistance effect in a conducting material, Ohms' law, and the properties of a magnetic field. When these principles are embodied in a physical device, certain inherent limitations appear. The multiplicity of transducers which have been designed represent attempts to tailor these limitations for special purposes, usually suppressing one at the expense of another (Table 1).

Consider an undamped spring-mass system which is driven by an oscillatory motion at the free end of the spring. The system will be resonant at some frequency f_n. For driving frequencies below f_n, the mass element moves with the spring, the system appearing nearly rigid, while for driving frequencies higher than f_n, the mass element tends to remain stationary in inertial space. In the first case the spring will deform slightly in proportion to the inertial reaction of the attached mass, and in the second case the spring will deform in proportion to relative displacement between the attached mass and the driven point. If spring deformation is converted into a proportional electrical signal, the spring-mass system becomes an electromechanical transducer–it is sensitive to inertial acceleration or to inertial displacement of the driven point depending on the ratio of driving frequency to f_n. With the exception of certain relative displacement devices, such as strain gages, this simple mechanism is applicable in principle to all commonly employed transducers. Velocity transducers operate in the displacement mode but sense velocity of the spring deformation rather than the spring deformation itself.*

Certain of the inherent limitations previously remarked on now become apparent. An acceleration transducer is limited to use for those driving frequencies which are below its

*It is also possible to construct a velocity transducer based on an overdamped mechanical system. In a recent verbal discussion, the author was informed that such a design had been built and used. However, no information is on hand regarding the accuracy or usefulness of the instrument.

Table 1
Some Characteristics of Commonly Employed Shock Transducers*

Measurement	Gage Type	Sensitivity	Full Scale Range	Natural Frequency	Damping	Weight	Volume	Normal Accessories†
Acceleration	Piezoelectric	3-200 mv/g	20-20,000 g	12-100 kc	–	0.1-3 oz	0.1-1 cu in.	High-impedance cathode follower or amplifier
	Piezoresistive	0.1-1.5 mv/g	250-2500 g	12-40 kc	–	1.25 oz	1 cu in.	Bridge voltage, bridge balance, dc amplifier
	Strain gage	0.08-40 mv/g	0.5-500 g	90-3000 cps	Fluid	3-14 oz	1-15 cu in.	Bridge voltage, bridge balance, dc amplifier
	Differential transformer	10^{-3} -10 v/g	1-700 g	15-825 cps	Fluid Magnetic	3 oz-1.75 lb	5-50 cu in.	AC bridge voltage (60-2000 cps), bridge balance, demodulator
	Variable Reluctance	2.7-9 mv/g	1-100 g	250-300 cps	Fluid	0.1 oz	0.2 cu in.	AC bridge (1.5-5 kc), demodulator
Velocity	Magnetic induction (small)	60-100 mv/ips	0.1-1.4 in. (p-p)	2.5-40 cps	Fluid Magnetic	2-10 oz	1-8 cu in.	None
	Magnetic induction (large)	4-15 mv/ips	2-6 in.(p-p)	2-4 cps	–	1-20 lb	10-500 cu in.	None
Displacement (Relative)	Differential transformer	2-50 v/in.	.01-2 in.(p-p)	–	–	0.1-12 oz	0.1-6 cu in.	AC bridge voltage (60-2000 cps), bridge balance, demodulator
	Potentiometer	.1-10 v/in.	3-15 in.(p-p)	–	–	0.5-5 lb		Bridge voltage, bridge balance
	Strain gage (metal)	5-20 mv‡	10^4-10^5 μin./in.	–	–	negligible	0.01-1.5 sq in.§	Bridge voltage, bridge balance, dc amplifier
	Strain gage (semiconductor)	120-1000 mv‡	3×10^3 μin./in.	–	–	negligible	0.03-0.15 sq in.§	Bridge voltage, bridge balance, dc amplifier
	High-speed camera (seismic suspension)		10-10^4 frames/sec	(1-5 cps)	–	10-50 lb	1-6 cu ft	Camera power, high-intensity lights
Displacement (Inertial)	Potentiometer (seismic)		1-12 in.	1 cps	–	2-10 lb	1-2 cu ft	Bridge voltage, bridge balance

* The indicated numbers are approximate minimum and maximum values. They apply to each class of instrument and not to any one particular unit.
† Normal accessories which are used when the signal is to be recorded on magnetic tape.
‡ Assuming a bridge voltage of 10 volts and a strain of 1000 μin./in.
§ Strain gage thickness dimension is usually negligible.

natural frequency and to an acceleration range over which its spring element remains linear. Similarly, a displacement or a velocity transducer is limited to use at frequencies above its natural frequency and to a displacement range determined by mechanical clearance between inertial and driven portions of the structure. Practical acceleration transducers are usually small and have relatively high natural frequencies, while displacement and velocity transducers are larger and have relatively low natural frequencies.

An undamped transducer is a theoretical but not a practical possibility. It is also not generally feasible, since sustained excitation at its resonant frequency would produce a meaningless large response. However, the type and control of damping does vary among commonly used transducers, some designs employing built-in damping and some including only the natural and unavoidable damping associated with their structural configuration. As a rule of thumb, where the gage resonant frequency is closer than a factor of about five to significant mechanical frequencies, some controlled damping should be included.

Most commonly, controlled damping is provided by a viscous fluid or by magnetic eddy currents, though some recent designs involve a "gas damping" technique which is claimed as a superior method. Viscous damping has one prominent problem in that the fluids employed are temperature sensitive; typically, a viscosity change in the order of 1%/°F at normal room temperature may be expected. Magnetic damping, which is less temperature sensitive, requires an internal magnetic field and sufficient relative motion within the gage to induce significant energy dissipation.

Addition of damping in a transducer modifies its internal relative motion, producing frequency-sensitive phase and amplitude changes which extend well beyond the undamped natural frequency. This, in turn, degrades the proportionality between the mechanical input to the gage and its electrical output. The problem has been studied at some length in efforts to minimize its effects. In a steady-state frequency domain, the phase and amplitude characteristics can be described both analytically and empirically with good precision. However, in the transient domain, any general description is complicated by an infinite variety of waveshape possibilities, each of which would require individual attention. Studies have been made of half sine, square, and triangular waveshapes, in the expectation that more complicated waveshapes can be so approximated (1). Present practice is to control the damping coefficient, where possible, at about 70% of critical. This results in a linear phase-shift characteristic at frequencies below the gage natural frequency, with no resultant waveshape distortion.

Various means are employed for sensing the internal relative motion of a transducer, and as a matter of fact these means mark a major distinguishing feature between commonly used transducers.

In a piezoelectric accelerometer, elastic distortion of a crystal–which is usually the spring element of the spring-mass system–produces a proportional charge separation between opposite faces. The major disadvantage of such a gage is that the process of electrically measuring the charge separation is, itself, responsible for reducing the separation. Practically, this imposes a low-frequency limit which is determined by the resistance-capacitance product of the gage and its connected electronics. The limit appears as a first-order falloff in response, whose 3-db point (30% reduction in amplitude response, associated with a 45° phase shift) is in the order of 1 to 10 cps under normal conditions. On the other hand, piezoelectric gages are small, lightweight, rugged, and comparatively high in output (Fig. 1). They are used extensively in rocket studies.

Piezoresistive and strain gage accelerometers are electrically the same. Both detect resistance change due to deformation of an electrical conducting element, four such elements being interconnected to form a Wheatstone bridge circuit. Normally, the conducting elements

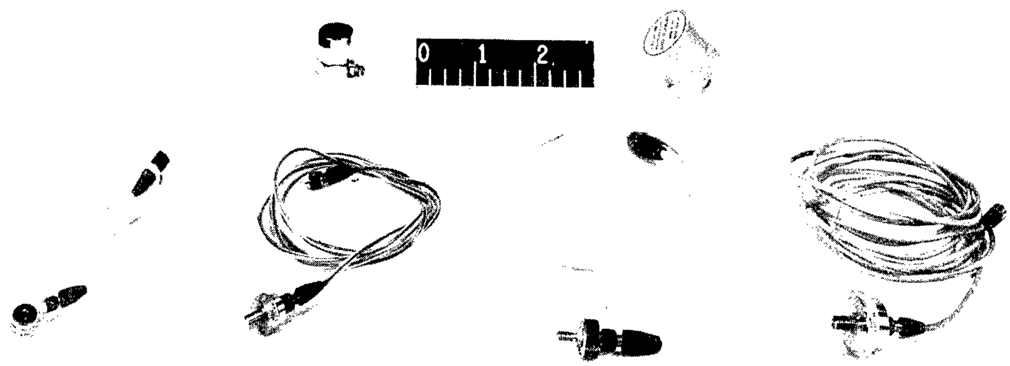
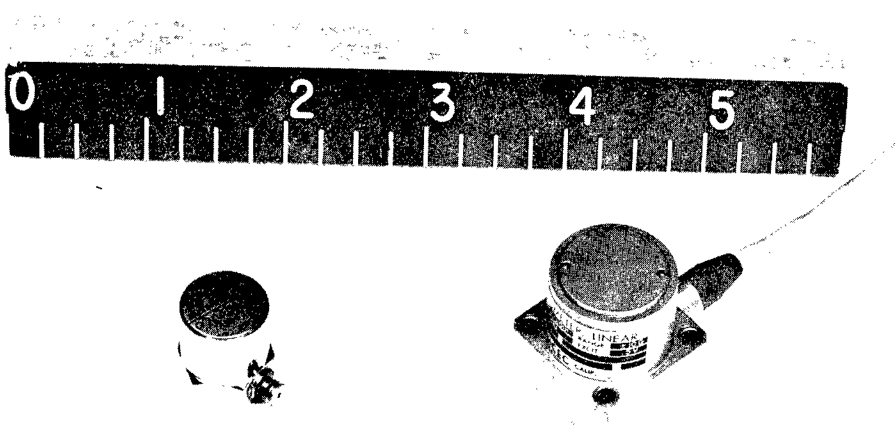


Fig. 1 - Piezoelectric accelerometers. These gages are commercially available in a great variety of ranges and configurations. The physically small sizes are generally of lower sensitivity and higher natural frequency; many are so small that the electrical connection to the gage contributes significantly to size and weight.

are also the spring of the spring-mass system, although a less common "bonded" strain gage accelerometer employs a separate spring. Significantly, bridge accelerometers are usable for static acceleration measurements. The acceleration range, upper frequency limit, and sensitivity of strain gage accelerometers are considerably more limited than those of the piezoelectric type (2) (Fig. 2). However, the recently introduced piezoresistance accelerometer gives promise of an improvement in these qualities.

Differential transformer, variable reluctance, and magnetic induction gages make use of various properties of a magnetic field. In the first, energy in a driven (primary) coil is

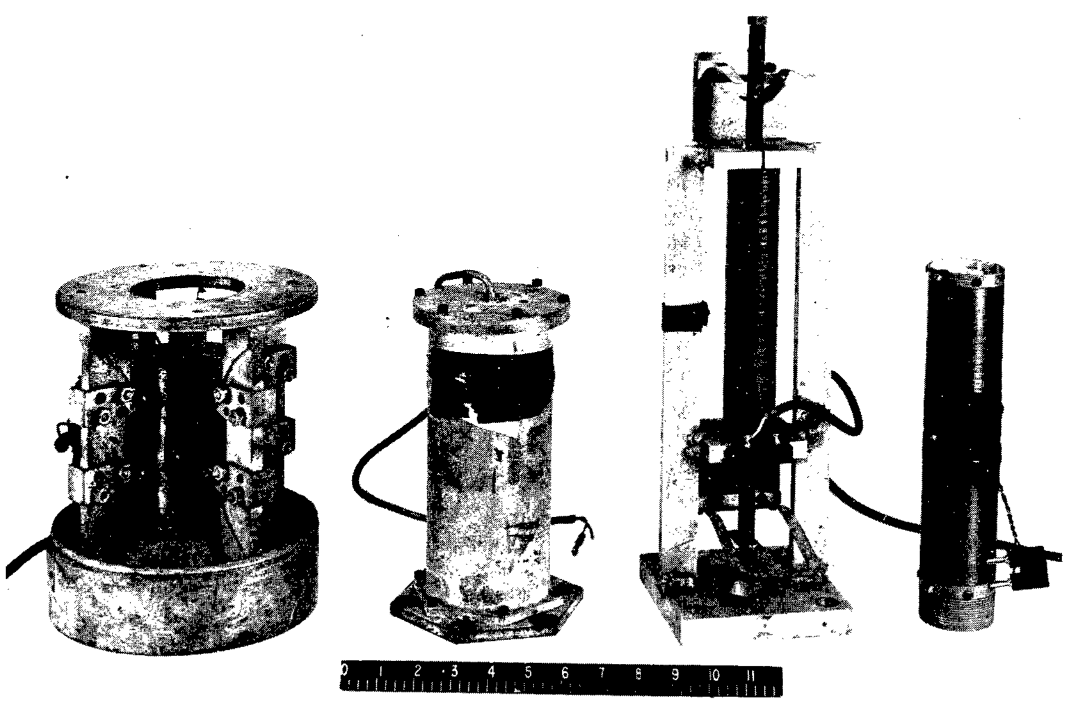


(a) (b)

Fig. 2 - Typical (a) piezoelectric accelerometer as compared to (b) a strain gage accelerometer

electromagnetically coupled into two adjacent (secondary) coils; the secondary coils being interconnected in such a way that their induced voltages are in phase opposition. Magnetic balance between the primary and the two secondary coils is controlled by a movable ferromagnetic core. A shift in position of the core relative to the three coils produces a net ac output voltage whose amplitude is proportional to displacement from a "null" position and whose phase depends on the direction of shift from the null position (3). When configured as an accelerometer, the ferromagnetic core is restrained by spring attachments to the coil structure. A variable reluctance gage is quite similar, except that the ferromagnetic core is used to control the inductance balance in two coils which form two arms of an inductance bridge. Both of these gages require ac excitation. However, they have the advantage of response to static acceleration without the necessity of an associated dc amplifier. It is usually convenient to amplify the ac gage output signal prior to its conversion (detection) back to a proportional dc voltage. (It should be remarked that strain-bridge type gages may also be supplied with an ac excitation.)

Magnetic induction is employed in velocity transducer designs. If relative motion occurs between a magnetic field and a conductor, an induced voltage in the conductor will be proportional to their relative velocity. Most velocity transducer designs include a strong permanent magnet attached to a coil by soft springs, the coil structure being mechanically driven. In some, however, the magnet is driven and the coil suspended; and in one older design an electromagnet was used in lieu of a permanent magnet. Velocity transducers are commonly employed for shipboard shock measurement, where their weight and size are tolerable (Fig. 3). As a result of considerable development, modern designs



(a) (b) (c) (d)

Fig. 3 - Various noncommercially designed velocity meters which are in current use: (a) British velocity meter (45 lb), (b) NRL velocity meter (11 lb), (c) DTMB velocity meter (6 lb), and (d) UERD velocity meter (1 lb)

are rugged, sensitive, and simple to use. On the other hand, the inherent limitations in the basic mechanism, as remarked previously, are frequently onerous to the experimenter. Several more or less successful attempts have been made to improve velocity transducer records by correcting the data in a digital computer format (4). While such correction is slow and expensive, it may still be economical when judged along with the simplicity and ease of use of the transducer. It is worth observing that comparatively few commercially designed velocity transducers are available, and these for the most part are not suited to shock studies (Fig. 4).

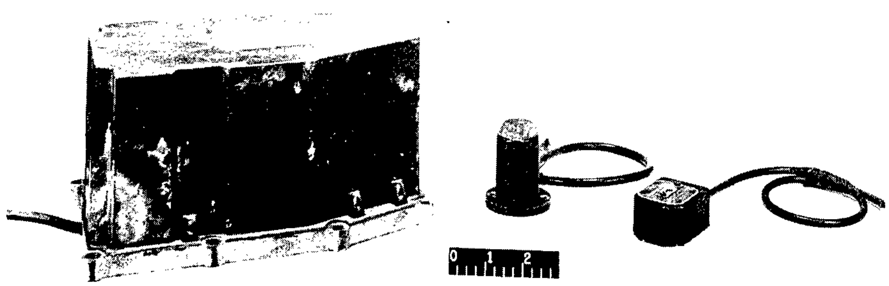


Fig. 4 - Commercially designed velocity meters. The unit on the left (18 lb) is suited to shipboard type shock measurement because of its relatively large internal clearance.

Various potentiometric gage designs are in use; here the gage output voltage is determined by the position of a movable contact along the length of a linear resistance voltage divider. The need for precise positioning of the movable contact limits this sensing mechanism to gages which develop comparatively large internal relative motion. For this reason it is most frequently used in displacement transducers.

Some fundamental limitations on electromechanical transducers were identified above. We can now make another similar observation, this time primarily related to the particular electrical conversion or sensing means employed in an acceleration transducer. In each case, some intrinsic property of the conversion mechanism imposes a limitation which requires a trade-off between sensitivity, maximum range, and natural frequency. In a strain gage accelerometer, for example, the strain induced change in wire resistance is a physical characteristic of the metal which is linear over a limited range. Adjustment of the mass element or of the wire dimensions will change the basic transduction sensitivity (volts/g) but only with a concomitant change in natural frequency and maximum acceleration range (2). Similarly, the other sensing mechanisms have their own intrinsic limitations. In general, an increase in transduction sensitivity is accompanied by a decrease in both full-scale range and natural frequency. This is one reason for the variety of accelerometer designs which are on the market.

There are some transducer limitations which are of a less intrinsic nature, but still significant. Linearity, stability, cross-axis sensitivity, and environmental ruggedness are largely associated with the quality of mechanical design and production. Typically, linearity specifications are in the order of 1% to 2% of a "best straight line" over the rated range, and cross-axis coupling is 2% to 5%. However, there is evidence to indicate that cross-axis coupling becomes more prominent in the presence of a simultaneous direct-axis signal, a condition more likely to occur in practice than on the calibration bench (2). Long-term stability is usually of limited importance in shock work, since we are normally concerned with short-duration signals. Environmental capabilities vary greatly, even among gages of the same basic mechanism, and this variation is one more reason for the proliferation of otherwise similar designs.

Perhaps we should not finish the discussion of transducers without remarking on two types of device which do not fall in the above pattern, namely, single point or passive devices and the high-speed camera. Both have a meaningful status in shock measurement, and both are frequently used. Photographic coverage of shock effects is particularly valuable as an educational (and sometimes entertainment) tool. The camera is usually either suspended on soft springs within the shock target or set some distance away on a rigid foundation. Effects associated with gross motion, such as mechanical rupture, can be dramatically evident. However, the ability of an observer to perceive and scale small motions from such films is limited, particularly if the framing includes many, or complicated devices. If measurement is anticipated, the camera field should be simple and concentrated on the measurement objective.

Passive measurement devices include those which are preset to trip at a certain level, and those which retain some kind of a maximum indication. Properly employed, they can provide useful, though limited, data. A piece of lead, for example, installed in the clearance space between adjacent structural surfaces, will plastically deform if the surfaces move together. In similar fashion, a preloaded mass can, if acceleration forces exceed the preload, produce a dent or other mark on a plastic anvil. Most such devices are designed for a particular application, though some commercial models are available. One should, however, recognize that the very simplicity can be misleading. In one particular application, a lead gage, used for relative motion measurement during a shock test, deformed due to its own inertial load, producing excessive relative motion indications, and equally excessive consternation among the experimenters.

APPLICATIONS

Within the past few months personnel from the Naval Research Laboratory have been involved in a shock measurement program at the San Francisco Naval Shipyard. The program was quite extensive, producing some 1500 shock records from a variety of transducers. For the purposes of this text, some of the instrumentation applications involved may serve as useful examples.

Broadly, the physical circumstances of the program were these: The test structure involved relatively fragile missiles, a missile stowage frame, and a simulated section of heavy steel ship deck welded into a specially constructed shock barge. Rubber shock isolation mounts attached between the stowage frame and the simulated decking were designed to deform 2 to 6 inches under shock loading. Explosive charges suspended under water at specified distances from the shock barge were detonated to produce shock loadings of controlled severity, the more severe of which resulted in a 12 to 16 inch vertical displacement of the barge. The gross weight of the shock barge and its installed assemblies was about 50 tons.

In the sense of the outline presented on page 2 the function of the collected data was primarily investigative. Concurrent analysis and interpretation was necessary both to identify faulty instruments and to assess the probability of damage as progressively more severe shocks were employed. On-site test personnel, including those with specialized knowledge of each significant structural element and of the instrumentation system (but exclusive of handling and construction personnel), numbered nine or ten, which was a barely sufficient crew.

Fifty-five to sixty-five transducers were used to study the behavior of the barge and the missile stowage system. These included accelerometers, velocity meters, strain gages, special relative displacement gages, high-speed cameras, and passive devices. The electrical signals were recorded on magnetic tape and subsequently reproduced on an oscillograph record for interpretive analysis.

The most severe instrumented locations were those on the simulated deck, which had quite rigid mechanical coupling to the incident shock. Velocity transducers, and several units of a developmental "integrated accelerometer" design were installed.

The velocity meters were secured to the deck surface by intermediate welded base-plates; physical clearance for the gage sometimes caused a problem, but the gage weight did not, since it imposed an insignificant load on the 1-inch steel deck. The velocity meter circuit required no accessories beyond a calibration signal source and the tape recorder (Fig. 5).

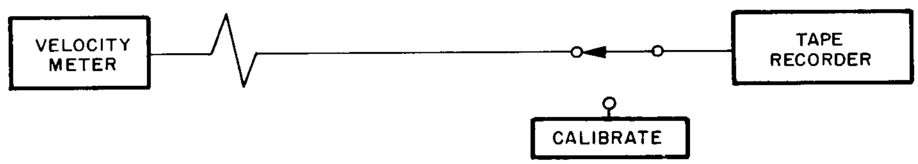


Fig. 5 - Electrical connection block diagram of a velocity meter circuit. The broken line indicates a long instrumentation cable; the velocity meter to the left is installed in the shock target, while the instruments to the right are at a remotely located recording station.

The developmental integrated accelerometers used were the latest and most successful of several attempts to produce a more satisfactory substitute for the velocity transducer. In principle, the design involves a bridge-type accelerometer and an electronic integrator. The practical problem has been to find an accelerometer capable of stable and linear operation in the extremely severe shock environment and to develop an electronic circuit capable of the same stability, linearity, and reliability (5). At rigid deck locations, the dynamic range of significant acceleration shock components may easily be 60 db to 80 db–from a fraction of a g to several thousand g. In the present application, a piezoresistive transducer was installed in a mechanical mount which isolated the gage at high frequencies (6) (Fig. 6). A compatible transistorized electronic circuit was designed to provide not only the signal integration but bridge voltage, bridge balance, and electrical calibration functions for the gage. To preclude long-term integration of gage or circuit drift, the integrator was also designed with a second-order low-frequency cutoff (this cutoff is an analog to the velocity transducer seismic suspension, but one which is an order of magnitude lower in frequency) (7). Physical installation of the integrated accelerometer was simplified, in comparison to the velocity meter, by its smaller dimensions and lighter weight. However, the circuit was somewhat more complicated; it included the electronics, which were installed on the shock barge, and a power supply at the remote recording station (Fig. 7).

At several deck locations, a velocity transducer and an integrated accelerometer were installed together so that their signals could subsequently be compared. On reproduction, the recorded velocity signals from each gage were integrated (using the same type of circuit as that mentioned above) and transcribed as both velocity and displacement. Records produced by the two gages were alike within the limitations of the gage types. The velocity

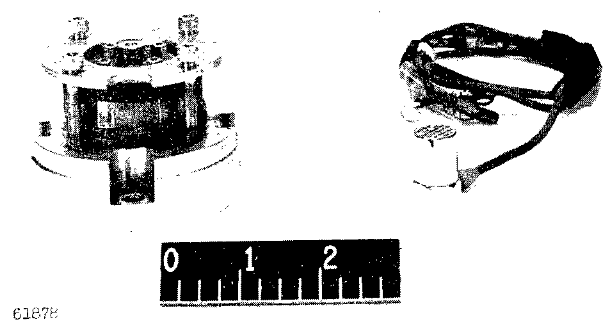


Fig. 6 - Piezoresistive accelerometer and mechanical isolation mount of the style used in a recent series of shock measurements

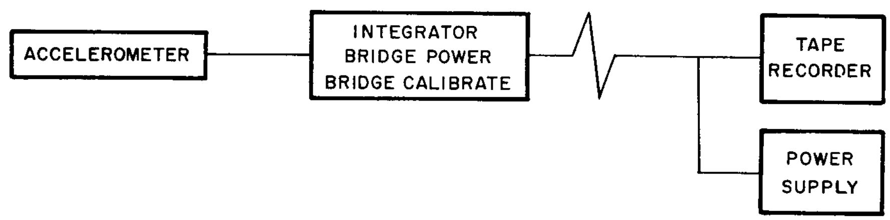
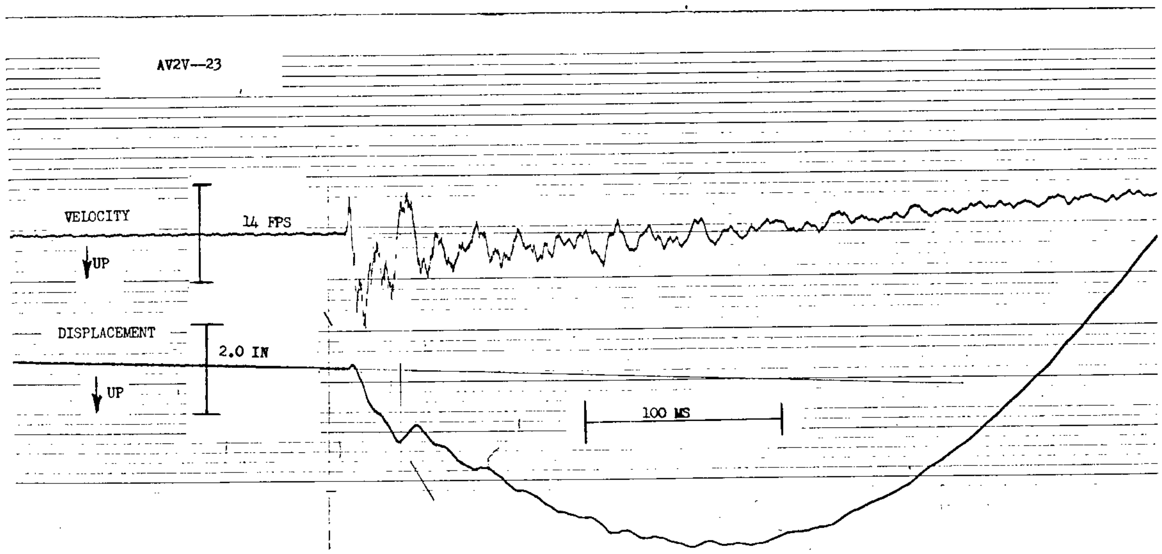


Fig. 7 - Electrical block diagram of the developmental integrated accelerometer circuit

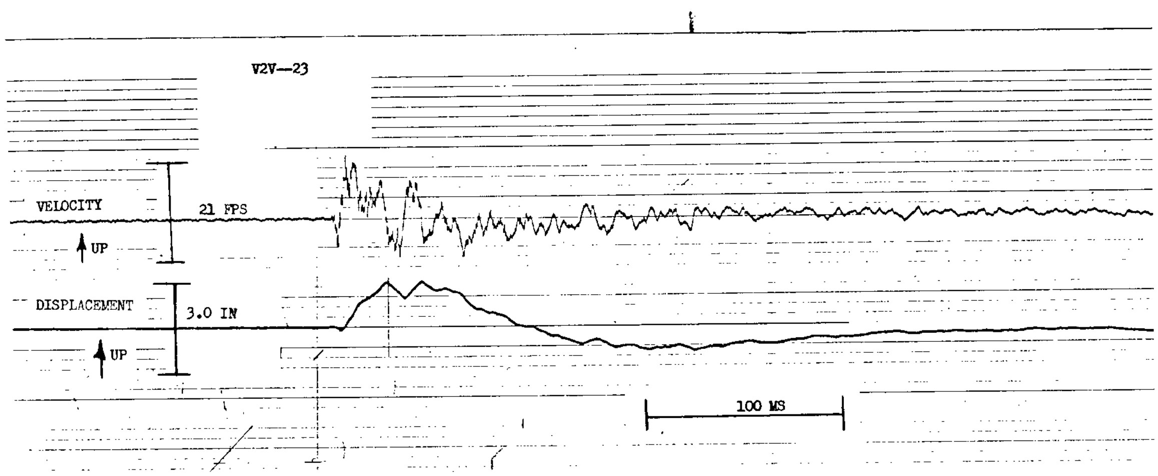
transducer records were noticeably distorted by the low frequency cutoff of the gage and in some cases by "bottoming." The integrated accelerometer records indicated a less prominent low-frequency distortion and nothing comparable to bottoming, but on occasion were slightly degraded by a preshot slope in the zero line, due to residual "ringing" of the lightly damped natural frequency of the integrator (Figs. 8 and 9).

Though not associated with this particular test program, it is worth mentioning that several previous attempts had been made to employ piezoelectric accelerometers in the integrated acceleration fashion. In most cases where severe acceleration shocks occurred, large spurious pulses appeared in the integrated (velocity) signal (Fig. 10). The mechanism of these anomalous signals has not been identified. However, the effect, together with the lack of low-frequency response characteristic of piezoelectric gages, has prevented further use.

The problem of instrumenting the missiles and the stowage frame differed from that of the deck in two significant aspects; the structures themselves were relatively light and nonrigid, and much lower acceleration shock levels could be expected. Also, motion at the low natural frequencies of the rubber-mounted stowage system (of the order of 4 to 10 cps) was an important measurement requirement which, of itself, eliminated application of piezoelectric type gages. Strain gage accelerometers in the range of 25 to 100 g were actually used. On missile surfaces the gages were secured with dental cement, and on the somewhat sturdier frame, with an epoxy cement. Because of their small size and weight, physical installation was usually uncomplicated. However, the circuits required electronic accessories, namely, a bridge excitation, balance, and calibrating unit on the shock barge and a dc amplifier at the recording station (Fig. 11).

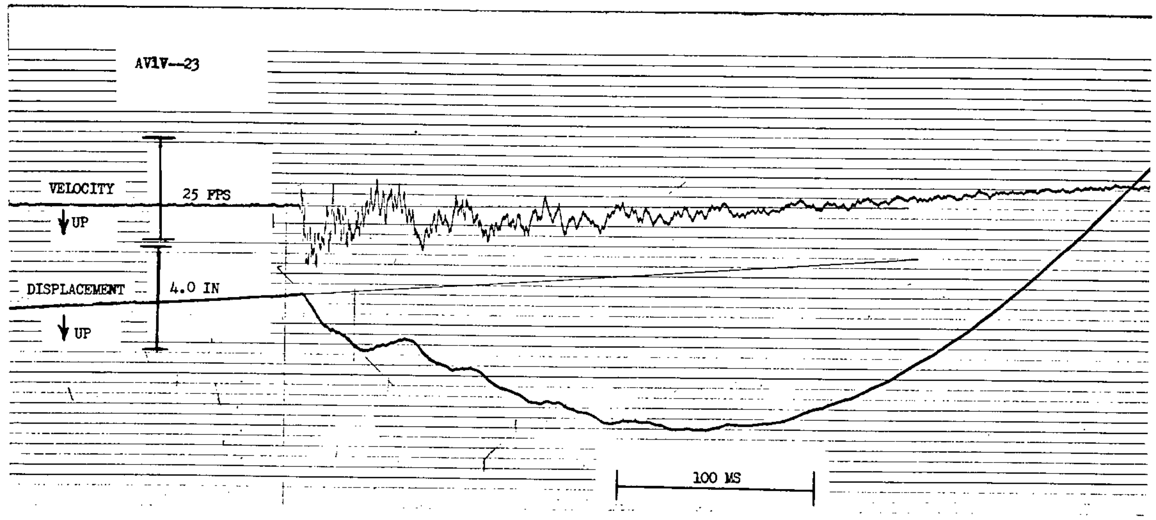


(a)



(b)

Fig. 8 - Shock response records from redundantly installed (a) integrated accelerometer, and (b) velocity transducer. No bottoming is noted in the velocity meter record, but the relatively high seismic suspension frequency is evidenced by the rapid return to zero of the displacement trace.



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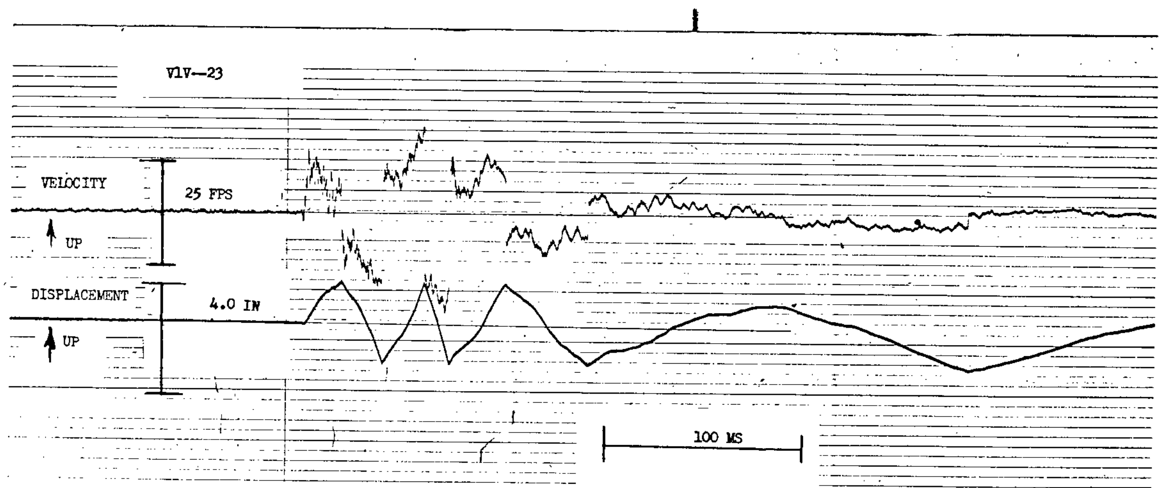


(b)

Fig. 9 - Shock response records from another set of redundantly installed gages. Both the velocity and displacement traces of the velocity transducer signal (b) indicate prominent bottoming of the instrument. The slope of the integrated accelerometer trace prior to shock incidence is associated with the integration technique; it can be partially compensated by establishing a tangent and zero reference line.

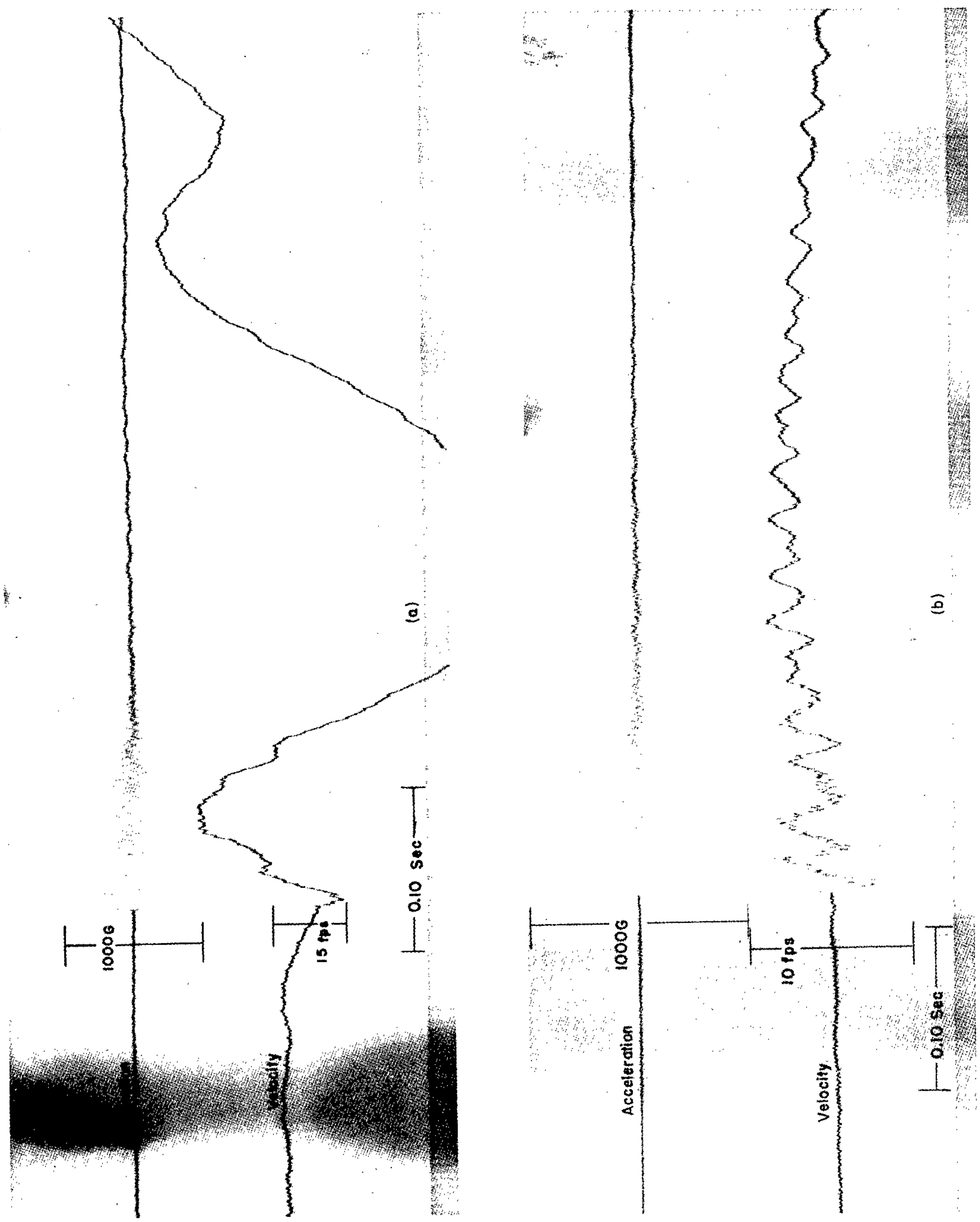


Fig. 10 - Shock response acceleration and velocity signals taken from (a) a 20,000-g piezoelectric accelerometer and (b) a 250-g strain gage accelerometer. These gages were at adjacent points on the same structure. The large indicated velocity of (a) was physically unrealizable in the particular test.

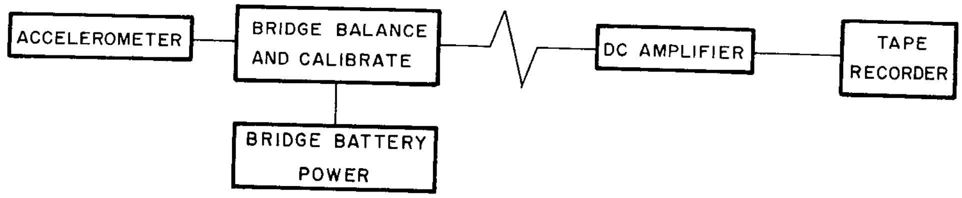


Fig. 11 - Electrical block diagram of a strain gage accelerometer circuit

On reproduction, strain gage accelerometer signals were transcribed directly (acceleration), as a first integral (velocity), and as a second integral (displacement) (Fig. 12). There are some notable points in regard to this transcription. First, the procedure of integrating and double integrating is not a simple one when real gages and their associated equipment are involved. Attempts to do so with conventional analog computer elements are usually frustrated at the start by what would otherwise be a trivial dc instability preceding the shock. A modification of the device developed for use with the integrated accelerometer was used here; the modification involved extending the low-frequency resonance of the integrator to about a 6.5-second period and adding a switchable high-damping circuit. The integrated records included an error due to the integrator low-frequency characteristic of course, but for time intervals which were short compared to the period this error was tolerable. A second point in regard to this transcription involves the gage and its associated circuit. Any anomalous circuit noise or zero shift in the recorded signal was integrated as if it were part of the mechanical motion. As a matter of fact, this characteristic was helpful in identifying faulty instrument operation, since the double integration of such signal components usually produced much more obvious discrepancies in the displacement traces than in the direct acceleration traces. As an order of magnitude, we can note that a 0.1-g zero shift doubly integrated for 0.5 second would produce an apparent displacement error of almost 5 inches. Referred to the ±100-g gages, 0.1 g is 0.1% of full range.

A somewhat unusual shock measurement problem occurred as a result of the rubber shock isolation mounts. The problem was to measure relative deflection across these mounts, where the deflections were quite large, included similarly large cross-axis components, and occurred simultaneously with severe deck shock motion. No commercially available gages suited such an application; therefore a special gage was designed. (Design of special gages is usually uneconomical if otherwise suitable models can be purchased.) It involved a flexible steel cable kept under constant tension between a pulley at one reference point and an attachment bracket at the second reference point. An electrical signal was obtained from a precision potentiometer mechanically coupled to the pulley shaft. The design proved generally satisfactory, although some problems were encountered due to whipping of the steel cable. During the course of the program, another potentiometric gage, also of special design, was tried. However in this second design, relatively rigid gage structures were damaged by the severe deck shock. Physically, both gages required fabrication of special installation brackets and comparatively large clearances (Fig. 13). Electrically, they were connected in a bridge circuit, requiring bridge balance and bridge power accessories on the shock barge and a calibration signal source at the recording station (Fig. 14). Both produced acceptable relative displacement signals, although the second design exhibited greater noise due to shock induced bounce of the potentiometer contact arm.

ACCURACY

Experience suggests that most of us who are concerned with experimental studies have an understanding of the accuracies attainable which can best be described as intuitive. We

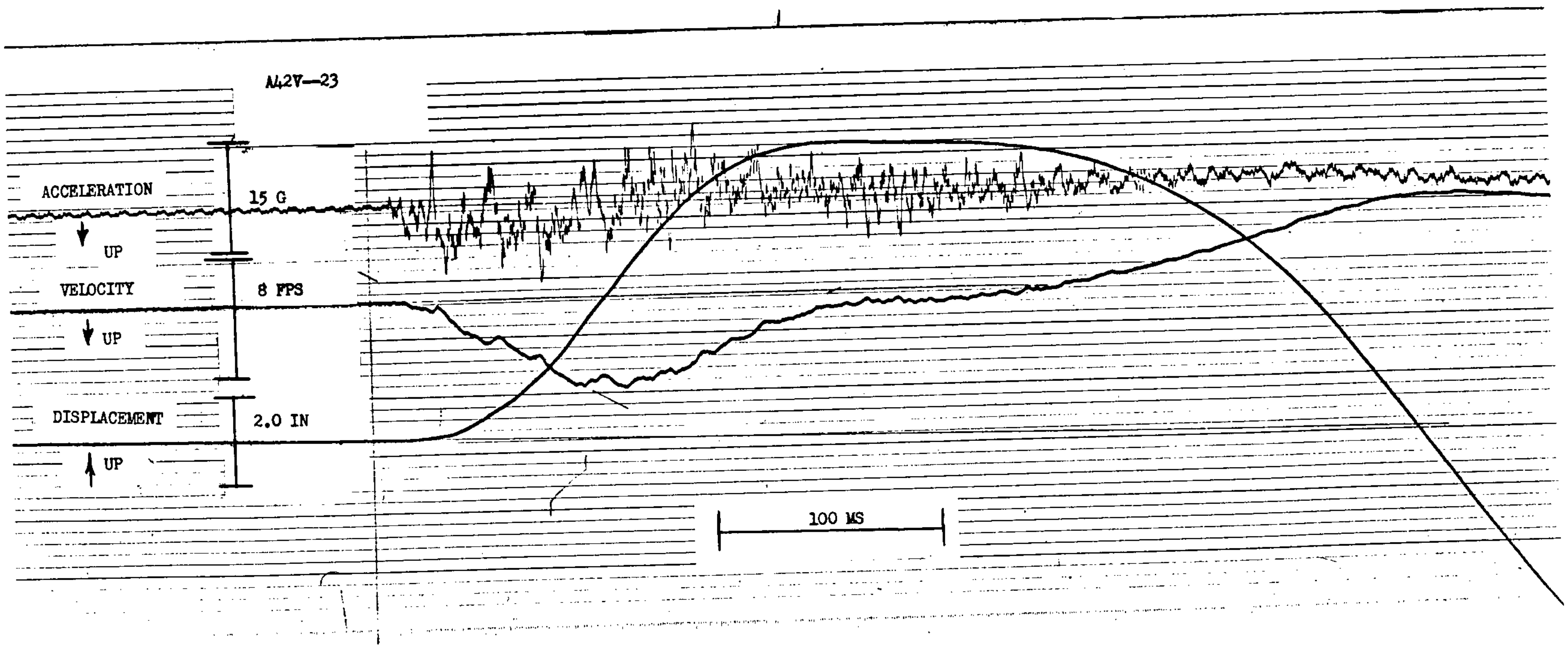


Fig. 12 - Shock signal traces reproduced from a strain gage accelerometer, including the direct signal and two successive integrations. The inertial displacement indication is in significant error after about 200 milliseconds as a result of the integration technique. However, the initial portion of the displacement record is reasonably accurate, and even the later portions are useful in comparison with nearby gages as a means of determining gage malfunction.

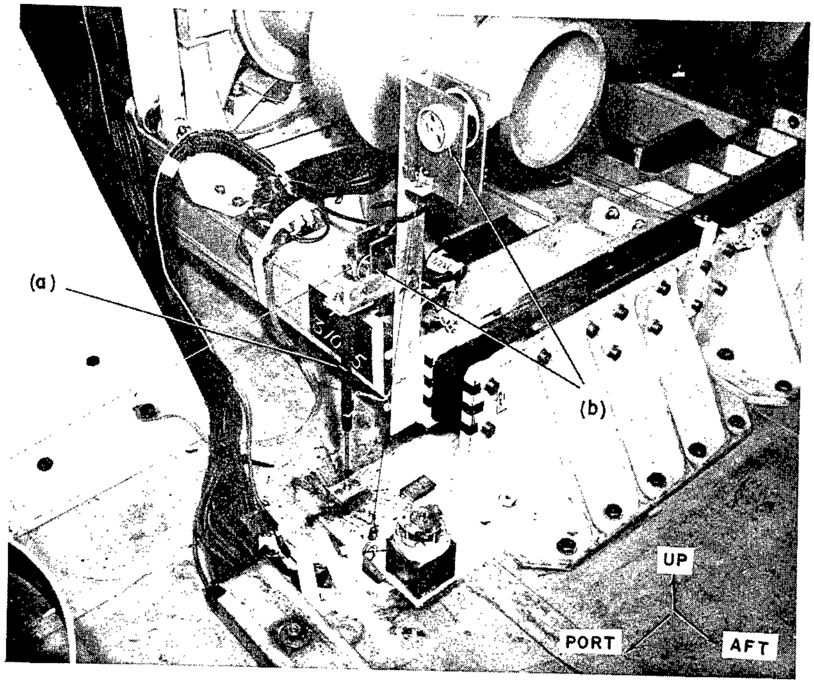


Fig. 13 - Two types of specially designed relative displacement transducers installed across rubber shock isolating mounts. Type (a) was comparatively rigid and as a result was damaged by severe shock loading. Type (b) employed a flexible steel wire connection which on occasion developed excessive whipping during shock. However, both produced usable records.

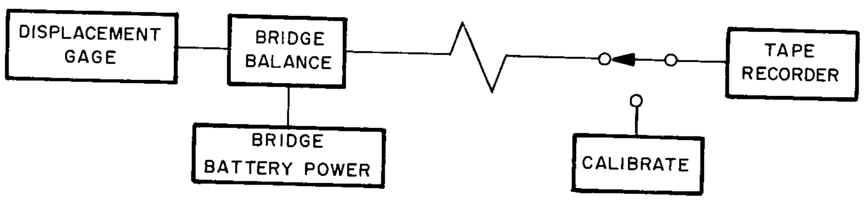


Fig. 14 - Electrical block diagram of a potentiometric displacement gage circuit

see and understand a gage manufacturer's accuracy specification, know that components of a measuring system introduce their own inaccuracies, and recognize that we cannot scale an oscillographic trace or read a meter with absolute precision. But seldom do we actually sit down and look at these potential error sources in detail and in combination. Perhaps this is quite satisfactory. If structural data cannot be interpreted with numerical precision, then something approaching order-of-magnitude data may be acceptable and accuracy is no problem. On the other hand, elementary accuracy considerations are not difficult and can be instructive.

We may start by recalling a few fundamental relationships concerning combinations of numbers having relatively small percentage errors (8):

1. If two numbers X and Y are added, the percentage of error in the sum is equal to or less than the larger of the two component percentage errors.

2. If X and Y are subtracted, the percentage of error in the difference may become very large, possibly approaching infinity as the two numbers approach equality.

3. In multiplication or division, the percentage of error in the result is equal to the algebraic sum or difference of the percentage errors in the component numbers X and Y.

4. The percentage error of a number raised to a power is equal to the percentage error of the number, multiplied by the power.

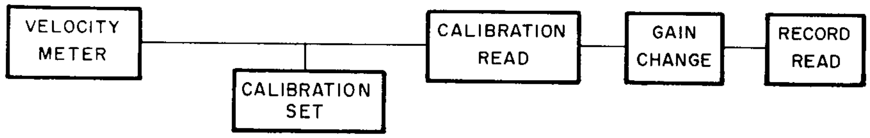
5. In a product process (multiplication or division) involving several numbers, the maximum possible percentage of error in the result equals the sum of the absolute component percentage errors. However, if the component errors are unrelated, the most probable percentage error will be given by the square root of the summed squares of the component percentage errors. In this case, probable implies a 50% probability that the error will be less than the value indicated.

It is also desirable to distinguish between two related terms, namely "precision" and "accuracy." Precision is frequently defined in terms of repeatability. For example if several individuals independently observe a particular voltmeter indication, their readings will differ slightly as a result of interpolating scale divisions on the meter face. This lack of precise repeatability is related to the smallest unambiguous unit of the measurement. However, accuracy relates to a resultant error; it is defined as the degree of conformity between the measurement and a true value. We may log an experimental number of five significant figures; if the second digit is in error, the number will be precise but quite inaccurate.

The accuracy of a single reading will be no better than the precision with which the reading can be taken; it is further limited by systematic error and, when expressed as a percentage, by the base number. Using the voltmeter illustration again, assume a 100-volt linear scale which can be read with a 1-volt precision. At the 25-volt indication, accuracy is initially limited to 4% by this scale precision. It may be additionally limited by calibration error and perhaps by such things as zero error and nonlinearity in the movement mechanism. It should be noted that indicating instruments and various other classes of measurement device have percentage accuracy specifications which are based on some "full scale" number. For lesser values of the variable, the precision limitation may produce an actual percentage error much in excess of that stipulated.

With these few simple rules, we can consider some representative accuracy considerations as they apply to the measurement systems described in the preceding section.

The block diagram of Fig. 15 refers to a velocity transducer installation, but in terms of those elements which may have an effect on accuracy. We include the velocity meter calibration accuracy, the accuracy with which an electrical calibration signal can be injected, the precision with which the reproduced calibration signal can be scaled from an oscillograph trace, the accuracy of a gain changing device (to accommodate differences in the calibration signal level and the shock signal level), the precision with which the signal transcription can be scaled, and, at various intermediate steps, the accuracy with which we can compute factors using a slide rule. Assumed component accuracies, the limiting accuracy, and the most probable accuracy are tabulated. Perhaps some additional comments are in order. First, the velocity transducer calibration inaccuracy may seem unduly large, but it is representative of experience, as are the other assumed inaccuracies. Second, the accuracy of a single slide rule setting is about 0.1%; for probable error calculations, the error in several sequential settings should be combined by the square root method. However, in this illustration the error introduced by computation is so small as to be significant only in the maximum error calculation. Finally, it should be noted that



Item	Estimated Accuracy
Velocity Meter Calibration	10%
Calibration Signal Level Set	1%
Calibration Equivalent - Compute (four slide-rule settings)	0.4%
Calibration Read	2%
Gain Change	1%
Record Factor Compute (four slide-rule settings)	0.4%
Record Read	2%
Value Compute (three slide-rule settings)	0.3%
Maximum Error	17.1%
Most Probable Error	10.5%

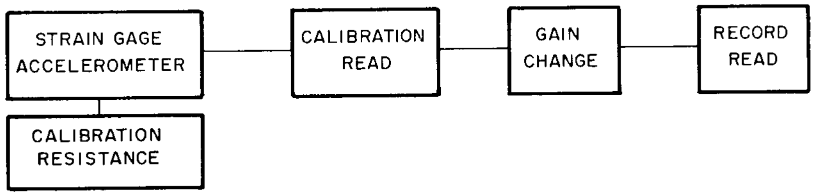
Fig. 15 - Accuracy block diagram and tabulation as applied to a representative velocity meter measurement

this calculation does not consider singular errors due to record interpretation, maloperation, or malfunction. These may, of course, be quite significant. In one case a voltmeter which was used to set the calibration signal level in a velocity meter circuit produced errors of 30% to 60% in several sets of data before its gross inaccuracy was identified. In another situation, erratic contact resistance of a galvanometer switch produced an erratic voltage-to-oscillographic trace-excursion function, which is a factor normally considered constant between calibration signal and shock signal transcriptions.

Figures 16 and 17 are similar accuracy diagrams pertaining to strain gage accelerometer records and to the integrated velocity and displacement traces. With respect to the integrating procedures, systematic errors resulting from the low-frequency limit of the integrating circuits are not included in the calculations.

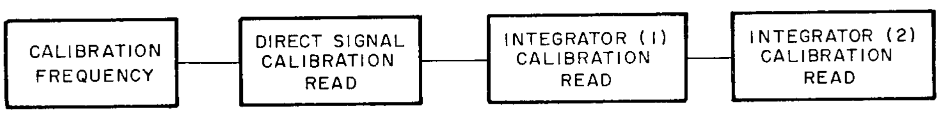
CONCLUSION

At this point, it should be clear that "limitations of instrumentation" is not a simple topic, nor is it subject to simple description. Even if, as was done here, we restrict consideration to shock measuring instruments and present the subject once-over-lightly, the topic is not simple. The fact is that "instrumentation" includes a sophisticated and complicated collection of devices which are continually in the process of change–just as are the theories and practices of structural dynamics. Marriage of the two technologies, if it is to be fruitful, requires not only the best of each but an informed mutual appreciation. That is the purpose of this discussion–to outline the deficiencies and the capabilities of instrumentation in the hope that they will be appreciated. To paraphrase one of the opening sentences, those of us who use instruments must understand their capabilities and limitations, for in the end the quality of data obtained is dependent on such understanding as it applies within the context of the problem.



Item	Estimated Accuracy
Accelerometer Calibration	3%
Accelerometer Resistance	0.5%
Calibration Resistance	1%
Calibration Equivalent - Compute (four slide-rule settings)	0.4%
Calibration Read	2%
Gain Change	1%
Record Factor Compute (four slide-rule settings)	0.4%
Record Read	2%
Value Compute (three slide-rule settings)	0.3%
Maximum Error	10.6%
Most Probable Error	4.5%

Fig. 16 - Accuracy block diagram and tabulation as applied to a representative strain gage accelerometer measurement



Item	Estimated Accuracy
First Integral - Calibration Frequency	0.5%
Direct Calibration Signal Read	2%
Integrator (1) Calibration Signal Read	2%
Compute Integration Factor (seven settings)	0.7%
Maximum Error	5.2%
Most Probable Error	3.0%
Second Integral - (Calibration Frequency)^2	1%
Direct Calibration Read	2%
Integrator (2) Calibration Signal Read	2%
Compute Integration Factor (seven settings)	0.7%
Maximum Error	5.7%
Most Probable Error	3.1%

* * * * *

Resultant Combined Error In Integrated Records

Velocity - Maximum Error	16%
Most Probable Error	5.3%
Displacement - Maximum Error	17%
Most Probable Error	5.4%

Fig. 17 - Accuracy calculations pertinent to integration and double integration, including resultant accuracies where strain gage accelerometer records are integrated to provide velocity and displacement data

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13. ABSTRACT

This report is basically a review of contemporary mechanical shock measurement practice, the applicable instruments, and their range of use. It includes discussion of the problem factors which condition selection of a measurement system, most of the commonly employed transducers, a representative shock measurement application, and elementary accuracy considerations. In selecting a shock measurement system, if the shock data are intended to support a theoretical thesis, then specific measurement conditions are established, whereas a primarily experimental investigation involves less anticipatable response and more complex instrumentation. When the data are intended to complement or extend existing data, continued use of even inadequate instrumentation may be desirable. Single point data are inexpensive compared to time-dependent data. The choice of instrumentation is interrelated with the choice of recording an acceleration, velocity, or displacement parameter–in either an inertial or a relative reference space. Simpler signal reproduction is required for a waveshape analysis than for a frequency analysis. The instrumentation selection also depends on whether field tests or laboratory tests are conducted, on whether a single test or repeated tests are made, on size and weight compatibility between the structure being tested and the attached measuring components, and on the number and qualifications of operating personnel. Although most electromechanical transducers employ only a few electrical and mechanical principles, in embodying these principles they have competing limitations, accounting for a multiplicity of somewhat interchangeable transducers. A recent program carried out at the San Francisco Naval Shipyard involving 1500 shock records provides useful examples of shock measurement applications of a variety of transducers. Sometimes it is useful to make accuracy determinations rather than depend on an intuitive understanding of the accuracy. (In such determinations, accuracy must be distinguished from precision.) No specific conclusions or recommendations are presented in this report, since the purpose is to outline the capabilities and limitations of instrumentation suited for use in a variety of measurement problems.

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