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A PROCEDURE FOR THE CORRECTION OF VELOCITY METER RECORDS

by

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UNDERWATER EXPLOSIONS RESEARCH DIVISION
PORTSMOUTH, VIRGINIA

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ABSTRACT

Correction methods devised to compensate for certain mechanical characteristics of commonly used velocity meters are considered. The application of two corrections for such characteristics, usually referred to as seismic corrections and correction for bottoming, is illustrated and discussed for the measurement of absolute structural velocities.

ADMINISTRATIVE INFORMATION

This report is concerned with one phase of the project sponsored jointly by the Defense Atomic Support Agency and the Bureau of Ships under Web No. 14.069. It deals with data reduction procedures for handling velocity meter records.

INTRODUCTION

The measurement of absolute structural velocities is certainly one of the most important and most frequently encountered measurements in explosions research. In spite of the importance of this type of measurement, no transducer is available which is capable of adequately performing these measurements and directly producing an output signal proportional to the velocity of the structure being measured. Each transducer used for this type measurement has characteristics which cause the output signal to be altered so that it is a function not only of the velocity of the base of the instrument but also of certain mechanical and electrical characteristics of the instrument itself. Although this criticism is, in general, true of all types of transducers, those most frequently used for measurement of structural velocity are particularly vulnerable in this respect.

One way to extend the usefulness of these instruments is to accurately determine their characteristics and then compensate for the distortions or alterations which these characteristics produce in the output signal from the transducer. As the use of velocity meters and the records derived therefrom becomes more widespread, a general understanding of these compensation or correction procedures becomes increasingly important. The purpose of this report therefore, is to describe the procedures most frequently used at the David Taylor Model Basin (DTMB) to compensate for certain of the characteristics of the most commonly used velocity meters. The particular corrections to be discussed here are those which are frequently called seismic corrections and corrections for bottoming.

QUALITATIVE DISCUSSION OF CERTAIN VELOCITY METER CHARACTERISTICS

The velocity meters most frequently used at the Underwater Explosions Research Division of DTMB are described in detail in Reference 1.* The correction methods described here, however, are not restricted to those particular instruments, but are general in nature and are applicable to any velocity meter based on the same principles of operation. For this reason, those principles and the characteristics of such instruments which lead to and allow the correction methods described here, will be briefly discussed.

BASIC PRINCIPLE OF OPERATION

Velocity meters most commonly used for shock testing are quite simple in construction and principle. They consist of two primary components which have relative movement to each other. One of these components provides a constant magnetic field, usually by means of a permanent magnet, and the other component contains a coil of wire which is within the magnetic field. Thus, as one component moves with respect to the other, a voltage is generated within the coil that is directly proportional to the relative velocity between the two components. The relative displacement range over which the voltage generated per-unit-velocity (velocity sensitivity) is constant, generally is referred to as the linear range of the instrument.

MEASUREMENT OF RELATIVE STRUCTURAL VELOCITIES

In the situations where the measurement desired is the velocity of one part of a structure relative to that of another part, or of one structure relative to another, it is often possible to mount one component of the transducer on each of the members of interest so that the desired measurement may be obtained directly. In these particular cases, the signal from the transducer requires no corrections if the linear range of the meter is not exceeded. Usually instruments having sufficient linear range for this type of application can be obtained.

MEASUREMENT OF ABSOLUTE STRUCTURAL VELOCITIES

The type of velocity measurement most frequently desired during the majority of the shock tests, is that of the velocity of a point on a structure relative to a fixed point on the earth. This is commonly called the "absolute" velocity of the point of interest on the structure. To attempt the measurement of absolute structural velocities, one of the two major components of the meter (either the coil form or the magnet, but more frequently the coil form) is attached rigidly to the structure at the point of interest. The other component (usually the magnet) is suspended from that point by means of fairly soft springs so as to form a system having a low natural frequency. This approach allows a complete self-contained transducer to be built and only a single attachment to the structure is required. Henceforth in this report, for clarity and simplicity, the coil form will be the component considered to be rigidly attached to the structure and the magnet element the component suspended by springs, although in certain applications these components may be interchanged. Figure 1 is a picture of a typical velocity meter used for shock motion measurements. For this figure a portion of the coil form has been cut away in order to reveal the magnet suspension system.

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*References are listed on page 13.

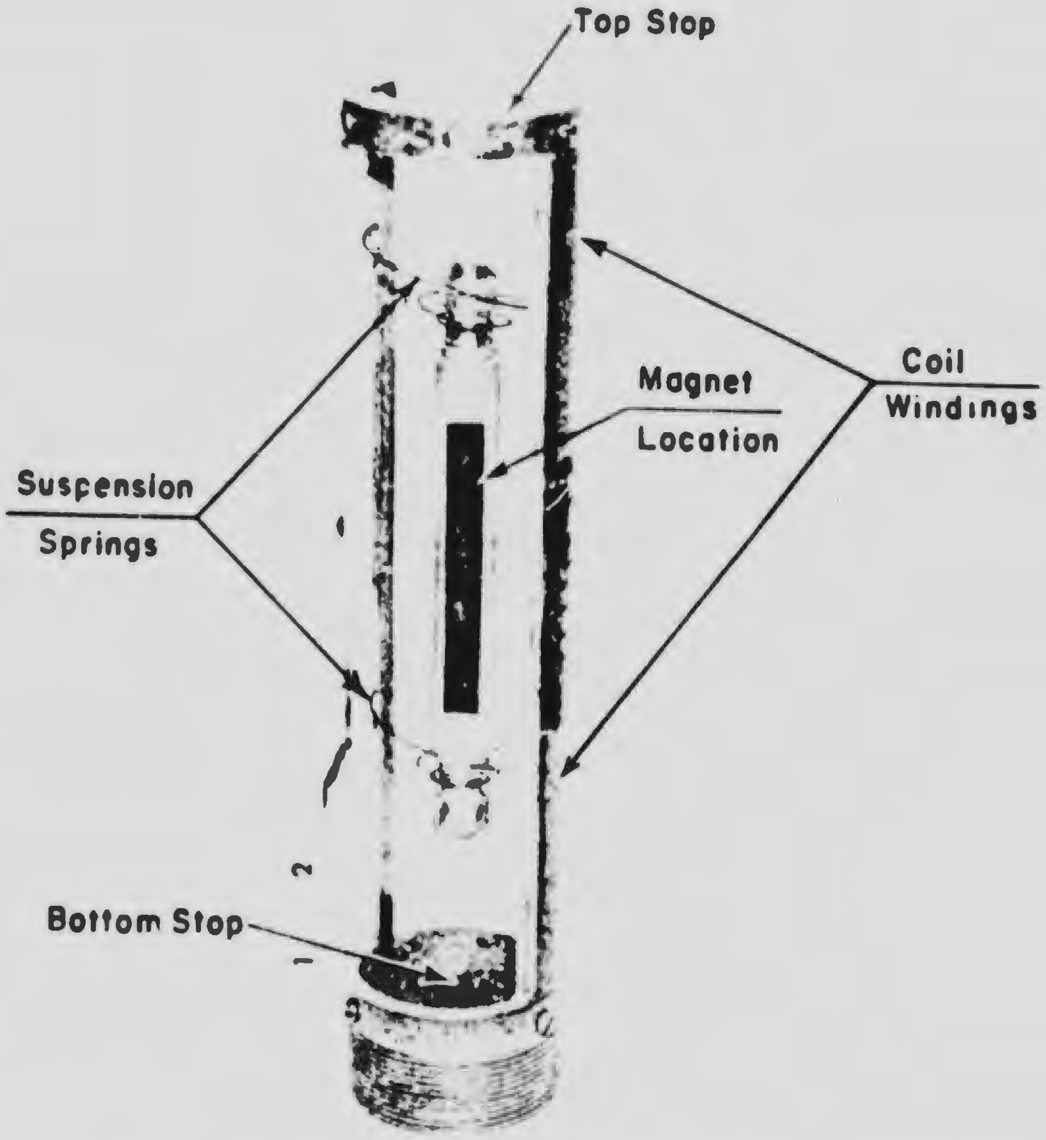


Figure 1 - Typical Velocity Meter

When the structure upon which the instrument is mounted is suddenly subjected to shock forces, the velocity of the coil form is essentially equal to that of the structure for frequency components below the high frequency resonances of the coil form itself. The magnet, on the other hand, tends to remain stationary because of its own inertia and the fact that the forces transmitted by the suspension springs are small until the relative displacement becomes appreciable. Thus for a short period of time the relative velocity between the coil and the magnet is equal to the absolute velocity of the point of attachment. The period of time over which this relative velocity is essentially equal to the absolute velocity is determined by the characteristics of the magnet suspension system: the natural frequency, and the damping present in the system.

Suspension Damping

For the measurement of transient velocities such as are obtained in shock tests, a velocity meter having a suspension system which is essentially undamped or only very slightly damped will, for a given undamped natural frequency, provide an essentially correct output over a longer period of time than an instrument having greater damping. For example, Figure 2 compares the response of an undamped meter to a step velocity input with that of a meter having the same undamped natural frequency but having damping equal to 0.707 of critical. As indicated in this figure, the error of the undamped meter is less than 5 percent for a period of time equal to about 5 percent of the natural period of the meter. For most shock velocities recorded using undamped meters this fact provides a reasonable rule-of-thumb: Corrections of the meter output are not generally required if the period of interest, as measured from the initiation of the shock motion, does not exceed about 5 percent of the natural period of the meter, and the magnet in the meter does not hit a stop during that portion of the measurement. The curve corresponding to the response of an instrument having a damping ratio of 0.707 indicates a 5 percent error at a time only slightly greater than 1 percent of the undamped natural period. This rapid decrease, which occurs with an increase in damping, in the period of time while the output signal accurately indicates the absolute velocity, is the primary reason why the majority of the velocity meters designed for shock measurements are essentially undamped.

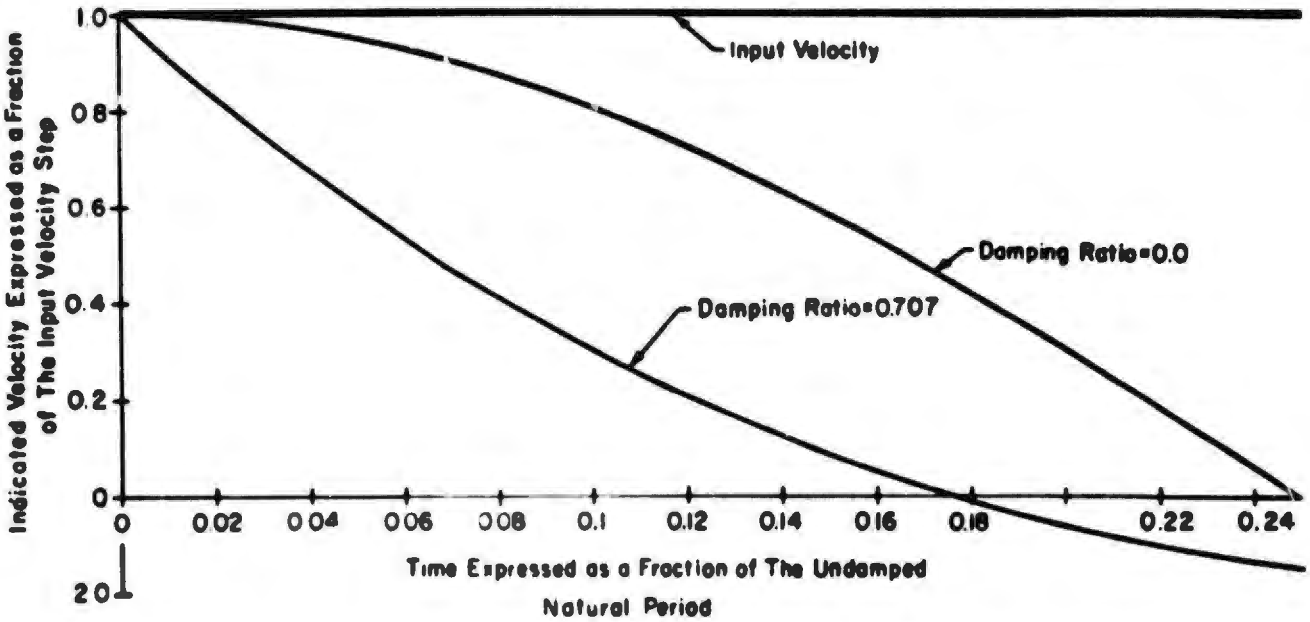


Figure 2 - Velocity Indicated by Meters Having Different Damping Ratios When a Step Velocity is Applied

Stops

Stops are generally inserted within a meter to perform two primary functions. First, they are located so as to prevent the magnet from exceeding the linear range of the instrument: Thus the output voltage remains at all times an accurate measure of the relative velocity between the magnet and the coil. Second, the stops by eliminating excessive relative displacements within the instrument prevent damage to the suspension system: This damage would lead to changes in the characteristics of the suspension during the time when measurement is being attempted. Of course, when the magnet hits a stop (commonly referred to as "bottoming"), large forces are exerted which radically alter the velocity of the magnet, which in turn, produces a voltage output from the meter that is not representative of the motion of the coil form only. Thus, large, rapid, velocity changes are indicated in the output signal as a result of bottomings.

CORRECTION OF RECORDS FROM VELOCITY METERS

A restriction which implies that the output of the velocity meter is correct only for the period of time after initiation of the shock input equal to 5 percent of the natural period of the meter constitutes a very serious limitation on the usefulness of such an instrument. The possibility of bottomings in the transducer response tends to restrict even further the applicability of this instrument. Fortunately though, both of these restrictions may be overcome to some extent by applying certain corrections to the output signal from the meter, provided the characteristics of the meter suspension system are sufficiently well known.

DERIVATION OF CORRECTION PROCEDURES

To derive the correction procedures, the equations of motion for the components of the velocity meter must be examined. Figure 3 is a schematic representation of a velocity meter where m is the mass of the magnet, K is the suspension spring constant, and C is the viscous damping present in the suspension system. The absolute displacement of the magnet is represented by Z and the absolute displacement of the coil form and the point of attachment is represented by Y; a dot above a variable indicates the derivative of that variable with respect to time.

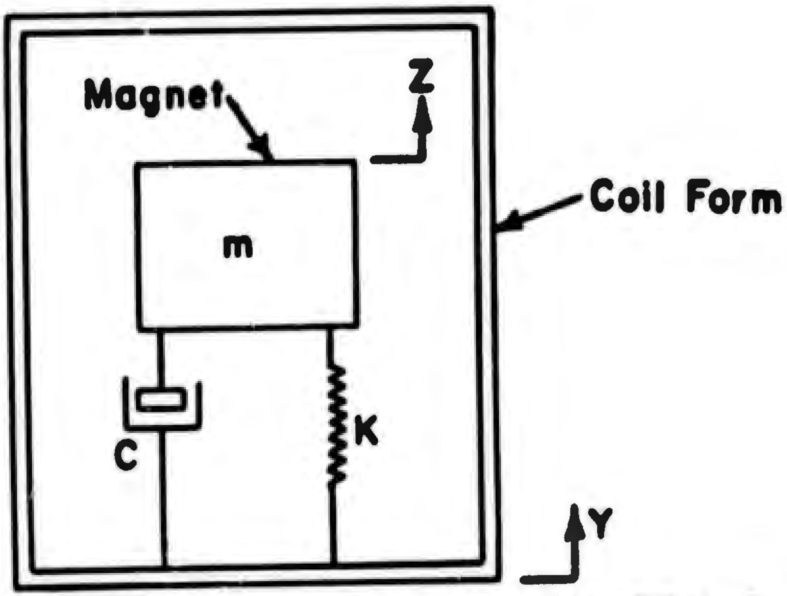


Figure 3 - Schematic Representation of Velocity Meter Suspension System

The equation of motion of the system illustrated in Figure 3, therefore, is

$$m\ddot{Z} = C(\dot{Y} - \dot{Z}) + K(Y - Z).$$

If we let $X = Y - Z,$

then $m\ddot{Y} - m\ddot{X} = C\dot{X} + KX;$

and let $2a\omega = C/m$ and $\omega^2 = K/m,$

then $\ddot{Y} = \ddot{X} + 2a\omega\dot{X} + \omega^2 X.$

At $t = 0$, the entire system is at rest, i.e., $\dot{Y} = \dot{X} = X = 0$,

hence
$$X = \int_0^t \dot{X}(\tau)d\tau .$$

Integration in this case yields

$$\dot{Y} = \dot{X} + 2\alpha\omega\int_0^t \dot{X}(\tau)d\tau + \omega^2 \int_0^t\int_0^\tau \dot{X}(\tau_1)d\tau_1\, d\tau. \qquad (1)$$

The parameter ω equals $2\pi/T$ where T is the undamped natural period of the suspended system; α is the damping ratio. The output of the meter, of course, is directly proportional to $\dot{X}$. Therefore, when the mathematical operations indicated in Equation (1) are performed on the output of a meter which has not bottomed, the resultant will be a true measure of the absolute velocity of the structure within the limitations imposed by the fit of the actual meter characteristics to the mathematical model.

The situation in which the magnet hits stops is a bit more complex, however. At the time of bottoming, a large force is applied by the stop to the magnet for a short period of time, and thus a very rapid change in the absolute velocity of the magnet results. Figure 4 indicates schematically the situation where forces may be transmitted to the magnet by means other than the suspension system, such as stops. This figure is identical to Figure 3 except that an additional force is indicated on the mass.

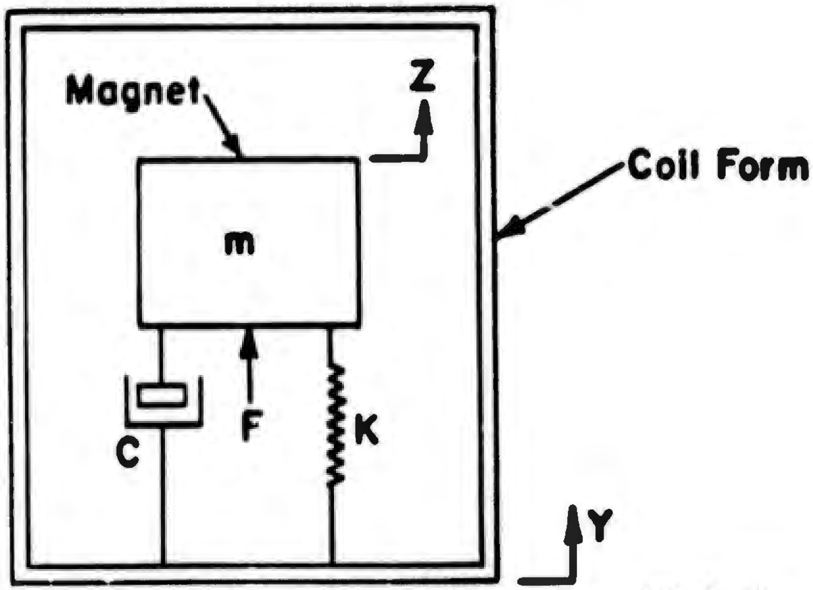


Figure 4 - Schematic Representation of Velocity Meter Indicating Force Which May Be Applied by Stops

Using the same symbols as before with the addition that F = force exerted on the magnet by stops, the equation of motion for this system is as follows:

$$m\ddot{Z} = C(\dot{Y} - \dot{Z}) + K(Y - Z) + F.$$

If we divide by m and substitute the terms

$$X = Y - Z, \quad 2a\omega = C/m, \quad \text{and} \quad \omega^2 = K/m,$$

then

$$\ddot{Y} = \ddot{X} + 2a\omega\dot{X} + \omega^2 X + F/m.$$

When, as before, the system is at rest or at $t = 0$, $\dot{Y} = \dot{X} = \ddot{X} = 0$.

Integration in this case yields

$$\dot{Y} = \dot{X} + 2a\omega\int_0^t \dot{X}(\tau)d\tau + \omega^2\int_0^t\int_0^\tau \dot{X}(\tau_1)d\tau_1\,d\tau + \frac{1}{m}\int_0^t F(\tau)d\tau$$

or

$$\dot{Y} - \frac{1}{m}\int_0^t F(\tau)d\tau = \dot{X} + 2a\omega\int_0^t \dot{X}(\tau)d\tau + \omega^2\int_0^t\int_0^\tau \dot{X}(\tau_1)d\tau_1\,d\tau. \qquad (2)$$

The force F is, of course, zero at all times other than when the magnet is actually in contact with a stop. The term $\frac{1}{m}\int_0^t F(\tau)d\tau$ in Equation (2), in which the magnet is assumed not initially in contact with a stop, is zero until the magnet collides with a stop; it changes rapidly during contact, but upon separation remains constant at the new value until another stop is contacted. Since most velocity meters are constructed so that the duration of contact of the magnet with a stop will be extremely short, this term in Equation (2) consists of essentially step changes in velocity whose magnitudes correspond to the velocity changes imparted to the magnet by the stops alone.

The right side of Equation (2) is identical to the right side of Equation (1); these equations differ only by the term corresponding to the step velocity changes undergone by the magnet. As a matter of fact, Equation (1) represents merely a special case of Equation (2) wherein the stops are never hit. Equation (2), therefore, provides a means for correcting the response of the velocity meter for magnet motions resulting from bottoming as well as those resulting from forces transmitted by the suspension system.

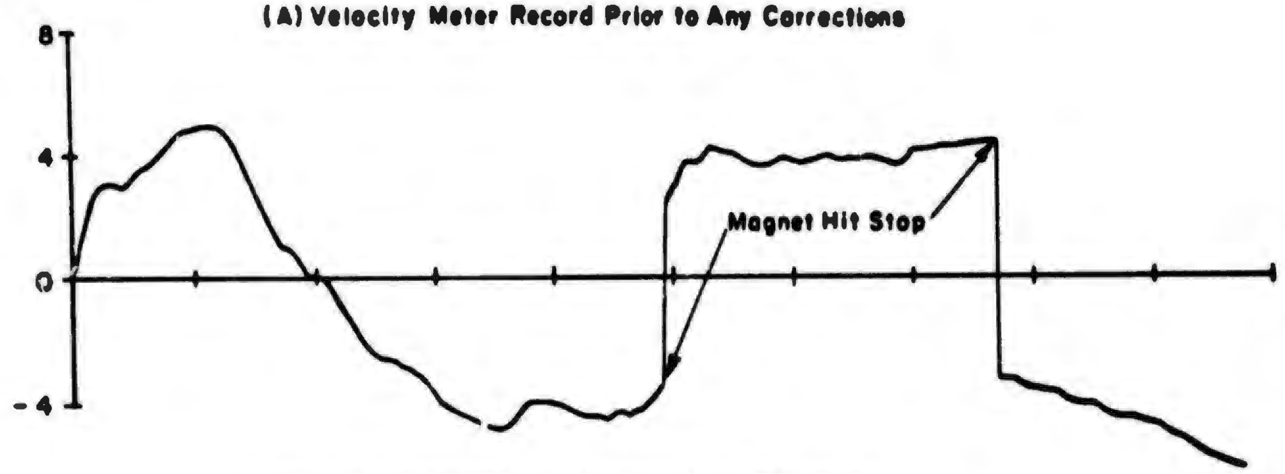
DETAILED CORRECTION PROCEDURE

The correction of the velocity meter output may be treated in two parts. The first is the correction for magnet motions resulting from suspension system forces and is commonly called the seismic correction. The second correction is to compensate for the velocity changes imparted to the magnet by the stops.

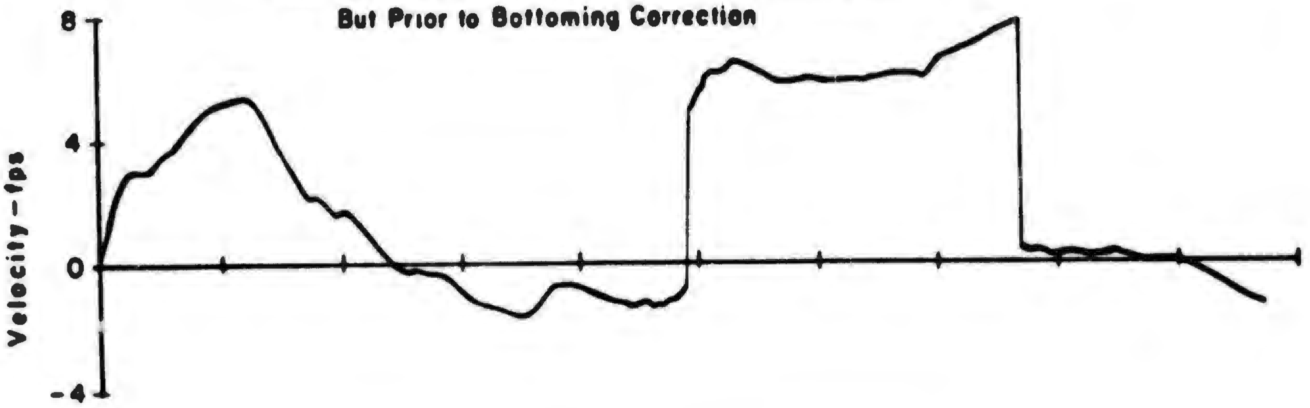
The seismic correction is effected by computing the right side of Equation (2) using the meter output as $\dot{X}$. The computation must cover a period of time which begins prior to any disturbance of the system and continue through the entire period of interest. This calculation is made throughout the record, regardless of whether or not it contains bottomings. If any bottomings are present they are temporarily ignored and the seismic correction is made right on through the region containing them as if they were not present. Of course, no further corrections are necessary if no stops were hit.

If, however, bottomings have occurred, their effects may be removed after seismic correction of the record. As indicated by Equation (2), application of the seismic correction results in a record which is equal to the difference between the desired motion of the structure and the step changes in velocity undergone by the magnet during contact with the stops. These step changes in magnet velocity can be removed by adding equal step velocity changes to the record at the location of the bottoming. This addition is accomplished most readily and simply by merely shifting the entire length of record, from the point of bottoming through the remainder of the record, by an amount equal to the velocity jump at the point of bottoming. If additional bottomings have occurred, the same procedure applies, i.e., shifting the remainder of the record from the point of the bottoming by an amount equal to the velocity jump at that point. Figure 5 illustrates the effect of each of the correction procedures on a typical velocity meter record from an explosion test. Two stops were hit in this particular example.

(A) Velocity Meter Record Prior to Any Corrections



(B) Velocity Meter Record Seismically Corrected But Prior to Bottoming Correction



(C) Velocity Meter Record Seismically Corrected and Corrected for Bottoming

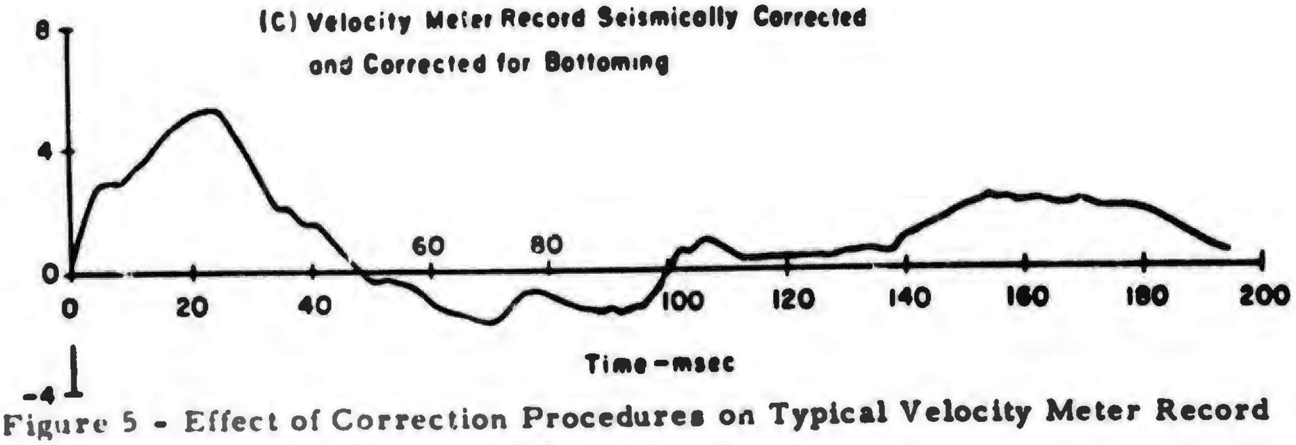


Figure 5 - Effect of Correction Procedures on Typical Velocity Meter Record

The sequence in which the corrections are made is emphasized once again because the sequence is critical. The seismic correction must be made prior to attempting any bottoming correction.

The corrections have been treated here separately to illustrate the contribution of each to the record and for purposes of clarity. The corrections can be and normally are made in one computational process, but care must be exercised to assure that the integrations are performed only on the signal as transmitted directly from the velocity meter.

COMPUTATION METHODS

The correction procedures described herein have been programmed for use with the IBM 7090, which will accept as data input magnetic tapes that have been automatically digitized at a fixed rate. Programs are also available for use on the IBM 650 with punched card input. Fixed time intervals between data points in this case are not necessary.

Seismic corrections are routinely performed by means of electronic analog computation on velocity meter records which have been recorded on magnetic tape. Figure 6 is an unscaled computer diagram for performing the correction. Bottoming corrections, however, are not presently performed by means of an analog computation.

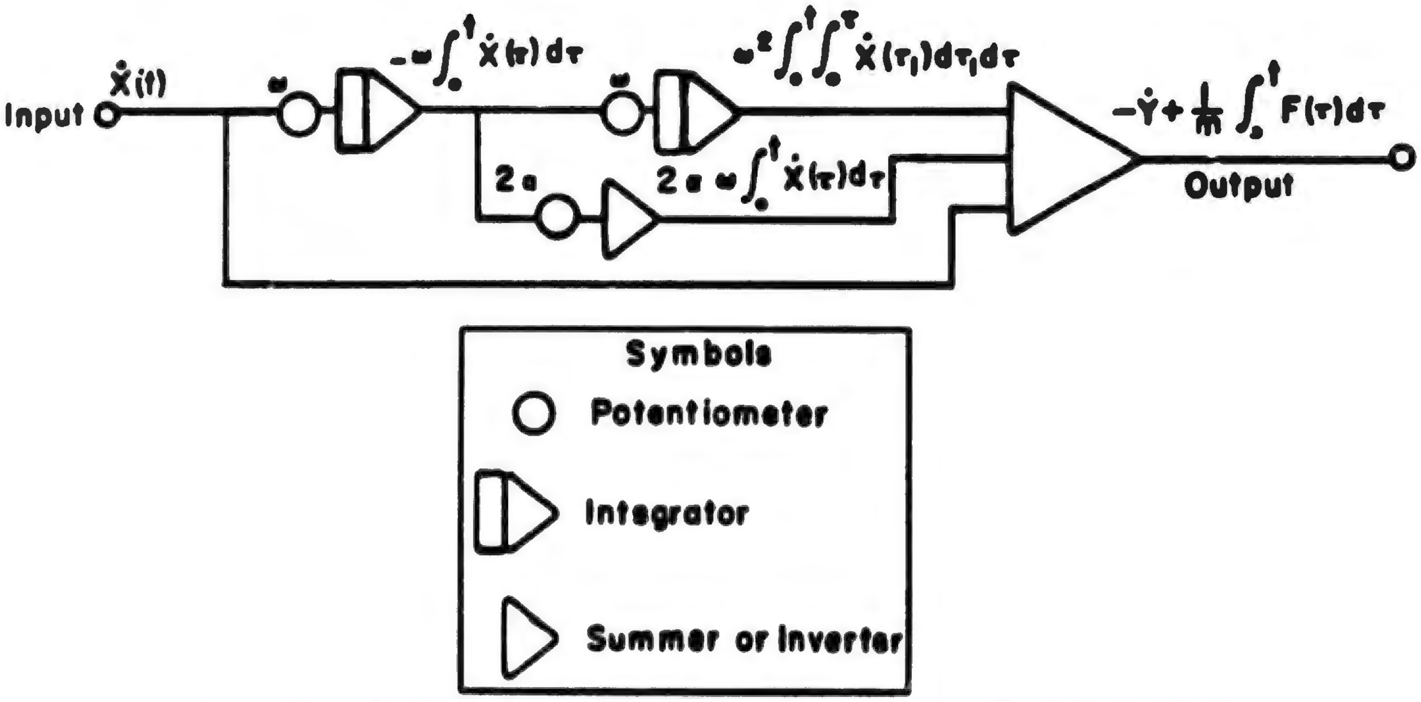


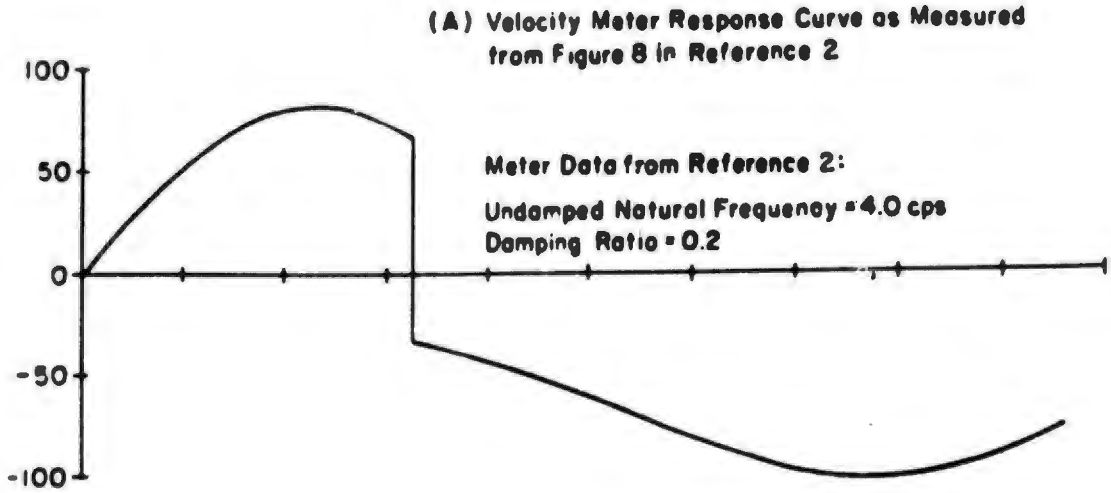
Figure 6 - Unscaled Analog Computer Diagram for Performing Seismic Correction

DISCUSSION

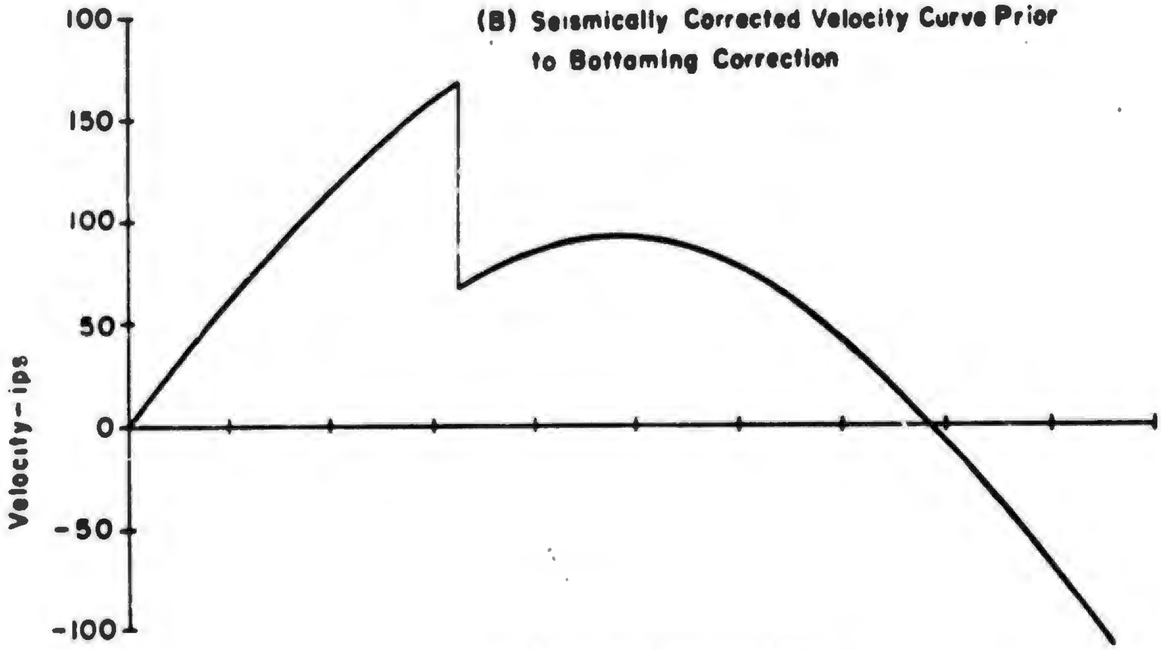
To check the validity of the entire correction procedure a velocity meter record that has been obtained from an instrument having a known input motion is required. This record need not, however, be an experimentally derived measurement. The response of a velocity meter to fairly simple input motions can be readily calculated from the equations of motion. A calculation of this kind can then be corrected in the same manner as an experimental record to re-derive the simulated input motion and thus verify that the correction procedures do truly perform as expected. In Reference 2 the response of a hypothetical velocity meter to a sinusoidal input velocity has been derived. The response curve of Reference 2 is used here to demonstrate the correction procedure; the record was read from a plot in the report and was replotted in Figure 7(a). The correction procedures described herein were applied in the same manner as for any other experimental record. The result of the seismic correction procedure prior to removal of the step velocity change is given in Figure 7(b). The result of the correction procedure including the removal of the step velocity change caused by bottoming is given in Figure 7(c). Also plotted are several points which correspond to points on the analytic input function applied to the hypothetical velocity meter.

The error in the corrected response curve of Figure 7(c) is well within the range of errors which can be expected to accumulate because of difficulties in establishing a base line and reading the curve from a report page, as well as from those distortions resulting from the processes of reproduction and printing used in producing a report. These errors, however, serve to illustrate another important point. Corrections applied to any experimental records are not capable of extending the period of accurate measurement indefinitely. Even though the correction procedures are mathematically correct when applied to an ideal system and have no theoretical limitations as to the time duration over which the corrections apply, instrument peculiarities such as suspension nonlinearity, nonconstant velocity sensitivity over the displacement range, cross-axis sensitivity, and noise signals contribute to the errors which tend to limit the duration of accurate measurements. Inaccuracies in the recording and data reduction processes also, of course, produce errors in the final result just as do meter defects. In fact, the errors shown in Figure 7(c) are those associated with the recording (printing) and data reduction (reading from the curve in the report) processes since the original data from which the velocity meter response curve in Reference 2 was originally plotted were calculated and thus mathematically correct. Had sufficient points of this original data been used in the correction process, the errors illustrated would not have been present.

The most serious data inaccuracies are those which lead to errors that increase with time. The seismic correction is particularly susceptible to these errors because of the integration processes required. For example, any constant error, such as a slight shift in the zero velocity base line on the record, will result in an error in the first integral that increases linearly with time. This error is then compounded in the second integration and thereby leads to a parabolically increasing error in the double integral. Errors of this particular nature, when they occur, are usually introduced during the recording and/or data reduction processes. This source, of course, is not the only one of time growing errors; most of the instrument peculiarities mentioned above lead to similar errors.



(A) Velocity Meter Response Curve as Measured from Figure 8 in Reference 2



(B) Seismically Corrected Velocity Curve Prior to Bottoming Correction

(C) Corrected Velocity Curve

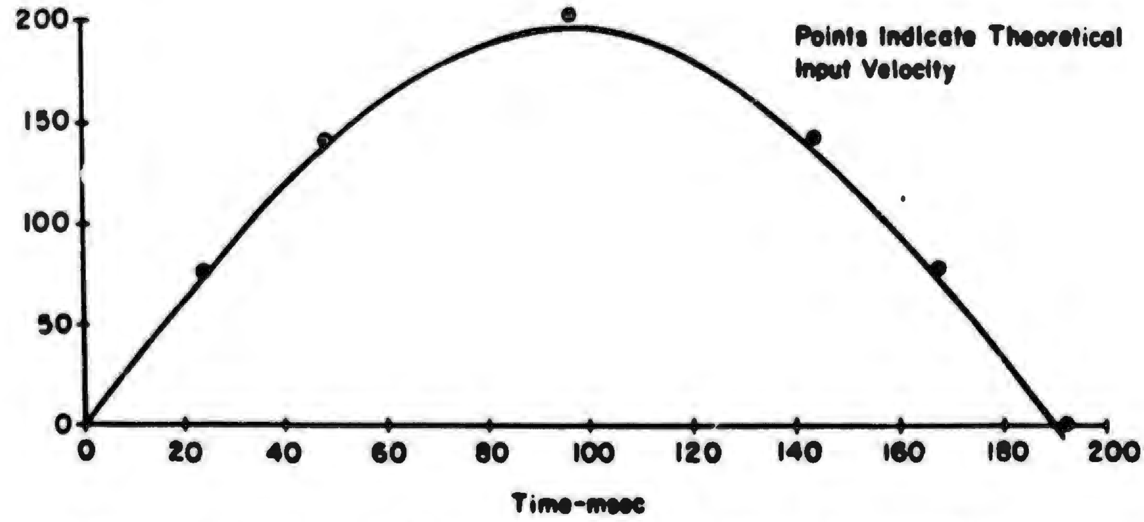


Figure 7 - Results of Correction Procedures Applied to Hypothetical Velocity Meter Response

Accordingly, where corrections involve the process of integration, the probability that time growing errors will occur is high. Since these integrations are dictated by the equations of motion, any correction procedure designed to compensate for the magnet motions must of necessity involve similar integration procedures and thus be subject to errors of the same general form.

Some practical difficulties are also involved in eliminating the effects of bottomings from experimental records. A primary cause of these difficulties arises from the fact that when bottoming occurs, the magnet remains in contact with the stop for a finite period of time. During this period of time, since the magnet-stop interaction characteristics cannot be adequately described, information about the input motion to the coil form is lost. If, therefore, the bottoming occurs at a time when the input velocity is changing rapidly and irregularly, the actual change in magnet velocity cannot be accurately determined. Thus, bottoming corrections tend to become unreliable when bottoming occurs during acceleration or deceleration phases of the local structure motion which the instrument is attempting to measure. These difficulties also are not limited to this particular correction procedure but would apply to any procedure not capable of defining and compensating for the magnet-stop interaction characteristics.

Although wide variation may occur in particular instances, application of the correction procedures may be expected to extend the duration of reasonably accurate measurement to a time roughly equivalent to the natural period of the velocity meter. Thus, in the case of an undamped meter, the corrections increase measurement time by a factor on the order of 20. If more than one or two bottomings occur during this period, the time would probably be somewhat less.

The role of the bottoming in the application of the seismic correction is frequently misunderstood. Reference 2, for instance, has implied that it is necessary to divide the record into segments bounded by the bottoming times. Such division is not necessary. Of course, the correction may be applied in the manner established in Reference 2, which requires dividing the velocity meter record into as many regions or segments as there are bottomings in the record. The corrected record is then obtained by separate computation for each of these regions in sequence using certain information obtained from the preceding regions. Although the method of Reference 2 is mathematically equivalent to the procedures described herein, it seems a bit more laborious.

One advantage of the procedures described here is that the seismic correction may be continuously computed without segmenting the record. This procedure is particularly desirable if the use of electronic analog computational methods is contemplated since integrations in this case may proceed without interruption.

The erroneous conclusion that the procedures described in this report are incorrect was drawn in Reference 2, when an attempt was made to apply them to the hypothetical velocity meter record of Figure 7(a) above. The result obtained in that case was correct until the time of bottoming but thenceforth the error increased rapidly until at the end of the record the indicated velocity was about -300 ips rather than the correct value of zero.

Apparently this result was obtained by computing the seismic correction in two independent segments rather than by means of one continuous computation starting from the beginning of the record. The first segment, that portion of the record preceding bottoming, indicates a correct solution. The second segment, the portion of the record after bottoming, rapidly deviates from the correct solution, however. The errors produced are those obtained when the seismic correction derived herein is applied only to the second segment, but ignoring the first segment and thus considering the system to be at rest at the time of the bottoming. This approach, of course, is erroneous since it ignores the contribution of the first segment to the integrals of the correction equation obtained when the procedure is properly applied. To begin the seismic correction at a bottoming, the correct initial conditions would have to be applied to the correction equation, which basically is the procedure advocated in Reference 2 for performing these seismic corrections.

SUMMARY

The correction procedures described in this report and long in use have been shown to be theoretically justified. These procedures for correcting the velocity meter output in the measurement of absolute velocities are based on two major premises: One is that the suspension system is linear, and the other is that the entire system is at rest prior to the arrival of the shock motion. Although the procedures thus derived will be applicable in most practical situations, no fundamental limitation dictates either requirement. The procedure can be readily extended to cover the situations where only one or neither of these requirements is met, provided of course, that those situations can be adequately described.

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13. ABSTRACT

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