DYNAMIC TESTING OF CIVIL ENGINEERING STRUCTURES

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SYNOPSIS

The use of dynamic testing of structures is described in research and engineering applications. These include confirmation of mathematical models, determination of damping, motion studies under wind and earthquakes, and short-term and long-term observation of structural behaviour under dynamic loadings. Instrumentation requirements, selection and placement of transducers and recording the signals on FM, digital and paper recorders are considered. Filtering, signal-to-noise ratio, analysis and interpretation of data are discussed.

RESUME

La mise en essai dynamique des structures est décrite dans des applications de recherche et de génie. On procède à la confirmation des modèles mathématiques, à la détermination de l'amortissement, à l'étude des mouvements causés par le vent et les tremblements de terre et à l'observation à court terme et à long terme du comportement des structures sous des charges dynamiques. Les exigences d'instrumentation, le choix et la mise en place des transducteurs et l'enregistrement des signaux sur bandes MF, sur papier et sur des magnétophones digitaux sont examinés. Le filtrage, le rapport signal/bruit, l'analyse et l'interprétation des données sont discutés.

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INTRODUCTION

The last decade has seen the field of dynamic testing of structures evolve from a research curiosity to a valuable tool for the practicing engineer. The trend toward more efficient use of materials results in structures that are more sensitive to vibrations caused by wind and service loads. Dynamic testing procedures are required to assess, and alleviate, vibration problems. The purpose of this paper is to describe some of the uses of dynamic testing of structures and to illustrate aspects of the planning and execution of measurement programs.

Many publications have discussed topics related to full-scale dynamic testing of buildings and other structures. Hudson (1) provided a survey of developments on dynamic testing with emphasis on the methods of applying forces, and an ASCE-EMD specialty conference dealt with dynamic testing and modeling (2). Dynamic testing of structures is also discussed in a book edited by Wiegel (3). Recent dynamic measurements on suspension bridges are reported in Refs. 4 to 7. Numerous contributions on this topic can be found, for example, in the Proceedings of the six World Conferences on Earthquake Engineering, the International Journal of Earthquake Engineering and Structural Dynamics, the Bulletin of the Seismological Society of America, and the journals of civil and structural engineering societies in many countries. Dynamic testing can be viewed as one of many nondestructive experimental techniques for observing and investigating the behaviour of structures. Although the method relies on principles of dynamics, useful information concerning static properties of structures can also be inferred.

Just as every elastic structure deforms under the application of a static load, every elastic structure vibrates, however minutely, under the action of fluctuating forces. If damping is small these vibrations occur predominantly at distinct frequencies that correspond to the eigenmodes of the structure. Eigenmodes are vibrational shapes that the structure assumes when it executes free vibration (typical ones for buildings are shown in Fig. 1). The theory of vibrations and of eigenmodes can be found in standard textbooks on dynamics, e.g., References 8 and 9. These mode shapes, together with the associated natural frequencies, are a function of the stiffness and mass properties of the structure. Information on damping characteristics can also be obtained. The dynamic test method involves detecting vibrations from wind and other forces, and evaluating and interpreting the results.

REASONS FOR DYNAMIC TESTING OF STRUCTURES

Areas where dynamic testing of structures can be used to advantage are found in both research and applications. Although this distinction is not always precise, for the present purposes research refers to investigations that are performed for general information rather than for finding the solution to a particular problem.

Research

One of the main reasons for performing dynamic tests on buildings is to confirm methods of mathematical modeling. Although highly sophisticated methods of analysis of buildings are now available, there are still practical limitations on modeling details, and some independent verification of the validity of simplifying assumptions is desirable. There is also considerable uncertainty about material properties, particularly of soil and reinforced concrete; comparisons between measurements and calculations indicate the appropriateness of the mathematical idealizations.

The dynamic response of structures to disturbances such as wind and earthquake depends on damping. Damping, which is a property of the material and the method of construction, is difficult to predict. Measurement of damping of similar or representative buildings enables one to draw general conclusions for future designs and possibly incorporate such properties in recommended design procedures or codes.

When structures are subjected to extreme loadings, such as earthquakes, blasts, and high winds, "softening" of the system occurs due to yielding or loosening of component elements. This results in an increase in the natural periods for the structure which is readily determined from dynamic measurements of the modal properties. Measurements should be made before the projected event to permit a "before" and "after" comparison. When an extreme loading occurs, such information becomes valuable data in assessing the changes experienced by the structure. It is therefore desirable that all structures instrumented with strong-motion seismographs be subjected to a full vibration survey. As a minimum, ambient vibrations should be monitored at the locations of strong-motion instruments and the spectra computed.

In seismically active regions of the world, the installation of strong-motion instrumentation in major structures such as buildings, bridges, dams and nuclear power stations, has become quite common. Records of structural response to strong ground motion provide useful information on linear and nonlinear behaviour of such structures and can assist in evaluating their integrity and safety after an earthquake. For example, the Mica Creek Dam in British Columbia contains three strong-motion seismographs (10). In Quebec, strong-motion seismographs have been installed at three levels in the Daniel Johnson Dam ("Manic 5"), a multiple arch concrete dam, and at "Manic 3", an earth-filled dam, both located on the Manicouagan River. Although these dams are not within the highest risk seismic zones of Canada, their proximity to areas of previous seismic activity and the possibility of reservoir-induced seismic activity, observed at other dam sites, prompted the installation of these instruments.

The rarity and severity of seismic events necessitates instruments with features such as self-starters, self-contained battery operation, rugged construction, and a high degree of reliability under adverse operating conditions. The recommendations of the California Building Strong Motion Earthquake Instrumentation Program, described in Ref. 11, provide useful guidance.

The design of tall buildings is, to a large extent, governed by the motion that occupants will tolerate. Measurement of motion of buildings and other structures under various wind conditions in conjunction with observations of occupant reactions can provide useful information on design criteria for acceptable motion. In addition to monitoring the motions at a few isolated locations, a full determination of the dynamic properties of the structure is required. This permits the extension of motion observations to other points in the structure even though they are not being monitored directly.

Under certain conditions, it is possible to determine the stiffness of structural components from dynamic measurements. For example, the foundation stiffness of buildings or bridges founded on flexible foundations can be determined from dynamic measurements (12, 13). The amplitude of foundation movement is measured along with the amplitudes of the structure to determine the modes of the over-all system. Equating the inertia forces of the structure with the resistance provided by the foundation enables one to solve for the stiffness components of base translation and rotation.

Applications

When dynamic phenomena in structures demand an assessment and possible remedial action, knowledge of the dynamic properties of the building is essential. This occurs, for example, when excessive vibrations due to wind occur in tall buildings or long bridges. In buildings such vibrations can be controlled by installing tuned resonance dampers (14), such as those designed for the Citicorp Center Building in New York, the John Hancock Tower in Boston, or the CN Tower (15) in Toronto. The natural frequency of the building mode to be damped has to be determined and this is obtained from measurements with greater accuracy and certainty than can be achieved from calculations.

Some tall buildings incorporate substantial damping in certain structural elements to reduce vibrational response under wind loads (16). The long-term effectiveness of such damping devices can be assessed by dynamic testing. Although the primary concern here is with the damping properties exhibited by the various modes, the modes of vibration themselves have to be identified first.

Before remedial measures for existing bridges or towers are determined or wind tunnel tests of scale models conducted it is essential to know the natural frequencies, mode shapes and damping characteristics of the real structure. Dynamic testing can provide these parameters directly. Monitoring the behaviour of the structure before and after the changes enables one to confirm the effectiveness of the remedial measures.

PLANNING FOR DYNAMIC TESTS OF STRUCTURES

When planning a dynamic test, consideration should be given to the purpose of the test, the instrumentation, equipment and personnel that are available, the analysis methods to be used, and the final use for which the information is being generated. It is quite possible to obtain useful data with the simplest set of instrumentation if it is appropriately deployed. The scope of the measurement program needs to be clearly outlined; the temptation to measure and record "everything" should be resisted.

An important decision that needs to be made in planning a dynamic testing program is the type of excitation that is to be used. Wind, waves, traffic and occupancy (machinery, people movements) usually produce measurable motions, sometimes called "ambient" vibrations and constitute a convenient source of excitation. Shakers provide controlled forcing functions and yield the most definitive results (1). Eccentric counter-rotating weights, electrohydraulic and electrodynamic shakers have been used as exciters. An electrohydraulic shaker employed in testing a concrete bridge is shown in Fig. 2 (17). The testing effort and cost of equipment is considerable, however, and many owners are reluctant to have their structure deliberately shaken, however lightly. The vibrational effects of high winds, earthquakes and other artificial ground motions from nuclear or large conventional blasts are of great interest in themselves and are frequently monitored, but their rare occurrence makes them unsuitable for routine dynamic testing.

Dynamic tests can be categorized into two classes: short-term and long-term. These require different approaches in planning and executing the experiment.

Short-term tests require a number of days or weeks. The field work for an ambient vibration survey for determining natural frequencies, mode shapes and damping can be accomplished in a few days. Time is required, however, to plan the test and to assemble, check and calibrate the equipment. Considerable time may also elapse waiting for desirable environmental conditions. Of primary concern in these tests is the portability, reliability and ease of operation of equipment. Typically, the signals from accelerometers or velocity transducers would be carried from the points of observation via cables to a temporary recording station. The signals are filtered and amplified and recorded on a multichannel tape recorder. On-site calibration of relative sensitivity can be performed by placing all transducers close together, pointed in the same direction, and recording the signals as would be done in an actual test.

A seven- or eight-channel FM recording system represents about the right compromise between portability, efficiency of information storage, and capital cost. Four channels would be the smallest useful unit; although 14 or more channel FM recorders or digital recorders permit a larger number of channels to be monitored simultaneously, the individual components become substantially heavier and of course more costly. A measuring system used by the author and co-workers is shown in Fig. 3.

If the available number of transducers or recording channels is less than the required observation points, multiple recording sessions are required. A common transducer reference point or set of reference points is retained for successive sessions. This permits the scaling of the results relative to the common measuring points. These reference points must be chosen at a relatively large modal amplitude and not near a node. For buildings the single most suitable point is at the top of the building since at that location all modes have a reasonably large modal deflection, as is shown in Fig. 1. The same applies to torsional motion of buildings, for which two accelerometers on the same floor are required, oriented in the same (or opposite) direction and with the distance normal to their sensitive axis as large as possible. Subtraction or addition of the signals enables one to evaluate both translational and rotational motion. Long slender buildings or those with floors having low in-plane stiffness require three or more measuring stations per floor for an adequate modal representation. For bridges it is advisable that two or more common measuring stations be considered since the locations of nodes are not usually known a priori.

In symmetrical structures it is useful to adopt a symmetrical layout of transducers. This sometimes permits the resolution of closely spaced modes, notably those for translation and torsion in buildings and symmetrical and antisymmetrical modes in bridges.

The location of an exciter also has to be chosen with care, and in general, two or more locations should be considered. This minimizes the possibility of locating on a node and therefore not being able to excite a particular mode. On the other hand, this aspect can be used to advantage in separating closely spaced symmetric and antisymmetric modes. The concrete bridge in Fig. 4 was excited with an electrohydraulic shaker (Fig. 2), using shaker locations and instrument stations given in Fig. 5 (17). Shaker Location 2 produced both symmetric and antisymmetric modes with strong interference between the first two modes (Fig. 6), whereas Shaker Location 1 excited only the symmetric modes (Fig. 7). The latter still shows a small amount of distortion in the frequency response curve because of imperfect symmetry conditions. This is eliminated, however, in the signal from the symmetrically located Station K as shown in Fig. 8, which gives the frequency response curves for symmetric modes without interference from asymmetric ones. An analytical basis for resolving modal interference is presented in Ref. 18.

Observations that extend over some years require a more permanent installation of cables leading to a central recording station. For buildings the cables are best installed during construction. Digital recording techniques are usually used to permit simultaneous sampling of a large number of channels. Signals from nearby measuring points can be multiplexed at intermediate stations, thus reducing the number of long cables that lead to the central recording station. Care must be taken to shield the cables and ground the components so as to avoid pickup of electrical noise. Digital data acquisition also facilitates carrying out some simple calculations such as peak values, means, root-mean-squares and standard deviations, and a programmable monitoring program such as hourly reading and initiation of the recording process based on a predetermined trigger level of a signal. It is important that some spare capacity of channels, cables and observation points be incorporated so that adjustments can be made as preliminary results are obtained and the measuring program evolves. Only a few dynamic measuring points need be monitored continuously as these points can be related to the modal properties determined from a short-term ambient vibration survey. Examples of long-term observation programs are the CN Tower and Commerce Court (19) in Toronto and Century City in Los Angeles (1).

It is important to verify that the various interconnected components are functioning properly and to calibrate the system. For a long-term installation, calibration checks should be carried out periodically. Built-in calibration features of some transducers greatly facilitate this task.

The logistics of carrying out a dynamic test program on a structure should include consideration of accessibility to measuring points, dependence on means of transportation, e.g., elevators, and the necessity of climbing up ladders or stairs with heavy equipment. Telemetry may be employed to advantage in overcoming problems in long distance transmission of signals (1). Last but not least, the goodwill and cooperation of the building owner or his agent must be assured and retained. He should be kept informed of the activities associated with the measurements, and prior understanding must be reached on matters such as access to the building, time span of measurements, sharing of costs, and eventual release of the results.

MEASUREMENT INSTRUMENTATION

The instrumentation required for dynamic testing consists of sensors, signal conditioning, and recording apparatus. The choice of sensors (or transducers) will depend on the objectives of the measurement program and the resources at one's disposal. Structures can be measured using sensors which are displacement, velocity, or acceleration sensitive. The interaction and diverse requirements of the various components of an instrumentation package must be considered in planning and conducting a test.

The measurement of displacement, which is relatively difficult, has been carried out using mechanical (1) or optical means (21). An optical detector which locks onto a contrasting light-dark edge is installed in the CN Tower to measure the lateral displacement between the base and the restaurant level. The foundation rock under the CN Tower also contains deep-seated vertical rods which are brought to the surface within pipes. Relative movement between the base of the rod and the foundation level is obtained by this means.

At the Division of Building Research of the National Research Council of Canada, a displacement measuring device has been built which consists of two pairs of photocells mounted on a belt-driven carriage, to be placed near the top of a shaft in the building (Fig. 9). Servomotors keep the photocells "locked" onto a collimated laser beam projected from the building base. The movement of the building in the x and y directions relative to the stationary beam is converted into voltages proportional to the displacement. One such instrument has been installed in the CN Tower and another in the elevator shaft of the 57-storey Commerce Court building along with other transducers shown in Fig. 10 (19). The detector in Commerce Court has performed satisfactorily in stretches of eight months of continuous operation. Displacements recorded with this instrument are shown in Figs. 11 and 12 (19). Short trial runs of the instrument in the CN Tower showed that considerable swirling of the laser beam occurs due to thermally induced air turbulence inside the tower shaft. This instrument is thus not ideally suited for the tower shaft environment as the thermal turbulence subjects the displacement follower to considerable wear and tear. The major problems associated with obtaining reliable displacement measurements are the effects of air turbulence on the path of light between the source and receiver and the provision of a stable reference plane for the laser beam emitter or the detection system of other optical measuring devices. To have some assurance of getting a proper response from the displacement transducer, accelerometers should be installed so that the dynamic components from both methods can be compared.

Velocity transducers generally work on the principle of a suspended mass whose motion induces a voltage in a coil. With the appropriate amount of damping the output is proportional to velocity over a frequency range above the instrument's natural frequency. Outside this constant velocity range these transducers can still be utilized if suitable calibration of the instrument in that frequency range is available, or if the absolute magnitude is not of interest, for example, in determinations of frequency or mode shapes. Sensitive velocity transducers, also called "seismometers," are available for measuring in the range of 10^{-7} m/s with very little extraneous electrical noise. The sensitivity in upper frequency ranges drops off, thus high frequency vibrations are attenuated, leaving the low frequency signals relatively more prominent. This means that sometimes recordings can be made without the need for filtering. They are affected by magnetic fields, however, and have a limited permissible displacement range.

Strain-gauge- and servo-accelerometers can detect signals almost to 10^{-6} g, and only they will be dealt with here. These accelerometers respond down to 0 Hz, which implies that they are sensitive to orientation relative to the earth's gravitational field. When a horizontal acceleration measurement is also accompanied by rotation, a correction for the rotational component has to be applied to obtain the true horizontal amplitude. This rotation can sometimes be measured by subtracting the output from two vertical transducers placed a certain distance apart. For vertical operation, a minimum transducer range greater than 1 g is required and the constant voltage that represents the 1 g acceleration needs to be filtered out or eliminated by adding an equal d-c voltage of opposite polarity. Having a transducer range of 1 g or greater also permits an easy check on transducer sensitivity. Turning the transducer from facing upward to facing downward produces a voltage change corresponding to 2 g acceleration. Servo-accelerometers carry considerable high frequency noise on the output signal which must be filtered out before amplification. Accelerometers are well suited to measure motion of buildings and long-span bridges since it has been observed that the Fourier or power spectrum of the acceleration signal does not vary **greatly** for a wide range of the low modal frequencies. This permits the identification of some of the higher modes, whose signals would be relatively more attenuated if a velocity sensitive transducer were used.

Bonded electrical strain gauges mounted on structural members of a building, e.g., beams, columns, reinforcing rods, can also be used to obtain dynamic information about the structure. It should be emphasized that strain gauges provide only very localized information. Comparing the strain gauge output with that of other transducers, however, may enable one to relate building movement to the strain and stress induced in some instrumented components (19).

Dynamic measurement programs on buildings frequently also involve the monitoring of other factors such as wind pressure, wind velocity, and foundation strain. These involve techniques similar to those already discussed.

SIGNAL CONDITIONING AND RECORDING

Recording of signals invariably involves filtering to attenuate unwanted frequency components. Analogue filtering should preferably be performed in the same way on all channels since filtering introduces phase shifts near the filter cut-off frequencies.

High-pass filters are often used to eliminate d-c components or other low frequencies when they are not of interest; low-pass filtering attenuates frequency components above the range of interest. Such unwanted components can originate from instrumentation noise as well as from real, high-frequency vibrations. A common extraneous component is 60 Hz which can arise from electrical pickup or real vibrations produced by rotating machinery. After filtering, the signal may have to be amplified or attenuated to bring it to the optimum level demanded by the recording equipment. Many modern recorders incorporate adequate switchable voltage ranges, and this may obviate external amplifiers.

The length of recording sessions will depend on the particular application and on the analysis requirements. Typical record lengths for ambient vibrations vary from a minimum of 10 minutes up to 30 minutes or more. For critical or irreplaceable data, backup storage or duplication of recorded data as well as an uninterruptible power supply should be considered.

For FM (frequency modulation) tape recorders, the background noise level associated with the motions of the magnetic tape determines the smallest useful signal that can be distinguished. The signal to be recorded should therefore be as large as possible, but should not exceed the maximum voltage range of the recorder in order to avoid clipping. The ratio of the voltages of the maximum signal to the noise level of the recorder is called signal-to-noise ratio (S/N). In FM recorders, S/N is typically in the range 50 : 1 to 100 : 1; this can be improved somewhat by flutter compensation. Although this is a built-in option in some machines, flutter compensation can be accomplished on playback by subtracting from each signal an output obtained from a channel on which no external signal was recorded. This feature has the disadvantage, however that it preempts one channel on the tape recorder. To achieve a sufficiently high level of a small low-frequency component, larger amplitude components at higher frequencies need to be filtered out before the signal is recorded. This then permits sufficient amplification to be applied to raise the weak component well above the tape noise. On the other hand, if the signal into the recorder exceeds the specified maximum voltage level its peaks will be clipped. If this occurs frequently, significant distortion of the computed spectrum amplitude peaks can result. For signals that vary over a wide range or that are of uncertain magnitude, it may be necessary to record the same signal on two channels using different amplifications.

FM tape recorders are relatively efficient in storing signals that have components over a wide frequency range. Although playback of signals is simple, there can be problems during recording due to interference from radio signals, including walkie-talkies, that are operated nearby.

In digital recording systems the signal-to-noise ratio depends on the word length and the noise introduced by the analogue-to-digital converter, the latter noise being negligible in most cases. Common digital recorders have 12-bit words; with one bit reserved for the sign the word length is $(2)^{11} = 2048$, and the noise level is then represented by the last bit. The resulting S/N ratio of approximately 2000 : 1 enables digital systems to accommodate a much larger range of signal levels than FM recorders. Digital systems require that the incoming signal be filtered at less than the Nyquist frequency, i.e., one half the sampling rate (23). The sampling rate in turn is governed by the highest frequency that is to be recorded. For an adequate representation of the signal, however, it is desirable to choose a sampling rate between six and ten times the highest frequency component that is to be fully represented. An advantage of digital data logging systems is the possibility of processing data before recording it on tape. Examples include the computation of sums, distribution functions recorded at predetermined time intervals, and root-mean-squares. Recording can be started or stopped depending on amplitude levels or other characteristics of the data. Interference of radio signals with stored programs has also been experienced with digital systems.

The signals from transducers can also be recorded on paper by using photosensitive, heat sensitive, pressure sensitive, or ink pen recorders. The frequency response of the recorder has to be adequate for the frequency content of the signal to be displayed. Filtering may be necessary. Before further data processing can be done on random-type signals, the traces must be digitized or converted to an electrical analogue signal. This is usually very laborious. Paper recorders, however, make ideal monitoring instruments in parallel with a tape recorder, thus permitting simultaneous viewing of the incoming signals. They are also useful for displaying the final signals from steady-state vibrations since these usually do not require further signal processing. A portable oscilloscope is an invaluable tool for instantaneous examination of signals and monitoring the proper functioning of the various components of an instrumentation system.

ANALYSIS OF DATA

Before the analysis of data is begun, the adequacy and quality of data have to be verified. Signal clipping, "blips," and record gaps will introduce distortions into the computed results. Visual examination on a strip chart, oscilloscope, or computer-plotted traces is a necessity.

The extraction of useful information invariably requires the computation of spectra - Fourier amplitude, power, or cross spectra. The identification of associated mode shapes requires the determination of phase between the signals from the various measuring stations. This can be achieved by simple addition and subtraction of signals and observing how the amplitudes of the spectrum peaks change. Frequency components that are in phase result in increasing resonance peaks of an added signal; out-of-phase signals result in decreasing resonance peaks. The real part of the cross spectrum of two signals also provides the phase information, in-phase components giving positive peaks, out-of-phase negative ones. These methods of determining phase are applicable if the frequency components are either in-phase or out-of-phase, i.e., they constitute normal modes with only real components. In the general case where this assumption cannot be made, phase can be computed directly from the polar representation of the cross spectrum.

Damping can be determined by a number of methods. The half-power-bandwidth method gives the critical damping ratio as

$$\xi = \Delta f/2f_o \tag{1}$$

where Δf is the width of the spectrum peak at one-half the peak magnitude of the power spectrum or at 0.707 the peak of a Fourier amplitude spectrum, and f_o is the resonance frequency. This is illustrated in Fig. 13. Autocorrelation calculated from the power spectrum of an isolated resonance peak gives a decaying curve from which

$$\xi = \frac{1}{2\pi n} \ln \frac{x_n}{x_o} \tag{2}$$

where x_n is the amplitude of the nth peak past the amplitude x_o of the zeroth peak. Reference 22 describes the "Partial Moment Method," which utilizes the power spectrum of a signal. Other methods of calculating damping are presented in Ref. 23. The random decrement method (24,25) depicted in Fig. 14, sums finite lengths of the record starting from successive ascending and descending portions of excursions that exceed a preselected signal level; the signal must be filtered to contain only one modal response. The result is a curve of decaying amplitudes shown in Fig. 15(a); the damping ratio is computed using Eq. (2). When more than one closely spaced frequency component is present in a signal, the random decrement will exhibit a beat pattern, Fig. 15(b); application to this of Eq. (2) can result in misleading information.

Possibly the most direct method of determining damping is from the filtered impulse decay curve and by using Eq. (2). Unfortunately it is often difficult to generate such a decay curve in major structures. The impulse decay curve shown in Fig. 16(a) was obtained on the Lions' Gate Suspension Bridge during a brief bridge closure by driving a truck in the outside lane, turning sharply normal to the bridge and stopping. Filtering is performed by making use of the Fast Fourier Transform algorithm. The Fourier transform is computed as shown in Fig. 16(b), unwanted frequency components are rejected as in Fig. 16(c), and the result inverted back to the time domain. The filtered decay curve for the mode under consideration is shown in Fig. 16(d). Damping is then obtained using Eq. (2). The cyclic nature of the Discrete Fourier Transform has to be accounted for properly so that the residual vibrations of the filtered signal are zero or acceptably small. This can be achieved by shaping functions or adding zeros to the beginning and ends of the original signals (26).

Seldom do any two methods of calculating damping give answers that agree closely. This can be traced to inherent differences in the theory upon which the damping calculations are based, experimental or computational shortcomings, or most probably to the fact that the basic assumptions underlying the theory are not fully satisfied by the data. Slight variations in response frequencies of a mode can make the calculation of damping quite misleading or impossible because the resonance peaks are artificially widened; the computed damping ratio is then larger than would ordinarily be the case. This difficulty has been encountered with dynamic measurements on suspension bridges (4, 7) and tall buildings (19). This area of dynamics of structures needs more attention and research.

Other quantities of interest, particularly from a statistical point of view, are maximum amplitudes, means, root-mean-squares, and standard deviations. Finally it should not be overlooked that simply filtering in selected frequency bands and displaying the resulting signals can provide much useful information on frequency, phase, and amplitude of various modal components of a. signal.

Data can be analysed either on a general purpose digital computer or by special purpose instruments such as spectrum analyzers, correlators, or specialized minicomputers. Although the general purpose digital computer offers a wide choice of data manipulation and practically unlimited options for calculations, the special purpose instruments enjoy great popularity. Simplicity of operation, ready accessibility and the possibility of on-site operation make these instruments a valuable addition to any dynamic measurement system. A vital part of any computational facility is also the capability of displaying signals and results of calculations in hard copy; the graph of a spectrum, for example, contains most of the information that is needed.

INTERPRETATION OF RESULTS

Interpreting the results of dynamic measurements in buildings must be done in light of the experimental procedures and the analysis methods employed. This may be self-evident, but it cannot be overemphasized. For example, the results from dynamic measurements obtained from low-level vibrations (ambient or shaker excitation) may not be directly applicable to conditions that exist with earthquakes or high winds. Where nonlinearities are associated with high amplitudes, changes occur in natural frequencies, mode shapes and damping ratios. The problem is complicated by the fact that reinforced concrete, prestressed concrete, steel, and "nonstructural" elements, such as interior partitions, differ in their amplitude-strain dependence.

The presence of flexible foundations in buildings, bridges and other structures should also be considered. Flexible foundations in buildings introduce rocking and horizontal base motion which affect the mode shapes and lower the natural frequencies. Similar effects occur in bridges on flexible foundations.

Measured and calculated dynamic properties of structures frequently do not agree closely. Possible reasons are, in order of relative importance and frequency of occurrence: unknown or uncertain material properties (e.g., soil, concrete or wood); faulty or inadequate mathematical model for the structure (e.g., oversimplified or inappropriate allowance for "nonstructural" elements, expansion joints or flexible foundations); errors in interpreting the results; experimental errors. The last-mentioned can be minimized by exercising due care and by taking some independent duplicate measurements.

Considerable effort was required to achieve reasonable agreement between measured and calculated results for the Lions' Gate Suspension Bridge in Vancouver, B.C. (6). Uncertainties in modeling the torsional stiffness of the deck and partial restraints from bearings and tie rods required an extensive parametric study in order to assess the dynamic behaviour of the bridge.

A useful indicator of the reasonableness of the mathematical model is the ratio of modal frequencies relative to the fundamental frequency. If these computed ratios agree reasonably well with the measured ones, one can assume with some assurance that the distribution of stiffness and mass in the mathematical model are reasonable. Agreement with actual frequencies can then be reached by scaling the material stiffness or the mass, although the latter is usually known more reliably and therefore is less likely to be the major cause of discrepancy.

Finally, the interpretation of damping should be done with caution. A wide resonance peak resulting from slight temporal variations of resonance frequency can lead to inappropriately high damping values. The same is true if only the first few cycles of the autocorrelation or random decrement curves are examined; the presence of beats, as shown in Fig. 15(b) makes the routine application of damping calculations inappropriate.

CONCLUSION

Dynamic testing of structures has emerged as a useful engineering tool, both for the researcher and the practicing engineer. The method has been demonstrated in numerous cases for short-term and long-term observations.

The results of a dynamic testing program usually result in structural properties such as mode shapes, natural frequencies, damping values and maximum or rms response levels. Caution needs to be exercised, however, in interpreting the results, particularly those for damping.

Planning and performing a measurement program should take account of the objectives of the tests, the characteristics of the instruments employed and the requirements imposed by the methods of analysis of the data. A variety of suitable instrumentation for carrying out the measurements and analysis are available.

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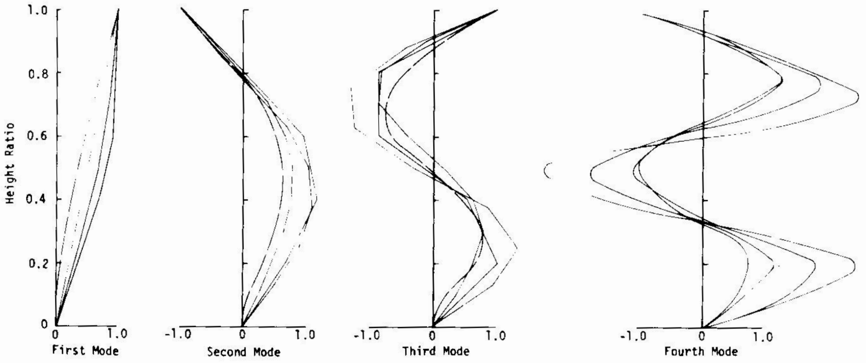

Figure 1 Typical mode shapes for buildings (Ref. 11)

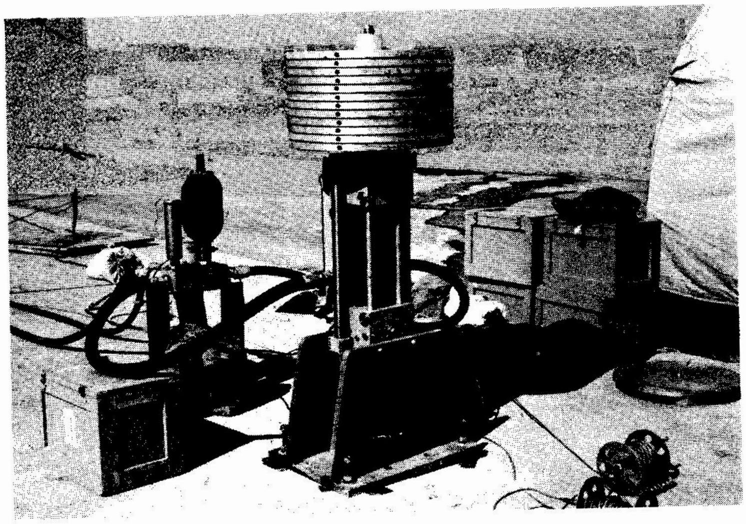

Figure 2 Electrohydraulic shaker mounted on bridge median

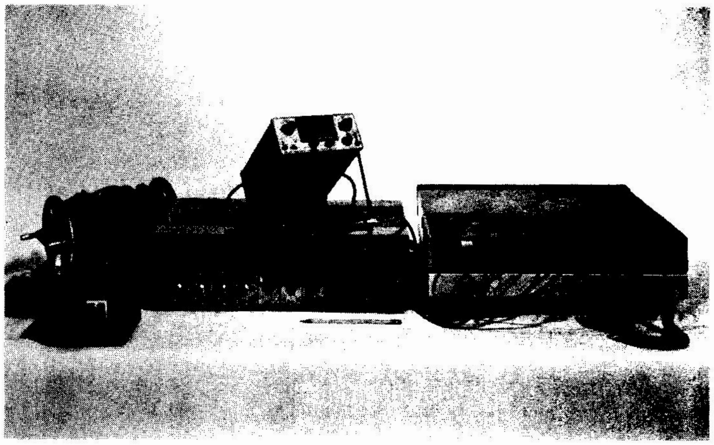

Figure 3 Components of a portable dynamic measuring system for structures. (From left to right, bottom to top of picture: one unit of a servo-accelerometer mounted on a base, power supply, cable reel; 7-channel amplifier, filter and d-c compensation unit; monitoring oscilloscope; 7-channel FM tape recorder)

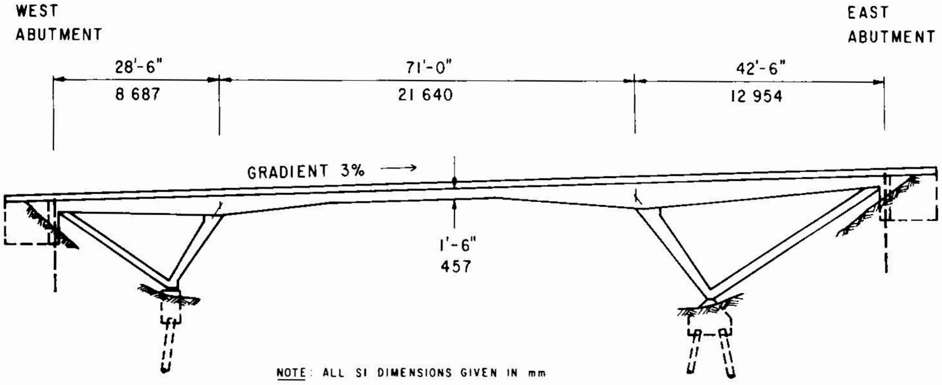

Figure 4 South elevation, former Ottawa River Parkway Service Road Bridge. (Width of bridge = 103'-0" (31 394 mm) skewed at 10° 50'

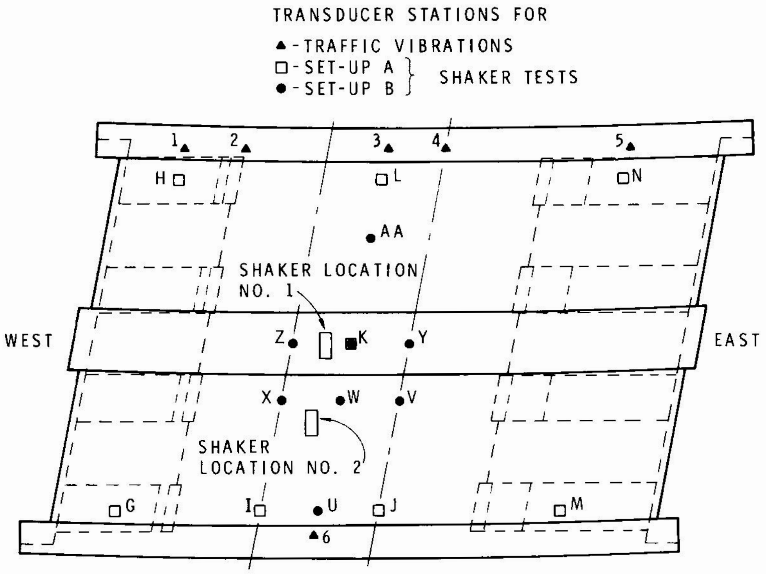

Figure 5 Instrumentation layout on bridge deck

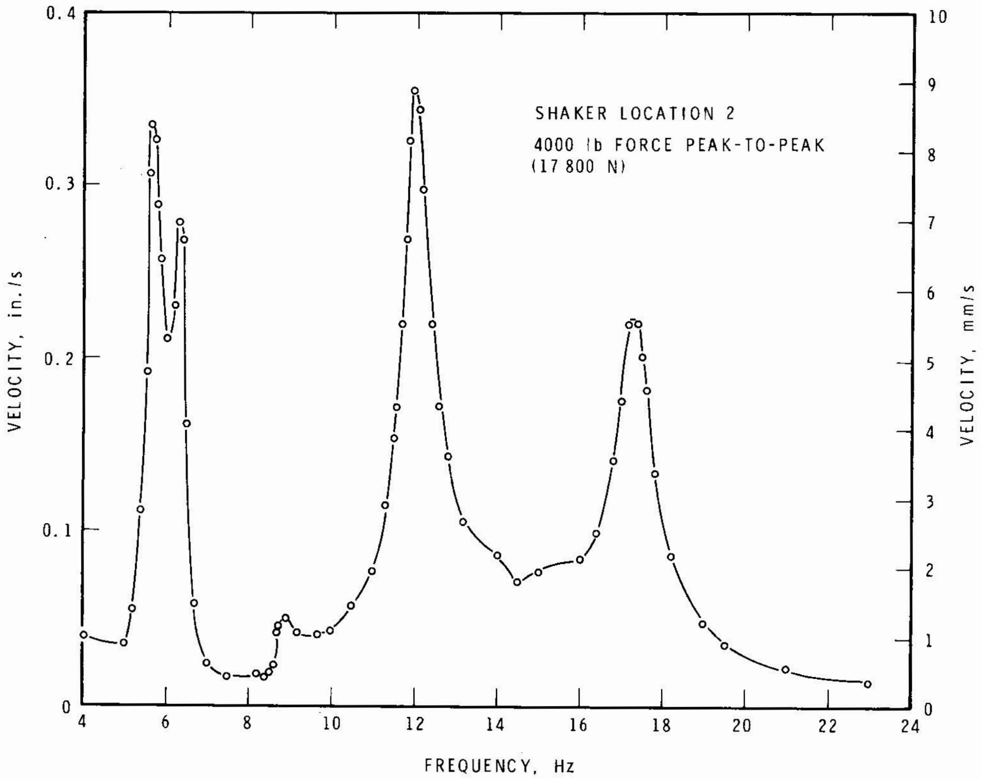

Figure 6 Frequency response curve for Station AA, Test No. 5

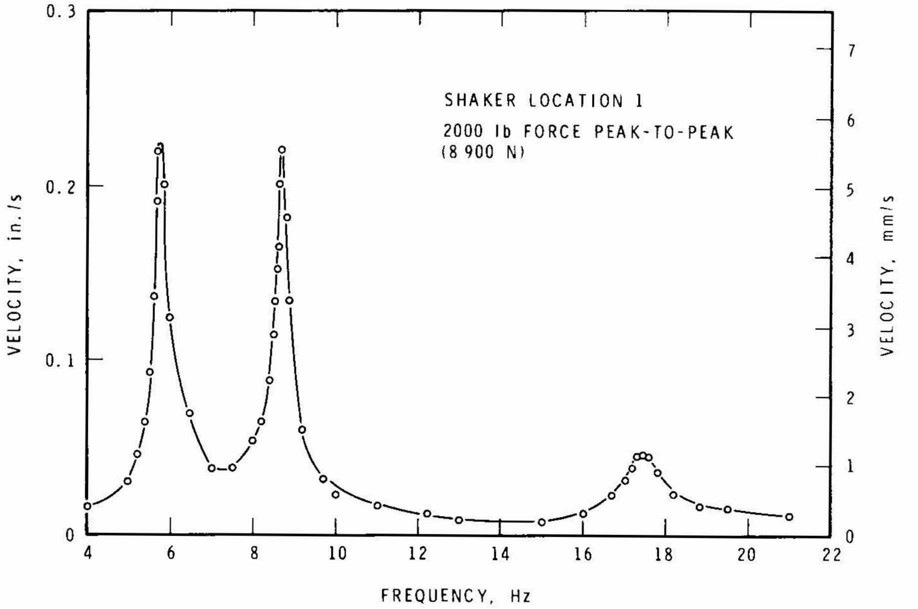

Figure 7 Frequency response curve for Station U, Test No. 4B

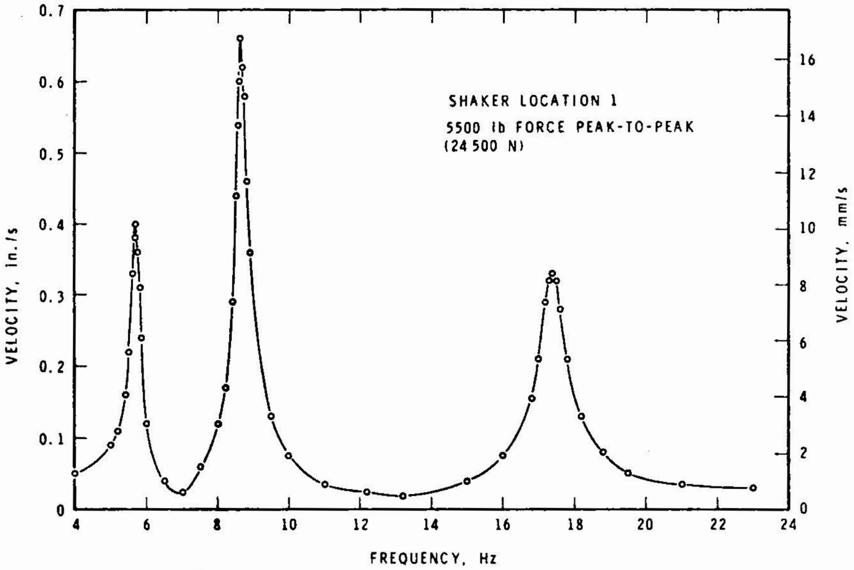

Figure 8 Frequency response curve for Station K, Test No. 4C

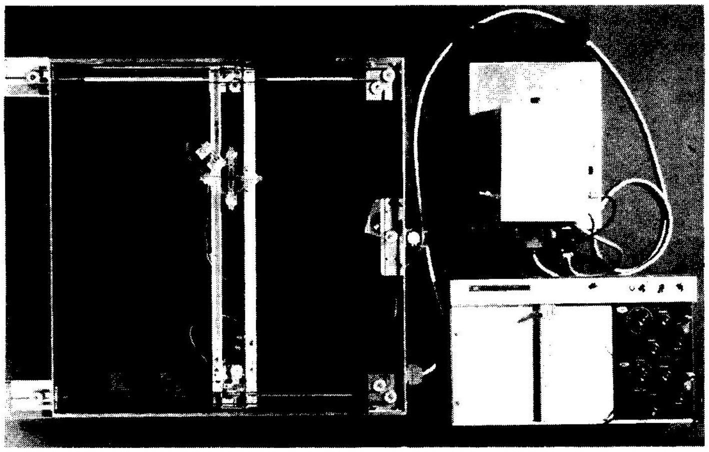

Figure 9 Top view of servo-controlled electromechanical displacement detector. (Photocells on carriage lock onto stationary laser beam; x-y plotter displays relative carriage motion: power supply and servo-control unit at top right)

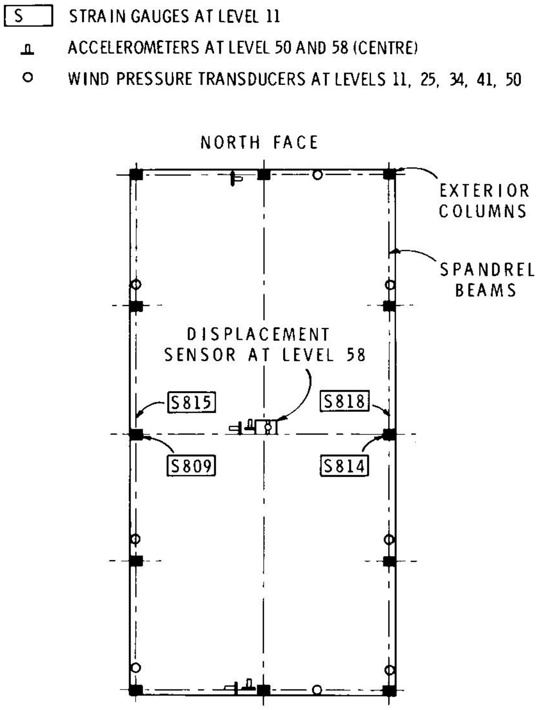

Figure 10 Plan view of instrumentation layout, Commerce Court, Toronto

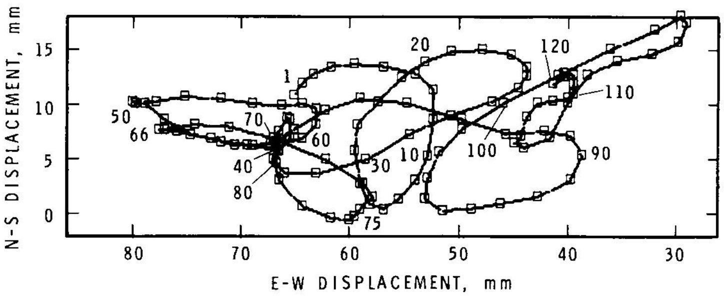

Figure 11 One minute path of building centre (squares of 0.5 s intervals)

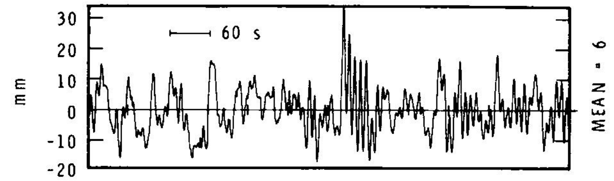

Figure 12 North-south displacement at level 58 from east-northeast wind at 18.4 m/s

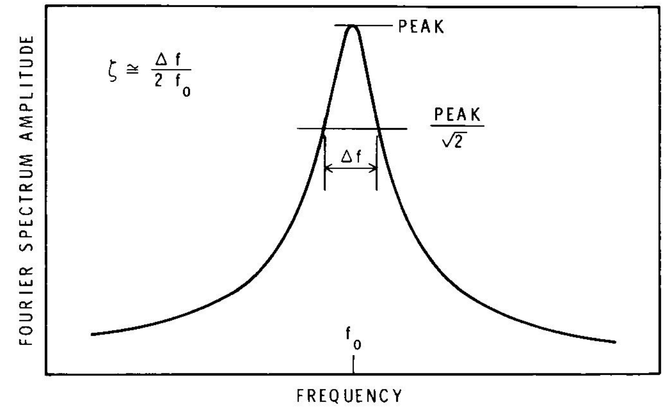

Figure 13 Calculation of damping ratio from Fourier spectrum on resonance curve

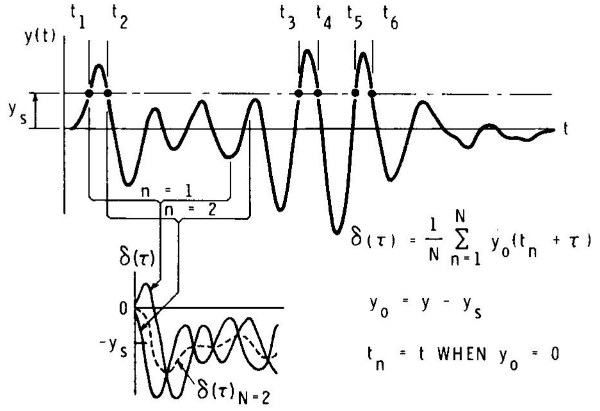

Figure 14 Evolution of random decrement signature, $\delta(\tau)$

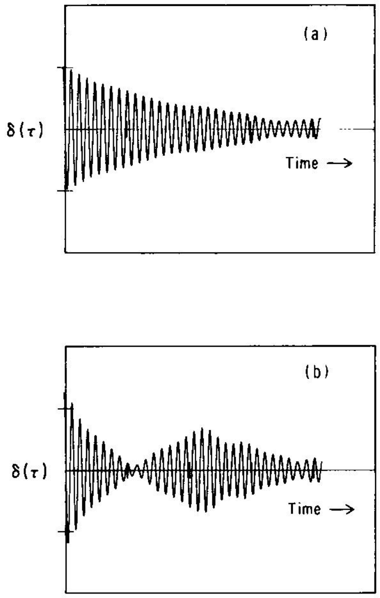

Figure 15 Random decrement **signature:** (a) from filtered acceleration trace; (b) from signal having closely spaced frequency components

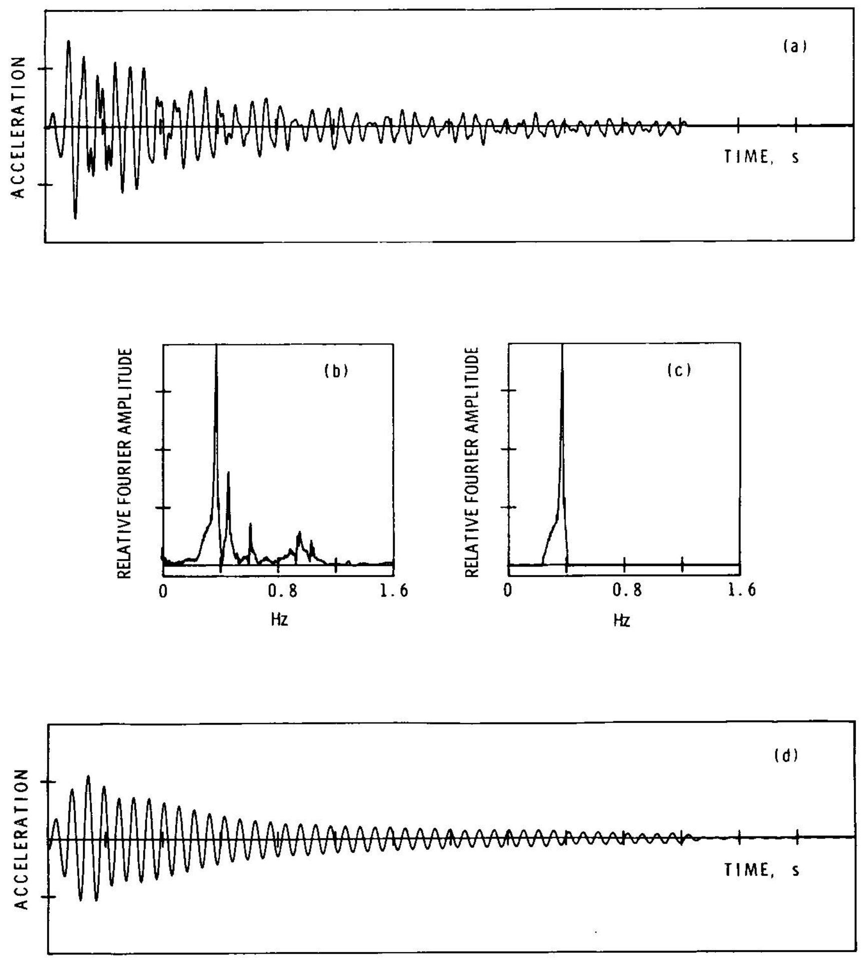

Figure 16 Determination of damping from impulse decay, Lions' Gate Bridge, Vancouver, B.C.: (a) Torsional response to truck impact at centre span; (b) Discrete Fourier transform; (c) Truncated Fourier transform; (d) Filtered responses