



Standard Test Methods for Modulus and Damping of Soils by the Resonant-Column Method¹

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1. Scope

1.1 These test methods cover the determination of shear modulus, shear damping, rod modulus (commonly referred to as Young's modulus), and rod damping for solid cylindrical specimens of soil in the undisturbed and remolded conditions by vibration using the resonant column. The vibration of the specimen may be superposed on a controlled ambient state of stress in the specimen. The vibration apparatus and specimen may be enclosed in a triaxial chamber and subjected to an all-around pressure and axial load. In addition, the specimen may be subjected to other controlled conditions (for example, pore-water pressure, degree of saturation, temperature). These test methods of modulus and damping determination are considered nondestructive when the strain amplitudes of vibration are less than 10^{-4} rad (10^{-4} in./in.), and many measurements may be made on the same specimen and with various states of ambient stress.

1.2 These test methods cover only the determination of the modulus and damping, the necessary vibration, and specimen preparation procedures related to the vibration, etc., and do not cover the application, measurement, or control of the ambient stress. The latter procedures may be covered by, but are not limited to, Test Methods D 2166 or D 2850.

1.3 *This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.*

2. Referenced Documents

2.1 ASTM Standards:

- D 2166 Test Method for Unconfined Compressive Strength of Cohesive Soil²
- D 2216 Test Method for Laboratory Determination of Water (Moisture) Content of Soil and Rock²
- D 2850 Test Method for Unconsolidated, Undrained Compressive Strength of Cohesive Soils in Triaxial Compression²

¹ These test methods are under the jurisdiction of ASTM Committee D18 on Soil and Rock and are the direct responsibility of Subcommittee D18.09 on Soil Dynamics.

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² *Annual Book of ASTM Standards*, Vol 04.08.

D 4767 Test Method for Consolidated-Undrained Triaxial Compression Test on Cohesive Soils²

3. Terminology

3.1 Definitions of Terms Specific to This Standard:

3.1.1 *ambient stress*—stresses applied to the specimen, during the test, that do not result from the vibration strains. These test methods do not cover the application and measurement of ambient stresses; however, the ambient stress at the time of measurement of the system resonant frequency and system damping shall be measured and recorded in accordance with the final section of the paper.

3.1.2 *apparatus model and constants*—the rigidity and mass distribution of the resonant column shall be as required in the following section in order for the resonant-column system to be accurately represented by the model shown in Fig. 1. The apparatus constants are the mass of the passive-end platen, M_P , including the mass of all attachments rigidly connected to it; the rotational inertia of the passive-end platen, J_P , including the rotational inertia of all attachments rigidly connected to it; similar mass, M_A , and rotational inertia, J_A , for the active-end platen and all attachments rigidly connected to it, such as portions of the vibration excitation device; the spring and damping constants for both longitudinal and torsional springs and dashpots (K_{SL} , K_{ST} , ADC_L , ADC_T); the apparatus resonant frequencies for longitudinal vibration, f_{oL} , and torsional vibration, f_{oT} ; the force/current constant, FCF , relating applied vibratory force to the current applied to the longitudinal excitation device; the torque/current constant, TCF , relating applied vibratory torque to the current applied to the torsional excitation device; and the motion transducer calibration factors (LCF_A , RCF_A , LCF_P , RCF_P) relating the transducer outputs to active- and passive-end longitudinal and rotational motion.

3.1.3 *moduli and damping capacities*—Young's modulus (herein called rod modulus), E , is determined from longitudinal vibration, and the shear modulus, G , is determined from torsional vibration. The rod and shear moduli shall be defined as the elastic moduli of a uniform, linearly viscoelastic (Voigt model) specimen of the same mass density and dimensions as the soil specimen necessary to produce a resonant column having the measured system resonant frequency and response due to a given vibratory force or torque input. The stress-strain relation for a steady-state vibration in the resonant column is a hysteresis loop. These moduli will correspond to the slope of a

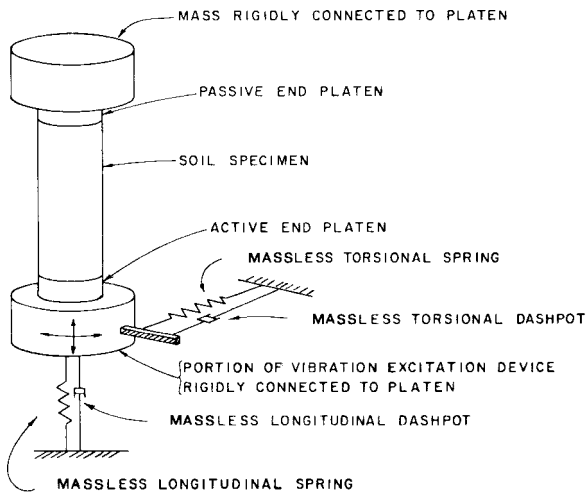


FIG. 1 Resonant-column Schematic

line through the end points of the hysteresis loop. The section on calculations provides for computation of rod and shear moduli from the measured system longitudinal and torsional resonant frequencies. The energy dissipated by the system is a measure of the damping of the soil. Damping will be described by the rod damping ratio, D_L , and the shear damping ratio, D_T , which are analogous to the critical viscous damping ratio, c/c_r , for a single-degree-of-freedom system. The damping ratios shall be defined by:

$$D_L = 0.5(\eta\omega/E) \quad (1)$$

where:

η = viscous coefficient for rod motion, N·s/m²,
 ω = circular resonant frequency, rad/s, and
 E = rod modulus, Pa.

and by:

$$D_T = 0.5(\mu\omega/G) \quad (2)$$

where:

μ = viscous coefficient for torsional motion, N·s/m², and
 G = shear modulus, Pa.

3.1.3.1 Values of damping determined in this way will correspond to the area of the stress-strain hysteresis loop divided by 4π times the elastic strain energy stored in the specimen at maximum strain. Methods for determining damping ratio are prescribed later. In viscoelastic theory, it is common to use complex moduli to express both modulus and damping. The complex rod modulus is given by:

$$E^* = E(1 + 2iD_L) \quad (3)$$

and the complex shear modulus is given by:

$$G^* = G(1 + 2iD_T) \quad (4)$$

where $i = \sqrt{-1}$.

3.1.4 *resonant-column system*—a system consisting of a cylindrical specimen or column of soil that has platens attached

to each end as shown in Fig. 1. A sinusoidal vibration excitation device is attached to the active-end platen. The other end is the passive-end platen. It may be rigidly fixed (the criterion for establishing fixity is given later) or its mass and rotational inertia must be known. The vibration excitation device may incorporate springs and dashpots connected to the active-end platen, where the spring constants and viscous damping coefficients are known. Vibration excitation may be longitudinal or torsional. A given apparatus may have the capability of applying one or the other, or both. The mass and rotational inertia of the active-end platen and portions of the vibration excitation device moving with it must be known. Transducers are used to measure the vibration amplitudes for each type of motion at the active end and also at the passive end if it is not rigidly fixed. The frequency of excitation will be adjusted to produce resonance of the system, composed of the specimen and its attached platens and vibration excitation device.

3.1.5 *specimen strain*—for longitudinal motion, the strain, ϵ , is the average axial strain in the entire specimen. For torsional motion, the strain, γ , is the average shear strain in the specimen. In the case of torsion, shear strain in each cross section varies from zero along the axis of rotation to a maximum at the perimeter of the specimen, and the average shear strain for each cross section occurs at a radius equal to 80 percent the radius of the specimen. Methods for calculating specimen strain are given later in the calculations section.

3.1.6 *system resonant frequency*—the definition of system resonance depends on both apparatus and specimen characteristics. For the case where the passive-end platen is fixed, motion at the active end is used to establish resonance, which is defined as the lowest frequency for which the sinusoidal excitation force (or moment) is in phase with the velocity of the active-end platen. For the case where the passive-end platen mass (or passive end platen rotational inertia) is greater than 100 times the corresponding value of the specimen and is not rigidly fixed, resonance is the lowest frequency for which the sinusoidal excitation force (or moment) is 180° out of phase with the velocity of the active-end platen. Otherwise, motion at the passive end is used to establish resonance, which is the second lowest frequency for which the sinusoidal excitation force (or moment) is in phase with the velocity of the passive-end platen. (The lowest frequency for this condition is not used because it does not produce significant strains in the specimen.) In general, the system resonant frequency for torsional excitation will be different from the system resonant frequency for longitudinal excitation.

4. Significance and Use

4.1 The modulus and damping of a given soil, as measured by the resonant-column technique herein described, depend upon the strain amplitude of vibration, the ambient state of effective stress, and the void ratio of the soil, temperature, time, etc. Since the application and control of the ambient stresses and the void ratio are not prescribed in these methods, the applicability of the results to field conditions will depend on the degree to which the application and control of the ambient stresses and the void ratio, as well as other parameters such as soil structure, duplicate field conditions. The techniques used

to simulate field conditions depend on many factors and it is up to the engineer to decide on which techniques apply to a given situation and soil type.

5. Apparatus

5.1 *General*—The complete test apparatus includes the platens for holding the specimen in the pressure cell, the vibration excitation device, transducers for measuring the response, the control and readout instrumentation, and auxiliary equipment for specimen preparation.

5.2 *Specimen Platens*—Both the active-end and passive-end platens shall be constructed of noncorrosive material having a modulus at least ten times the modulus of the material to be tested. Each platen shall have a circular cross section and a plane surface of contact with the specimen, except that the plane surface of contact may be roughened to provide for more efficient coupling with the ends of the specimen. The diameter of platens shall be equal to or greater than the diameter of the specimen. The construction of the platens shall be such that their stiffness is at least ten times the stiffness of the specimen. The active-end platen may have a portion of the excitation device, transducers, springs, and dashpots connected to it. The transducers and moving portions of the excitation device must be connected to the platen in such a fashion that they are to be considered part of the platen and have the same motion as the platen for the full range of frequencies to be encountered when testing soils. The theoretical model used for the resonant-column system represents the active-end platen, with all attachments, as a rigid mass that is attached to the specimen;

this mass may also have massless springs and dashpots attached to it as shown in Fig. 1. If springs are used, the excitation device and active-end platen (without the specimen in place) form a two degree-of-freedom system (one-degree-of-freedom system for devices designed for only longitudinal or only torsional motion) having undamped natural frequencies for longitudinal motion, f_{oL} , and torsional motion, f_{oT} . The device shall be constructed such that these modes of vibration are uncoupled. The passive-end platen may have a mass and transducers rigidly attached to it or it may be rigidly fixed. The passive-end platen may be assumed to be rigidly fixed when the inertia of it and the mass(es) attached to it and the stiffness of the support of the mass(es) provide a dimensionless frequency factor within 1 % of the dimensionless frequency factor for the passive-end inertia ratio equal to infinity. (Use Fig. 2 and the calculations section to get the dimensionless frequency factor.)

5.3 *Vibration Excitation Device*—This shall be an electromagnetic device capable of applying a sinusoidal longitudinal vibration or torsional vibration or both to the active-end platen to which it is rigidly coupled. The frequency of excitation shall be adjustable and controlled to within 0.5 %. The excitation device shall have a means of measuring the current applied to the drive coils that has at least a 5 % accuracy. The voltage drop across a fixed, temperature-and-frequency-stable power resistor in series with the drive coils may be used for this purpose. The force/current and torque/current factors for the vibration excitation devices must be linear within 5 % for the

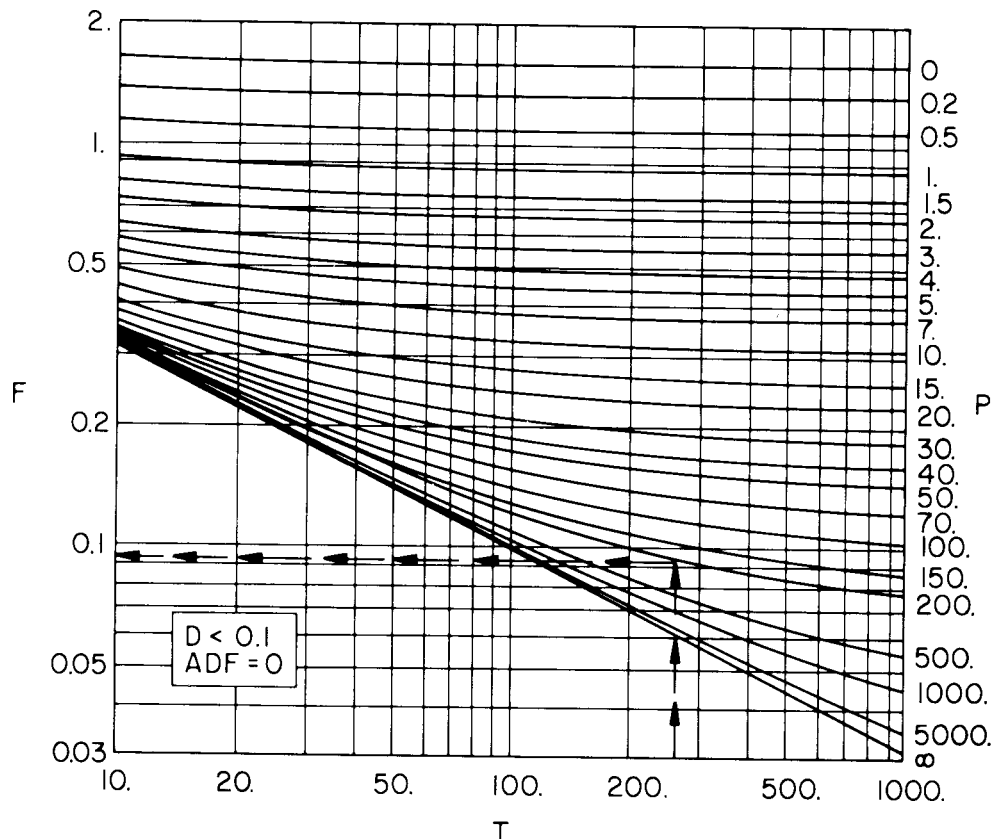


FIG. 2 (a) Dimensionless Frequency Factors³

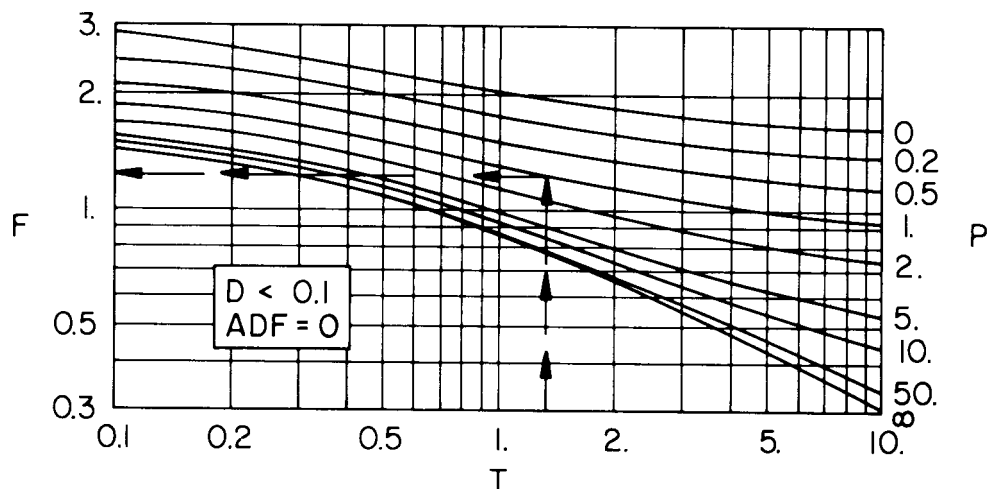


FIG. 2 (b) Dimensionless Frequency Factors³ (continued)

entire range of operating frequencies anticipated when testing soils.

5.4 Sine Wave Generator—The sine wave generator is an electric instrument capable of producing a sinusoidal current with a means of adjusting the frequency over the entire range of operating frequencies anticipated. This instrument shall provide sufficient power to produce the required vibration amplitude, or its output may be electronically amplified to provide sufficient power. The total distortion of the signal applied to the excitation device shall be less than 3 %.

5.5 Vibration-Measuring Devices and Readout Instruments—The vibration-measuring devices shall be acceleration, velocity, or displacement transducers that can be attached to and become a part of the active- and passive-end platens. On each platen, one transducer shall be mounted to produce a calibrated electrical output that is proportional to the longitudinal acceleration, velocity, or displacement of that platen (not required for torsion-only apparatus). The other transducer(s) shall be mounted to produce a calibrated electrical output that is proportional to the rotational acceleration, velocity, or displacement (not required for longitudinal-only apparatus). The readout instrument and transducers shall have a sensitivity such that a displacement of 2.5×10^{-6} m (10^{-4} in.) and a rotation of 10^{-5} rad can be measured with 10 % accuracy for the entire range of frequency anticipated. It is also necessary to have an x-y-time oscilloscope available for observing signal waveforms and for establishing the system resonant frequency. This oscilloscope must have at least one amplifier (vertical or horizontal) with sufficient gain to observe the motion transducer output over the entire range of output voltages and frequencies anticipated. For measurement of damping by the free-vibration method, and for calibration of the apparatus damping, the readout instrument shall be capable of recording the decay of free vibration. Either a strip-chart recorder with appropriate response time and chart speed or an oscilloscope and camera or a digital oscilloscope may be used for this purpose.

5.6 Support for Vibration Excitation Device—For the special case where the passive end of the specimen is rigidly fixed and the vibration excitation device and active-end platen are

placed on top of the specimen, it may be necessary to support all or a portion of the weight of the platen and excitation device to prevent excessive axial stress or compressive failure of the specimen. This support may be provided by a spring, counter-balance weights, or pneumatic cylinder as long as the supporting system does not prevent axial movement of the active-end platen and as long as it does not alter the vibration characteristics of the excitation device.

5.7 Temporary Platen Support Device—The temporary support may be any clamping device that can be used to support one or both end platens during attachment of vibration excitation device to prevent specimen disturbance during apparatus assembly. This device is to be removed prior to the application of vibration.

5.8 Specimen Dimension-Measuring Devices—Dimension-measuring devices are needed to measure portions of the apparatus during calibration and specimen diameter and length. All dimensions measurements should be accurate to 0.1 %. Any suitable device may be used to make these measurements except that the device(s) used to measure the length and diameter of the specimen must not deform or otherwise affect the specimen. Specially designed perimeter tapes that measure circumference but read out in diameter are preferred for measuring specimen diameters.

5.9 Balances—Devices for determining the mass of the soil specimens as well as portions of the device during calibration. All measurements of mass should be accurate to 0.1 %.

5.10 Specimen Preparation and Triaxial Equipment—These methods cover specimen preparation and procedures related to the vibration of the specimen and do not cover the application and control of ambient stresses. Any or all of the apparatus described in Test Methods D 2166, D 2850, or D 4767 may be used for specimen preparation and application of ambient stresses. Additional apparatus may be used for these purposes as required.

5.11 Miscellaneous Apparatus—The miscellaneous apparatus consists of specimen trimming and carving tools, a membrane expander, remolding apparatus, moisture content cans, and data sheets as required.

6. Test Specimen

6.1 *General*—These methods cover only the special specimen preparation procedures related to the vibration and resonant-column technique. Since the resonant-column test may be conducted in conjunction with controlled ambient stresses, the provisions for preparation of specimens in Test Methods D 2166, D 2850, or D 4767 may be applicable or may be used as a guide in connection with other methods of application and control of ambient stresses.

6.2 *Specimen Size*—Specimens shall be of uniform circular cross section with ends perpendicular to the axis of the specimen. Specimens shall have a minimum diameter of 33 mm (1.3 in.). The largest particle contained within the test specimen shall be smaller than one tenth of the specimen diameter except that, for specimens having a diameter of 70 mm (2.8 in.) or larger, the largest particle size shall be smaller than one sixth of the specimen diameter. If, after completion of a test, it is found that larger particles than permitted are present, indicate this information in the report of test data under "Remarks." The length-to-diameter ratio shall be not less than 2 nor more than 7 except that, when an ambient axial stress greater than the ambient lateral stress is applied to the specimen, the ratio of length to diameter shall be between 2 and 3. Measure the length at the third points along the perimeter and average the values. Measure two diameters at each of three elevations and average the values. Determine the weight of the test specimen. For determination of moisture content (Test Method D 2216), secure a representative specimen of the cuttings from undisturbed specimens, or of the extra soil for remolded specimens, placing the specimen immediately in a covered container.

6.3 *End Coupling for Torsion*—For torsional motion, complete coupling of the ends of the specimen to the specimen cap and base must be assured. Complete coupling for torsion may be assumed if the mobilized coefficient of friction between the end platens and the specimen is less than 0.2 for all shear strain amplitudes. The coefficient of friction is approximately given by:

$$\text{Coefficient of friction} = \gamma G / \sigma'_a \quad (5)$$

where:

γ = shear strain amplitude (see calculations section),
 G = shear modulus (see calculations section), and
 σ'_a = effective axial stress.

6.3.1 When this criterion is not met, other provisions such as the use of adhesives must be made in order to assure complete coupling. In such cases, the effectiveness of the coupling provisions shall be evaluated by testing two specimens of the same material but of different length. The lengths of these specimens shall differ by at least a factor of 1.5. The provisions for end coupling may be considered satisfactory if the values of the shear modulus for these two specimens of different length do not differ by more than 10 %.

7. Calibration

7.1 *Motion Transducers*—Motion transducers shall be calibrated with each other and with an independent method to ensure calibration accuracy within 5 %. Linear motion trans-

ducers whose axes are located fixed distances from the axis of rotation may be used to measure rotational motion if the cross-axis sensitivities of the transducers are less than 5 %. For this case the distance between the axis of rotation and the transducer axes shall be known to within 5 %. The calibration factors for longitudinal motion shall be expressed in terms of peak-meters/peak-volt. The calibration factors for rotational motion shall be expressed in terms of peak-radians/peak-volt. This means that for velocity and acceleration transducers the vibration frequency shall be included as a term in the calibration factor. For velocity transducers, the displacement calibration factors are given by:

$$LCF \text{ or } RCF = \text{velocity calibration factor} / (2\pi f) \quad (6)$$

where f = frequency, Hz.

For acceleration transducers, the displacement calibration factors are given by:

$$LCF \text{ or } RCF = \text{acceleration calibration factor} / (2\pi f)^2 \quad (7)$$

7.1.1 Thus, for velocity and acceleration transducers, the displacement calibration factors will not be constants but will vary with measured frequency, f . Calibration factors for longitudinal motion are given by the symbol LCF with a subscript A or P denoting whether the transducer is located on the active-end platen or passive-end platen. Likewise, the calibration factors for rotational motion will be given by the symbol RCF and will have subscripts A or P depending on their location.

7.2 *Passive-End Platen Mass and Rotational Inertia*—The mass and rotational inertia of the passive-end platen shall be determined with all transducers and other rigid attachments securely in place. The mass, M_P , is determined by use of a balance. The rotational inertia of the concentric solid cylindrical components of the passive-end platen and its attachments is given by:

$$(J_P)_1 = \frac{1}{8} \sum_{i=1}^n M_i d_i^2 \quad (8)$$

where:

M_i = mass of i th solid cylindrical component,
 d_i = diameter of i th solid cylindrical component, and
 n = number of solid cylindrical components.

Transducers and other masses attached to this platen can be accounted for by:

$$(J_P)_2 = \sum_{i=1}^n M_i r_i^2 \quad (9)$$

where:

M_i = mass of i th component,
 r_i = distance from the platen axis to center of mass for i th component, and
 n = number of components attached to passive-end platen and not covered in determination of $(J_P)_1$.

The total rotational inertia for the passive end is given by:

$$J_P = (J_P)_1 + (J_P)_2 \quad (10)$$

7.3 Active-End Platen Mass and Rotational Inertia—The mass, M_A , and rotational inertia, J_A , of the active-end platen shall be determined with all transducers and rigid attachments, including attached portions of the vibration excitation device, securely in place. The equations just given may be used to obtain the mass and rotational inertia. For rotational inertia, if all components do not have simple geometry, an alternative procedure that involves a metal calibration rod of known torsional stiffness may be used. One end of the rod shall be rigidly fixed and the other end shall be rigidly fastened to the active-end platen. Since it may be very difficult to fasten the calibration rod to the platen without adding rotational inertia, it is recommended that the calibration rod be permanently fastened by welding, etc., to an auxiliary platen. If the auxiliary platen is not identical to the one to be used in testing, the difference between its rotational inertia and that of the platen for soil testing must be taken into account by use of aforementioned equations. (For example, suppose that the value of the active-end rotational inertia with the calibration rod was J_1 and the rotational inertia of the calibration rod platen was J_2 . If the rotational inertia of the platen for testing soil is J_3 , then the value of J_A would be given by $J_A = J_1 - J_2 + J_3$.) The torsional stiffness of the calibration rod should be chosen such that the system resonant frequency with the calibration rod in place is near the middle of the range of system resonant frequencies anticipated for soil testing. Several calibration rods may be necessary to account for different specimen sizes. With the calibration rod in place, determine the low-amplitude system resonant frequency for torsional vibration, $(f_{rod})_T$. The rotational inertia of the active end platen system is calculated from:

$$J_A = \frac{(K_{rod})_T}{(2\pi)^2[(f_{rod})_T^2 - f_{oT}^2]} \quad (11)$$

where:

- $(K_{rod})_T$ = torsional stiffness of calibration rod,
= $(I_p G)/L$,
- I_p = polar moment of inertia of calibration rod,
= $(\pi d^4)/32$,
- d = calibration rod diameter,
- G = shear modulus for calibration rod material, and
- f_{oT} = apparatus torsional resonant frequency as described in the following subsection.

7.3.1 The foregoing equations assume that the rotational inertia of the calibration rods is much less than the corresponding values for the active-end platen system. A second alternative procedure is to couple the metal calibration rod to the platens in place of the specimen and then use the procedures of the Calculations section to backfigure the active end inertias from the known moduli of the rod.

7.4 Apparatus Resonant Frequencies, Spring Constants, and Damping Constants—Apparatus resonant frequencies and spring constants are defined only for those apparatus that have springs attached to the active-end platen system. To determine the resonant frequencies, set up the apparatus complete with active-end platen and O-rings but no specimen. Vibrate at low amplitude and adjust the frequency of vibration until the input

force is in phase with the velocity of the active-end platen system. For longitudinal vibration, this apparatus resonant frequency is f_{oL} and for torsional vibration it is f_{oT} . The longitudinal and torsional apparatus spring constants (K_{SL} , K_{ST}) may be calculated from:

$$\begin{aligned} K_{SL} &= (2\pi f_{oL})^2 M_A \\ K_{ST} &= (2\pi f_{oT})^2 J_A \end{aligned} \quad (12)$$

where M_A and J_A are defined in the previous subsection.

7.4.1 To measure the damping constants for the apparatus, attach the same masses as used for the determination of apparatus resonant frequencies. For apparatus without springs attached to the active-end platen, insert the calibration rod described in the previous subsection. With the apparatus vibrating at the resonant frequency, cut off the power to the excitation device and record the decay curve for the vibration of the apparatus. From the decay curve, compute the logarithmic decrement, δ , as follows:

$$\delta = (1/n) \ln (A_1/A_{n+1}) \quad (13)$$

where:

- A_1 = amplitude of vibration for first cycle after power is cut off, and
- A_{n+1} = amplitude for $(n + 1)$ th cycle.

The apparatus damping coefficient, ADC_L , from longitudinal vibration shall be given by:

$$ADC_{oL} = 2f_{oL} M_A \delta_L \quad (14)$$

where:

- f_{oL} = longitudinal motion resonant frequency measured during apparatus damping determination,
- M_A = active-end platen mass from previous subsection, and
- δ_L = logarithmic decrement for longitudinal motion.

For torsional motion, the apparatus damping coefficient, ADC_{oT} is given by:

$$ADC_{oT} = 2f_{oT} J_A \delta_T \quad (15)$$

where:

- f_{oT} = torsional motion resonant frequency measured during apparatus damping determination,
- J_A = active-end rotational inertia from previous subsection, and
- δ_T = logarithmic decrement for torsional motion.

7.5 Force/Current and Torque/Current—For apparatus without springs attached to the active-end platen, insert the calibration rod as described earlier. Determine the resonant frequency of this single-degree-of-freedom system consisting of the active-end platen and apparatus spring (or calibration rod) by use of the same procedure as described later in the procedures section. Then set the frequency to 0.707 times the resonant frequency and apply sufficient current to the vibration excitation device so that the vibration transducer output to the readout device has a signal of at least ten times the signal due to ambient vibrations and electrical noise when no power is applied to the excitation device. Read and record the output of

both the vibration transducer and the current measuring instrument. Next, set the frequency to 1.414 times the system resonant frequency and obtain the vibration transducer and current instrument readings in a similar fashion to those at 0.707 times the resonant frequency. Calculate C_1 and C_2 from:

$$C_1 = 0.5(VTCF)(TO1)/CR1 \quad (16)$$

$$C_2 = (VTCF)(TO2)/CR2$$

where:

$VTCF$ = active-end vibration transducer displacement calibration factor (LCF or RCF) (Note 1) depending on whether vibration is longitudinal or torsional,

$TO1$ = active-end transducer output at 0.707 times resonant frequency,

$CR1$ = current instrument reading at 0.707 times resonant frequency (Note 2),

$TO2$ = active-end transducer output at 1.414 times resonant frequency, and

$CR2$ = current instrument reading at 1.414 times resonant frequency (Note 2).

NOTE 1— LCF and RCF will be functions of frequency for velocity and acceleration measuring transducers (see 7.1).

NOTE 2—If a current-measuring instrument is used, the units will be amperes. Alternatively, voltage drop across a fixed resistance may also be measured and the units will then be volts.

C_1 and C_2 should agree within 10 %. By use of C_1 and C_2 from longitudinal vibration, the force/current calibration factor, FCF , is obtained from:

$$FCF = 0.5(C_1 + C_2)K \quad (17)$$

where K = apparatus spring constant (or for apparatus without springs, the calibrating rod spring constant) for longitudinal motion.

By use of C_1 and C_2 from torsional vibration, the torque/current calibration factor, TCF , is obtained from:

$$TCF = 0.5(C_1 + C_2)K \quad (18)$$

where K = apparatus spring constant (or for apparatus without springs, the calibrating rod spring constant) for torsional motion.

8. Procedure

8.1 *Test Setup*—The exact procedure to be followed during test setup will depend on the apparatus and electronic equipment used and on methods used for application, measurement, and control of the ambient stresses. However, the specimen shall be placed in the apparatus by procedures that will minimize the disturbance of the specimen. Particular care must be exercised when attaching the end platens to the specimen and when attaching the vibration excitation device to the platens. A temporary support as discussed earlier may be needed. For cases where ambient isotropic stresses are to be applied to a membrane-enclosed specimen, liquid- or air-confining media may be used for dry or partially saturated specimens. For tests where complete saturation is important, a liquid-confining medium should be used. Where the vibration excitation device is located within the pressure chamber, an

air-liquid interface is acceptable as long as the liquid covers the entire membrane that encloses the specimen.

8.2 *Electronic Equipment*—Connect the vibration excitation device to the sine wave generator (with amplifier, if required). The power supplied to the vibration excitation device should be very low in order not to exceed the amplitude of vibration prescribed later. Connect the vibration transducers to the readout instruments for the type of motion (longitudinal or torsional) to be applied. Adjust the readout instruments according to the instruction manuals for these instruments.

8.3 *Measurement of Resonant Frequency*—The procedure for measuring system resonant frequency is the same for both longitudinal and torsional vibration except that the longitudinal motion transducer is used for longitudinal motion and the rotational motion transducer is used for torsional motion. If the passive end is fixed or if $P > 100$ (see the calculations section for definition of P), motion of the active-end platen is used to establish resonance. Otherwise, motion of the passive-end platen is used. With the power as low as practical, increase the frequency of excitation from a very low value (for example, 10 Hz) until the system resonant frequency is obtained. The phase relationship describing resonance can be established by observing the Lissajous figure formed on an x-y oscilloscope with the voltage proportional to the driving current applied to the horizontal amplifier and the output from the transducer applied to the vertical amplifier. If a velocity transducer is used for vibration measurement, the system resonant frequency occurs when the figure formed is a straight, sloping line. If a displacement or acceleration transducer is used, the frequency should be adjusted to produce an ellipse with axes vertical and horizontal. (Refer to Definitions section to establish which resonant frequency should be recorded.) It is recommended that the frequency be measured with a digital electronic frequency meter and be recorded to at least three significant figures. The system resonant frequency for longitudinal motion shall be designated f_L and that for torsional motion shall be designated f_T .

8.4 *Measurement of Strain Amplitude*—The strain amplitude measurements shall be made only at the system resonant frequencies. Thus, for a given current applied to the excitation device, the vibration motion transducer outputs recorded at the system resonant frequency give sufficient information to calculate strain amplitude. To increase or decrease strain amplitude, the current to the vibration excitation device must be increased or decreased. After making a change in current applied to the vibration excitation device, the procedure of the previous subsection must be followed to establish the corresponding system resonant frequency before the transducer outputs can be used to establish the new strain amplitude value.

8.5 *Measurement of System Damping*—Associated with each strain amplitude and system resonant frequency is a value of damping. Two methods are available for measuring system damping: the steady-state vibration method and the amplitude decay method. Theoretically, both methods should give identical results. In practice, results of each method are usually close to each other. The steady-state method is easier and quicker. It is generally always used and the amplitude decay method is used for occasional spot-checking. The procedures

for both methods are independent of whether longitudinal or torsional motion is under consideration. For the steady-state method, the active-end or the passive-end vibration transducer output (depending on which end is used to establish resonance) and the current applied to the vibration excitation device must be measured at each resonant frequency. The calculations are outlined in the following section. For the free-vibration method, with the system vibrating at the system resonant frequency, cut off the power to the vibration excitation device and record the output of the transducer used in establishing resonance as a function of time. This gives the decay curve for free vibration. The calculations for damping are also outlined in the following section.

9. Calculation

9.1 General—Calculations require the apparatus calibration factors and the physical dimensions and weight of the specimen. In addition, for each ambient stress condition, one data set is required for each vibration strain amplitude. A data set consists of the type of vibration (longitudinal or torsional), duration of vibration (this time can be used to calculate the number of vibration cycles), system resonant frequency, active- or passive-end transducer outputs (depending on which end is used to establish resonance), the reading associated with the current applied to the vibration excitation device, and the free-vibration amplitude decay curve (if the amplitude decay method of measuring damping is also going to be used). The calculations outlined in this section may all be made by computer. A program for making some of the calculations is provided in Appendix X1. Other programs may be used to make a portion or all of the calculations as long as they provide identical results.

9.2 Soil Mass Density—The soil mass density, ρ , is given by:

$$\rho = \frac{M}{V} \quad (19)$$

where:

M = total mass of specimen, and
 V = volume of specimen.

9.3 Specimen Rotational Inertia—The specimen rotational inertia about the axis of rotation is given by:

$$J = \frac{Md^2}{8} \quad (20)$$

where d = diameter of specimen.

9.4 Active-End Inertia Factors:

9.4.1 The active-end inertia factor for longitudinal motion, T_L , is calculated from:

$$T_L = \frac{M_A}{M} [1 - (f_{oL}/f_L)^2] \quad (21)$$

where:

M_A = mass of active-end platen system as calculated earlier,
 f_{oL} = apparatus resonant frequency for longitudinal motion (for apparatus without springs attached to the active end platen, this term is zero), and

f_L = system resonant frequency for longitudinal motion.

9.4.2 The active-end inertia factor for torsional motion, T_T , is given by:

$$T_T = \frac{J_A}{J} [1 - (f_{oT}/f_T)^2] \quad (22)$$

where:

J_A = rotational inertia of active-end platen system as calculated earlier,
 J = specimen rotational inertia as calculated earlier,
 f_{oT} = apparatus resonant frequency for torsional motion (for apparatus without springs attached to the active-end platen, this factor is zero), and
 f_T = system resonant frequency for torsional motion.

9.5 Passive-End Inertia Ratios:

9.5.1 For longitudinal motion, the passive-end inertia ratio, P_L , is given by:

$$P_L = \frac{M_P}{M} \quad (23)$$

where M_P = mass of passive-end platen system as described earlier.

9.5.2 For torsional motion, the passive-end inertia ratio, P_T , is given by:

$$P_T = J_P/J \quad (24)$$

where J_P = rotational inertia of passive-end platen system as calculated earlier.

9.5.3 For the special case where the passive end of the specimen is rigidly fixed, P_L and P_T are equal to infinity.

9.6 Apparatus Damping Factors:

9.6.1 For longitudinal motion, the apparatus damping factor, ADF_L , is calculated from

$$ADF_L = ADC_{oL} [2\pi f_L M] \quad (25)$$

where ADC_{oL} = apparatus damping coefficient for longitudinal motion as described earlier.

9.6.2 For rotational motion, the apparatus damping factor, ADF_{oT} , is calculated from:

$$ADF_T = ADC_{oT} [2\pi f_T J] \quad (26)$$

where ADC_{oT} = apparatus damping coefficient for torsional motion as described earlier.

9.7 Dimensionless Frequency Factor—The dimensionless frequency factor, F , is used in calculating modulus. It is a function of system factors T , P , and ADF and of specimen damping ratio, D . Values of F are provided by the computer program in Appendix X1, which is written in FORTRAN IV. For cases where ADF is zero and specimen damping ratio is less than 10 % values of F can be obtained from Fig. 2. Fig. 2b is similar to Fig. 2a except that the range of T is different. This figure is independent of which end of the specimen is used to determine resonance.

9.8 Magnification Factors:

9.8.1 These factors are used in calculating damping. For longitudinal motion, the magnification factor is calculated from:

$$MMF_L = \left[\frac{(LCF)(LTO)}{(FCF)(CR_L)} \right] M(2\pi f_L)^2 \quad (27)$$

where:

LCF = longitudinal motion transducer displacement calibration factor for transducer used in establishing resonance (Note 3),³
LTO = longitudinal motion transducer output of transducer used in establishing resonance,
FCF = force/current factor given earlier, and
CR_L = current reading to longitudinal excitation system (Note 4).

NOTE 3—*LCF* and *RCF* will be functions of frequency for velocity- and acceleration-measuring transducers (see 7.1).

NOTE 4—If a current-measuring instrument is used, the units will be amperes. Alternatively, this may be a voltage measurement across a fixed resistance and in units of volts. In the latter case, the same fixed resistance use in calibration (see 7.5) must be used for these measurements.

9.8.2 For torsional motion, the magnification factor is calculated from:

$$MMF_T = \left[\frac{(RCF)(RTO)}{(TCF)(CR_T)} \right] J(2\pi f_T)^2 \quad (28)$$

where:

RCF = rotational transducer displacement calibration factor for transducer used in establishing resonance (Note 3)
RTO = rotational transducer output for transducer used in establishing resonance,
TCF = torque/current factor given earlier, and
CR_T = current reading to torsional excitation system (Note 4)

9.9 Moduli:

9.9.1 The rod modulus is calculated from:

$$E = \rho(2\pi L)^2(f_L/F_L)^2 \quad (29)$$

where:

ρ = specimen mass density given earlier,
f_L = system resonant frequency for longitudinal motion given earlier,
F_L = dimensionless frequency factor given earlier, and
L = specimen length.

9.9.2 The shear modulus is calculated from:

$$G = \rho(2\pi L)^2(f_T/F_T)^2 \quad (30)$$

where:

f_T = system resonant frequency for torsional motion given earlier, and
F_T = dimensionless frequency factor given earlier.

9.10 Strain Amplitude:

9.10.1 The average rod strain amplitude, ϵ , for longitudinal vibration shall be calculated from:

$$\epsilon = (LCF)(LTO)(SF/L) \quad (31)$$

where:

LCF = longitudinal motion transducer displacement calibration factor for the transducer used in establishing resonance (Note 5),
LTO = longitudinal transducer output for the transducer used in establishing resonance,
SF = strain factor calculated by program in the Appendix X1 or, for cases of *ADF* = 0 and specimen damping equal to 10 %, it may be obtained from Fig. 3. For other values of specimen damping ratio, values from Fig. 3 are only approximately correct. (Note that Fig. 3 is for the case where resonance is established by phase measurement between input force and motion at the active end and Fig. 3b is for the case where resonance is established by phase measurement between input force and motion at the passive end), and
L = specimen length.

NOTE 5—*LCF* and *RCF* will be functions of frequency for velocity- and acceleration-measuring transducers (see 7.1).

9.10.2 For torsional motion, the average shear strain amplitude, γ , shall be calculated from:

$$\gamma = \frac{RCF RTO SF d}{2.5L} \quad (32)$$

where:

RCF = rotational motion transducer displacement calibration factor for transducer used in establishing resonance (Note 5),
RTO = rotational transducer output for transducer used in establishing resonance,
SF = strain factor determined in same manner as described for rod strain amplitude, and
d = specimen diameter.

9.11 *Damping Ratio from Steady-State Vibration*—If the computer program in the Appendix is used, the damping ratio of the specimen is established as part of the output. Manual calculation of damping ratio may be done for cases where the apparatus damping factor, *ADF*, is zero or may be assumed to be zero (definition of *ADF* given earlier). The procedure requires that Fig. 4a be used if resonance is established by phase measurement between input force (or torque) and the longitudinal (or rotational) motion at the active-end platen. Fig. 4b is used for the case where resonance is established by phase measurement between the input force (or torque) and the longitudinal (or rotational) motion at the passive-end platen. The damping ratio, *D*, is calculated from:

$$D = 1/[A(MMF)] \quad (33)$$

where:

A = value from Fig. 4, and
MMF = magnification factor given earlier.

9.11.1 Damping ratios obtained from longitudinal vibration are not the same as damping ratios obtained from torsional vibration. Subscripts *L* and *T* should be used to relate the damping ratios to the type of vibration used in their determination.

³ Enlarged and detailed copies of Figs. 2a, 2b, 3a, 3b, 4a, and 4b may be obtained at a nominal charge from ASTM Headquarters, 1916 Race St., Philadelphia, Pa. 19103. Request Adjunct No. 12-440150-00.

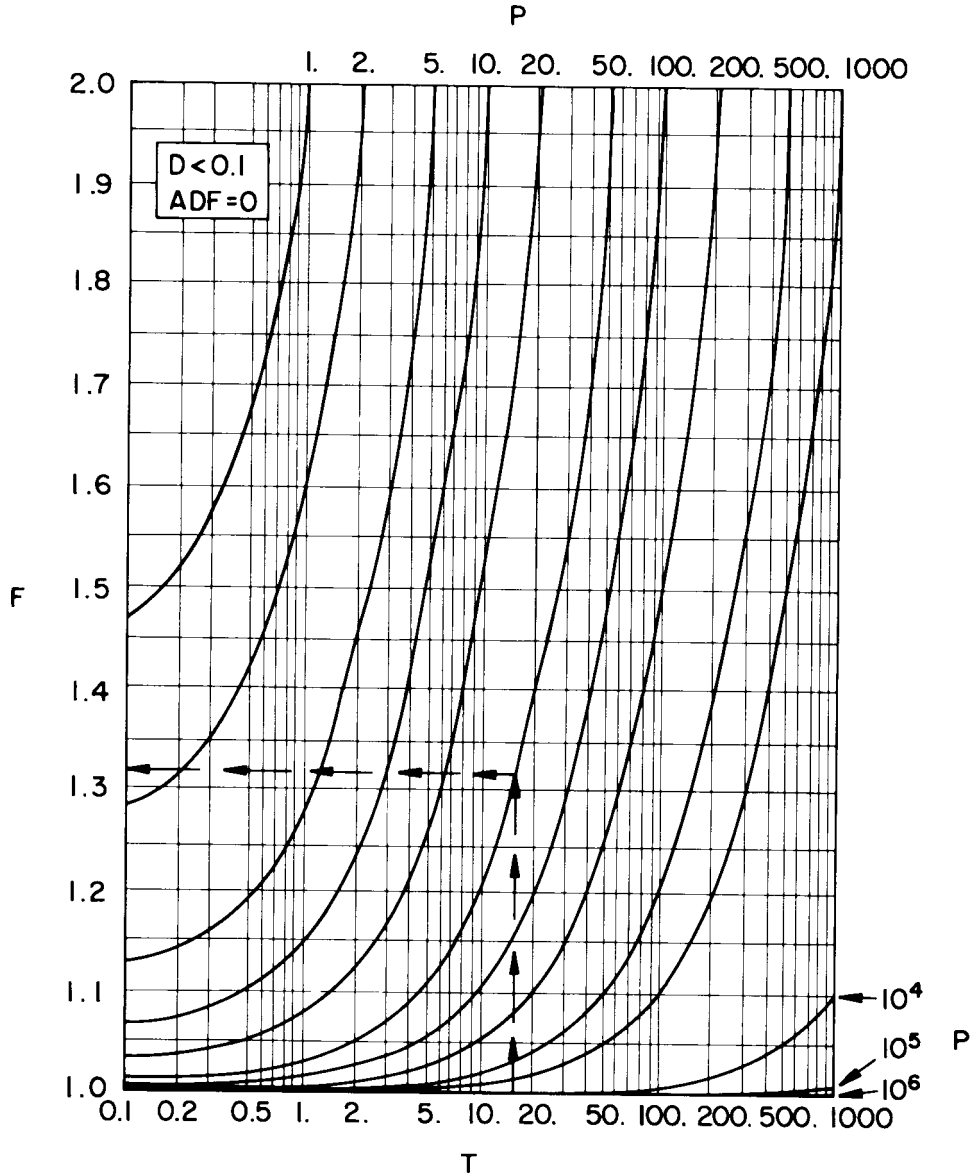


FIG. 3 (a) Strain Factors for Resonance Determined from Motion at Active End³

9.12 *Damping Ratio from Free Vibration*— This procedure is theoretically exact for apparatus where the passive end can be assumed to be rigidly fixed. For the cases where the passive end is not rigidly fixed, irrespective of which end of the specimen is used in establishing resonance, this method is approximate. The same transducer that is used to determine resonance must be used to obtain the amplitude decay curve. For the case where resonance is established by use of the passive transducer, values of T and P should both be greater than 10 when amplitude decay is used. For apparatus where the active-end platen is restrained by a spring, a system energy ratio must be calculated. For other apparatus, this factor is zero. For longitudinal motion, this ratio is calculated from:

$$S_L = (M_A/M)(f_{oL}F_L/f_L)^2 \quad (34)$$

and for torsional motion from:

$$S_T = (J_A/J)(f_{oT}F_T/f_T)^2 \quad (35)$$

where F_L, F_T = dimensionless frequency factors for longitudinal and torsional motion, respectively, from Fig. 2. Compute the system logarithmic decrement from the free-vibration decay curve (as obtained in the previous section) from:

$$\delta_s = (1/n) \ln (A_1/A_{n+1}) \quad (36)$$

where:

- A_1 = amplitude of vibration for first cycle after power is cut off,
- A_{n+1} = amplitude of vibration for $(n + 1)$ th cycle of free vibration, and
- n = number of free vibration cycles which must be 10 or less.

Finally, calculate the damping ratio from:

$$D = [\delta_s(1 + S) - S\delta]/(2\pi) \quad (37)$$

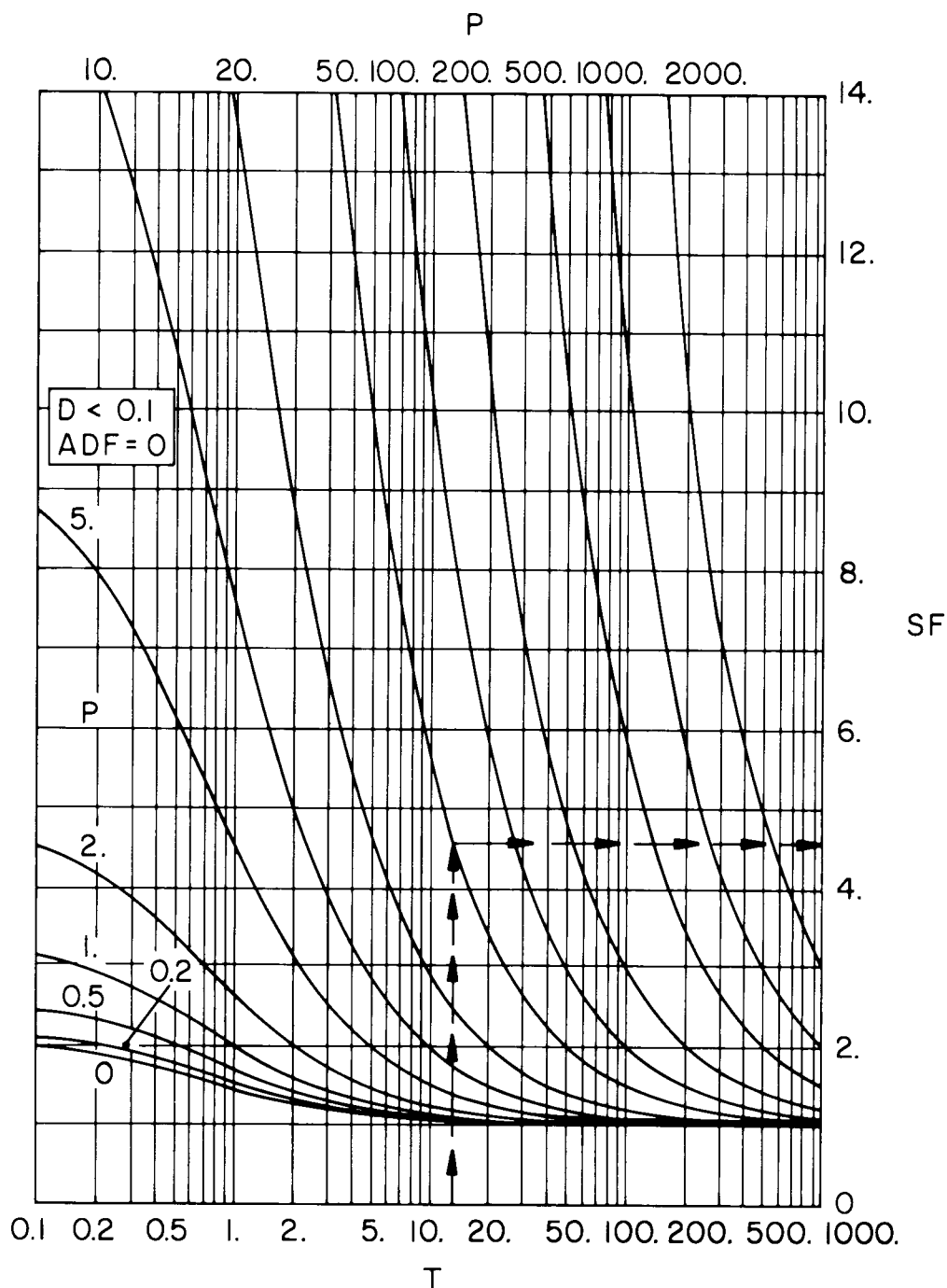


FIG. 3 (b) Strain Factors for Resonance Determined from Motion at Passive End³ (continued)

where:

- D = D_L or D_T depending on whether vibration is longitudinal or torsional,
- δ_s = δ_{sL} or δ_{sT} depending on whether vibration is longitudinal or torsional,
- S = S_L or S_T depending on whether vibration is longitudinal or torsional, and
- δ = δ_L or δ_T , apparatus logarithmic decrement given earlier.

10. Report

10.1 *General*—The report shall include characteristics of

the apparatus, specimen, ambient test conditions, and the results for each data set.

10.2 *Apparatus Characteristics*—The following apparatus characteristics shall be included: apparatus name, model number, and serial number; active-end and passive-end masses and rotational inertias (M_A , M_P , J_A , J_P); longitudinal and torsional apparatus resonant frequencies (f_{oL} , f_{oT}); longitudinal and torsional apparatus logarithmic decrements (δ_L , δ_T); the force/current and torque/current constants (FCF , TCF); and the applicable motion transducer calibration factors (LCF_A , LCF_P , RCF_A , RCF_P). (Note that if the passive end is fixed, inertias

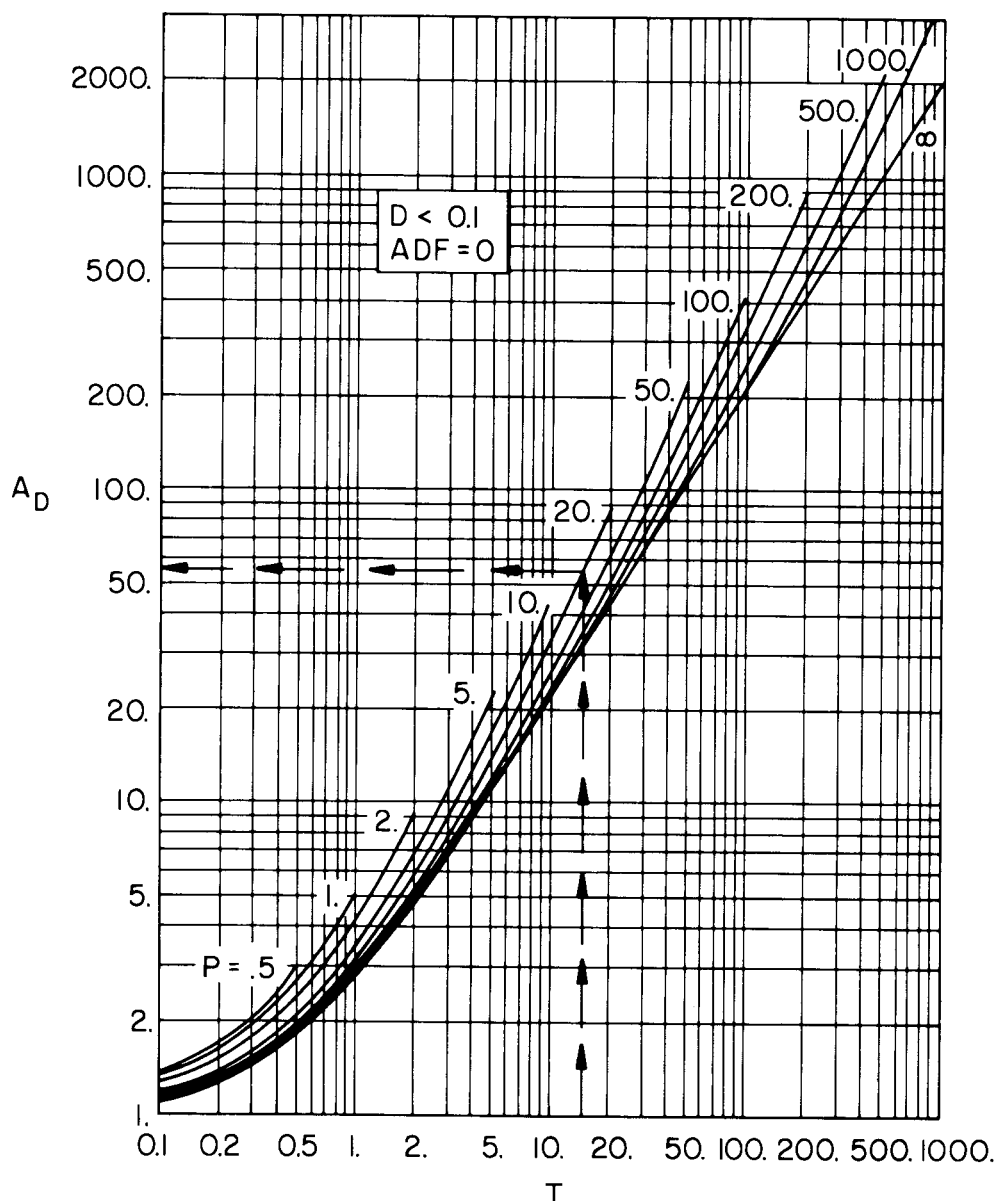


FIG. 4 (a) Damping Factors for Resonance Determined from Motion at Active End³

and transducers are not needed for the passive end. Likewise, if only one type of motion, longitudinal or torsional, is used, then only factors and inertias for that type need be given.)

10.3 Specimen Characteristics—A visual description and origin of the soil shall be given, including name, group symbol, and whether undisturbed or remolded. Initial and final specimen mass, dimensions, void ratio, water content, and degree of saturation shall also be given. Specimen preparation procedures and test setup procedures should be outlined.

10.4 Ambient Test Conditions—A complete description of the ambient stress conditions shall be given, including total stresses and pore water pressures, drainage conditions, and the procedures used to measure applied stresses, pore pressures, length change, and volume change.

10.5 Results for Each Data Set—For each data set, the following items shall be reported: approximate time of vibration at this strain amplitude, cell pressure, back or pore

pressure, axial stress, specimen length and volume, type of vibration, system resonant frequency, strain amplitude, modulus, and damping ratio.

11. Precision and Bias

11.1 Precision—Round-robin testing of soil using this test method has been attempted. The modulus and damping of soil depend upon strain amplitude of vibration, the ambient state of effective stress, and the void ratio of soil, as well as other factors. Further, these test methods allow for two different techniques for measurement of damping. Also, it provides the option for manual or computer data reduction. The manual process is less precise than the computer process because it does not consider apparatus damping and it requires interpolating from curves. Because of the above considerations, Subcommittee D18.09 deemed the results to be inappropriate for publication in this test method. Subcommittee D18.09 is

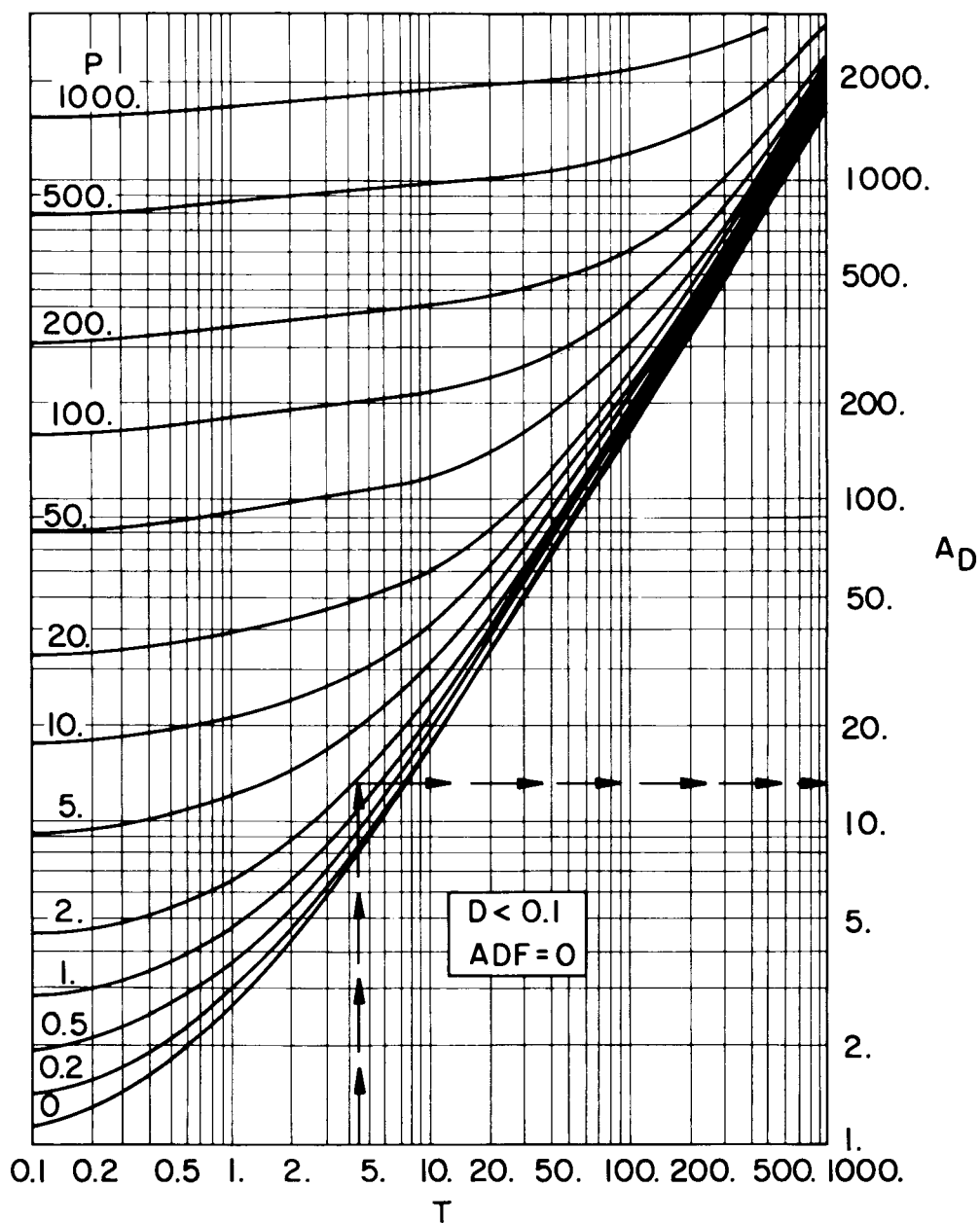


FIG. 4 (b) Damping Factors for Resonance Determined from Motion at Passive End³ (continued)

seeking assistance from users of the test method to resolve the problems.

11.2 *Bias*—The variability of soil and resultant inability to determine a true reference value prevent development of meaningful statement of bias.

12. Keywords

12.1 amplitude; confining pressure; damping; dynamic loading; elastic waves; elasticity modulus; frequency; labora-

tory tests; nondestructive tests; resonance; shear tests; soils; strain; stress; torsional oscillations; triaxial stress; vertical oscillations; vibrations; Young's modulus

APPENDIX

(Nonmandatory Information)

X1. COMPUTER PROGRAM FOR RESONANT COLUMN DATA REDUCTION (JUNE 1978)

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C.  COMPUTER PROGRAM FOR RESONANT COLUMN DATA REDUCTION                                RCP 0001
C                                                                                      RCP 0002
C                                                                                      RCP 0003
C-----DEFINITIONS OF INPUT-OUTPUT VARIABLES-----                                RCP 0004
C                                                                                      RCP 0005
C  ADF      APPARATUS DAMPING FACTOR (ADF > 0.)                                RCP 0006
C  D        SPECIMEN DAMPING RATIO (0.01% < D < 35%)                            RCP 0007
C  EPSD     ERROR CRITERION FOR D (DEFAULT VALUE: 0.0001)                        RCP 0008
C  EPSF     ERROR CRITERION FOR F (DEFAULT VALUE: 0.01)                         RCP 0009
C  F        FREQUENCY FACTOR                                                    RCP 0010
C  ITERD    MAXIMUM NUMBER OF ITERATIONS ALLOWED FOR D (DEFAULT                  RCP 0011
C            VALUE: 40)                                                           RCP 0012
C  ITERF    MAXIMUM NUMBER OF ITERATIONS ALLOWED FOR F (DEFAULT                  RCP 0013
C            VALUE: 40)                                                           RCP 0014
C  JPA      INDICATOR OF END WHERE MEASUREMENTS WERE TAKEN:                     RCP 0015
C            JPA = 0 FOR MEASUREMENTS AT THE ACTIVE END;                         RCP 0016
C            JPA = 1 FOR MEASUREMENTS AT THE PASSIVE END.                       RCP 0017
C  MMF      MODIFIED MAGNIFICATION FACTOR (MMF > 0.)                            RCP 0018
C  P        PASSIVE-END INERTIA RATIO (P > 0.; IF JPA = 0, THEN                   RCP 0019
C            P > 100. AND P > T)                                                 RCP 0020
C  SF       STRAIN FACTOR                                                         RCP 0021
C  T        ACTIVE-END INERTIA FACTOR (T > -10.)                                RCP 0022
C                                                                                      RCP 0023
C-----DEFINITIONS OF INPUT-OUTPUT VARIABLES-----                                RCP 0024
C                                                                                      RCP 0025
C  GIVEN VALUES OF T, P, ADF, MMF, AND JPA, THIS PROGRAM CALCULATES              RCP 0026
C  VALUES OF F, D, AND SF AND WILL PRINT VALUES OF ALL THESE                  RCP 0027
C  PARAMETERS.                                                                    RCP 0028
C                                                                                      RCP 0029
C-----DATA INPUT INSTRUCTIONS-----                                              RCP 0030
C                                                                                      RCP 0031
C  VALUES OF EPSF, ITERF, EPSD, AND ITERD MAY BE SPECIFIED ON THE              RCP 0032
C  FIRST DATA CARD ACCORDING TO THE FORMAT 2(F10.0,7X,I3). THESE               RCP 0033
C  PARAMETERS ARE REQUIRED IN THE ITERATIVE SOLUTION PROCEDURE TO CONTROL        RCP 0034
C  ACCURACY AND LIMIT THE NUMBER OF ITERATIONS. THIS DATA CARD                RCP 0035
C  MAY BE LEFT BLANK IF THE USER CHOOSES TO USE THE DEFAULT VALUES            RCP 0036
C  SPECIFIED BY THE PROGRAM. (SEE THE LIST OF DEFINITIONS OF INPUT-            RCP 0037
C  OUTPUT VARIABLES.) THE DEFAULT VALUES WILL GIVE GOOD RESULTS IN MOST        RCP 0038
C  CASES INVOLVING SMALL APPARATUS DAMPING. FOR LARGE APPARATUS DAMPING,      RCP 0039
C  OR TO CHECK RESULTS OBTAINED WITH THE DEFAULT VALUES, SMALLER VALUES     RCP 0040
C  OF ITERF AND ITERD SHOULD BE USED. (HOWEVER, IN SOME CASES OF LARGE        RCP 0041
C  APPARATUS DAMPING, ACCURATE CALCULATION OF D IS IMPOSSIBLE.)                RCP 0042
C                                                                                      RCP 0043
C  EACH SUBSEQUENT DATA CARD SHOULD CONTAIN A VALUE OF EACH OF THE            RCP 0044
C  PARAMETERS P, T, ADF, MMF, AND JPA ACCORDING TO THE FORMAT 4F10.0,          RCP 0045
C  9X,I1. 9X,I1. 9X,I1. 9X,I1. 9X,I1. 9X,I1. 9X,I1. 9X,I1. 9X,I1. 9X,I1.    RCP 0046
C  MENTAL TEST DATA. SEE THE LIST OF DEFINITIONS OF INPUT-OUTPUT              RCP 0047
C  VARIABLES FOR THE RANGES OF THESE VARIABLES ALLOWED BY THE PROGRAM.         RCP 0048
C  THE DATA CARDS SHOULD BE TERMINATED WITH A BLANK CARD.                     RCP 0049
C                                                                                      RCP 0050
C-----DEFINITIONS OF INPUT-OUTPUT VARIABLES-----                                RCP 0051
C                                                                                      RCP 0052
C  DIMENSION C(4),UP(11)                                                         RCP 0053
C  REAL MMF,MMFCAL                                                                RCP 0054
C  INTEGER OD                                                                      RCP 0055
C  COMMON /VALS/P,T,ADF,MMF,JPA,AMP,D,F /DLIM/DL,DR                             RCP 0056
C  COMMON /ALARM/KALARM /EPSIT/EPSP,ITERF,EPSD,ITERD                           RCP 0057
C  COMMON /PAR/PL,QL,C                                                            RCP 0058
C  COMMON /CRIT/MMFCAL,PHASE                                                       RCP 0059
C  EXTERNAL DELAMP                                                                RCP 0060
C  1000 FORMAT(4F10.0,9X,I1)                                                       RCP 0061
C  1005 FORMAT(2(F10.0,7X,I3))                                                       RCP 0062
C  1110 FORMAT(49H * * * * * W A R N I N G * * * * * POSSIBLY,                 RCP 0063
C        1 23H NOT ENOUGH ITERATIONS )                                             RCP 0064
C  1115 FORMAT(50H TO OBTAIN SPECIFIED ACCURACY FOR D WITH THE ABOVE,            RCP 0065
C        1 18H PARAMETER VALUES.)                                                 RCP 0066
C  1117 FORMAT(30H TRY A LARGER VALUE OF ITERD.)                                  RCP 0067
C  1120 FORMAT(46H * * * * * E R R O R * * * * * THE VALUE,                     RCP 0068
C        1 19H OF D FOR THE ABOVE)                                                 RCP 0069
C  1125 FORMAT(46H PARAMETERS LIES OUTSIDE THE ALLOWABLE RANGE, ,                 RCP 0070
C        1 14H0.001 TO 0.35.)                                                       RCP 0071
C  1140 FORMAT(31H THE ERROR CRITERION FOR F IS,E12.2/)                           RCP 0072
C                                                                                      RCP 0073

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1150 FORMAT(52H THE MAXIMUM NUMBER OF ITERATIONS ALLOWED FOR F IS, RCP 0074
1 I4/) RCP 0075
1160 FORMAT(31H THE ERROR CRITERION FOR D IS,E12.2/) RCP 0076
1170 FORMAT(52H THE MAXIMUM NUMBER OF ITERATIONS ALLOWED FOR D IS, RCP 0077
1 I4//) RCP 0078
1210 FORMAT(5X,1HT,9X,1HP,8X,3HADP,6X,3HMMF,4X,3HJPA,3X,1HF,8X,2HDZ, RCP 0079
1 8X,2HSF,6X,9HMMF(CALC),3X,5HPHASE/) RCP 0080
1220 FORMAT(3(1X,F9.4),1X,F9.5,1X,I1,2(1X,F9.6),1X,1PE9.3, RCP 0081
1 2(1X,OPF9.5)) RCP 0082
1230 FORMAT(53H * * * * * E R R O R * * * * * P MUST BE .GE.0.) RCP 0083
1240 FORMAT(50H * * * * * E R R O R * * * * * IF(JPA.EQ.0) , RCP 0084
1 19H P MUST BE .GE.100.) RCP 0085
1250 FORMAT(50H * * * * * E R R O R * * * * * IF(JPA.EQ.0) , RCP 0086
1 17H P MUST BE .GE. T) RCP 0087
1260 FORMAT(55H * * * * * E R R O R * * * * * T MUST BE .GE.-10.) RCP 0088
1270 FORMAT(55H * * * * * E R R O R * * * * * ADF MUST BE .GE.0.) RCP 0089
1280 FORMAT(54H * * * * * E R R O R * * * * * MF MUST BE .GT.0.) RCP 0090
1310 FORMAT(49H * * * * * W A R N I N G * * * * * POSSIBLY, RCP 0091
1 23H NOT ENOUGH ITERATIONS ) RCP 0092
1315 FORMAT(50H TO OBTAIN SPECIFIED ACCURACY FOR F WITH THE ABOVE, RCP 0093
1 12H PARAMETERS.) RCP 0094
1317 FORMAT(30H TRY A LARGER VALUE OF ITERF.) RCP 0095
1320 FORMAT(48H * * * * * E R R O R * * * * * THERE IS NO, RCP 0096
1 10H RESONANCE) RCP 0097
1330 FORMAT(51H (DISPLACEMENT ONE-QUARTER CYCLE OUT OF PHASE WITH, RCP 0098
1 19H FORCING FUNCTION) ) RCP 0099
1340 FORMAT(25H FOR THE ABOVE PARAMETERS) RCP 0100
1350 FORMAT(51H * * * * * W A R N I N G * * * * * BECAUSE OF, RCP 0101
1 16H LARGE APPARATUS) RCP 0102
1360 FORMAT(49H DAMPING, THE CALCULATED AMPLITUDE IS RELATIVELY, RCP 0103
1 15H INSENSITIVE TO) RCP 0104
1365 FORMAT(49H SPECIMEN DAMPING. CONSEQUENTLY, THE CALCULATED, RCP 0105
1 17H SPECIMEN DAMPING) RCP 0106
1367 FORMAT(37H RATIO ABOVE MAY BE VERY INACCURATE.) RCP 0107
C SET INPUT AND OUTPUT DEVICE CODES RCP 0108
ID = 5 RCP 0109
OD = 6 RCP 0110
READ(ID,1005) EPSF,ITERF,EPSP,ITERD RCP 0111
IF(EPSP.EQ.0.) EPSP = 1.E-4 RCP 0112
IF(ITERD.EQ.0.) ITERD = 40 RCP 0113
IF(EPSF.EQ.0.) EPSF = 1.E-2 RCP 0114
IF(ITERF.EQ.0.) ITERF = 40 RCP 0115
WRITE(OD,1140) EPSF RCP 0116
WRITE(OD,1150) ITERF RCP 0117
WRITE(OD,1160) EPSP RCP 0118
WRITE(OD,1170) ITERD RCP 0119
WRITE(OD,1210) RCP 0120
10 READ(ID,1000) T,P,ADF,MMF,JPA RCP 0121
IF(MMF.EQ.0.) GO TO 190 RCP 0122
MAL = 0 RCP 0123
IF(P.GE.0.) GO TO 20 RCP 0124
MAL = MAL + 1 RCP 0125
IF(MAL.EQ.1) WRITE(OD,1220) P,T,ADF,MMF,JPA RCP 0126
WRITE(OD,1230) RCP 0127
20 IF(JPA.EQ.1.OR.P.GE.100.) GO TO 30 RCP 0128
MAL = MAL + 1 RCP 0129
IF(MAL.EQ.1) WRITE(OD,1220) P,T,ADF,MMF,JPA RCP 0130
WRITE(OD,1240) RCP 0131
30 IF(JPA.EQ.1.OR.T.LE.P) GO TO 40 RCP 0132
MAL = MAL + 1 RCP 0133
IF(MAL.EQ.1) WRITE(OD,1220) P,T,ADF,MMF,JPA RCP 0134
WRITE(OD,1250) RCP 0135
40 IF(T.GE.-10.) GO TO 50 RCP 0136
MAL = MAL + 1 RCP 0137
IF(MAL.EQ.1) WRITE(OD,1220) P,T,ADF,MMF,JPA RCP 0138
WRITE(OD,1260) RCP 0139
50 IF(ADF.GE.0.) GO TO 60 RCP 0140
MAL = MAL + 1 RCP 0141
IF(MAL.EQ.1) WRITE(OD,1220) P,T,ADF,MMF,JPA RCP 0142
WRITE(OD,1270) RCP 0143
60 IF(MMF.GT.0.) GO TO 70 RCP 0144
MAL = MAL + 1 RCP 0145
IF(MAL.EQ.1) WRITE(OD,1220) P,T,ADF,MMF,JPA RCP 0146
WRITE(OD,1280) RCP 0147
70 IF(MAL.NE.0) GO TO 10 RCP 0148

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KALARM = 0
DL = 0.0001
DR = .35
CALL RTM12(D,AMPDEL,DELAMP,DL,DR,EPSD,ITERD,IER)
IF(KALARM.NE.1) GO TO 80
MAL = MAL + 1
IF(MAL.EQ.1) WRITE(OD,1220) P,T,ADF,MMF,JPA
WRITE(OD,1320)
WRITE(OD,1330)
WRITE(OD,1340)
GO TO 10
80 IF(IER.NE.2) GO TO 90
MAL = MAL + 1
IF(MAL.EQ.1) WRITE(OD,1220) P,T,ADF,MMF,JPA
WRITE(OD,1120)
WRITE(OD,1125)
GO TO 10
90 CONTINUE
DO 180 I=1,11
XR = (I-1)/10.
QLX = QL*XR
PLX = PL*XR
CC = COSH(QLX)*COS(PLX)
SC = SINH(QLX)*COS(PLX)
SS = SINH(QLX)*SIN(PLX)
CS = COSH(QLX)*SIN(PLX)
UP(I) = C(1)*(-PL*CS+QL*SC) + C(2)*(-PL*SS+QL*CC) +
1 C(3)*(PL*SC+QL*CS) + C(4)*(PL*CC+QL*SS)
180 CONTINUE
GAM = (UP(1)+UP(11)+4.*(UP(2)+UP(4)+UP(6)+UP(8)+UP(10))
1 +2.*(UP(3)+UP(5)+UP(7)+UP(9)))/30.
SF = ABS(GAM*F**2/MMF)
D = D*100.
WRITE(OD,1220) T,P,ADF,MMF,JPA,F,D,SF,MMFCAL,PHASE
IF(IER.NE.1) GO TO 110
WRITE(OD,1110)
WRITE(OD,1115)
WRITE(OD,1117)
110 IF(KALARM.NE.2) GO TO 120
WRITE(OD,1350)
WRITE(OD,1360)
WRITE(OD,1365)
WRITE(OD,1367)
120 IF(KALARM.NE.4) GO TO 140
WRITE(OD,1310)
WRITE(OD,1315)
WRITE(OD,1317)
140 CONTINUE
GO TO 10
190 STOP
END
C*****
FUNCTION DELAMP(D)
C*****
COMMON /VALS/P,T,ADF,MMF,JPA,AMP,DD,F /DLIM/DL,DR
COMMON /ALARM/KALARM /EPSIT/EPSF,ITERF,EPSD,ITERD
EXTERNAL VFCN
INTEGER OD
REAL MMF
OD = 6
DD = D
IF(T.LT.0.) GO TO 30
AA = -48*T*P - 7*(T+P) - 1
BB = 48*T*P + 20*(T+P) + 5
CC = -4*(T+P) - 4
BD2A = BB/(2*AA)
F = SQRT(12*(-BD2A-SQRT(BD2A**2-CC/AA)))
FL = .8*F
FR = 1.2*F
GO TO 60
30 IF(T.LT.-.1) GO TO 40
FL = 1.4
FR = 1.5*FL
GO TO 60
40 FL = 1.75
RCP 0149
RCP 0150
RCP 0151
RCP 0152
RCP 0153
RCP 0154
RCP 0155
RCP 0156
RCP 0157
RCP 0158
RCP 0159
RCP 0160
RCP 0161
RCP 0162
RCP 0163
RCP 0164
RCP 0165
RCP 0166
RCP 0167
RCP 0168
RCP 0169
RCP 0170
RCP 0171
RCP 0172
RCP 0173
RCP 0174
RCP 0175
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RCP 0196
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RCP 0198
RCP 0199
RCP 0200
RCP 0201
RCP 0202
RCP 0203
RCP 0204
RCP 0205
RCP 0206
RCP 0207
RCP 0208
RCP 0209
RCP 0210
RCP 0211
RCP 0212
RCP 0213
RCP 0214
RCP 0215
RCP 0216
RCP 0217
RCP 0218
RCP 0219
RCP 0220
RCP 0221
RCP 0222
RCP 0223

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FR = 1.5*FL
60 CONTINUE
CALL RTMI(F,V,VFCN,FL,FR,EPSF,ITERF,IER)
IF(IER.NE.2) GO TO 70
FL = .99*FR
FR = 1.5*FR
IF(FL.LE.8.) GO TO 60
KALARM = 1
GO TO 120
70 IF(IER.EQ.1) KALARM = 4
90 CONTINUE
V = VFCN(F)
A = AMP
AM = MMF/F**2
DELAMP = A - AM
IF(D.EQ.DL) DELL = DELAMP
IF(D.EQ.DL) AML = A
IF(D.NE.DR) GO TO 120
DELR = DELAMP
AMR = A
DIF = AML - AMR
RELDIF = DIF/AML
IF(RELDIF.LE.0.20) KALARM = 2
120 CONTINUE
RETURN
END
C*****
FUNCTION VFCN(F)
C*****
DIMENSION A(4,4),C(4)
REAL MMFCAL
COMMON /VALS/P,T,ADF,MMF,JPA,AMP,D,FF
COMMON /PAR/PL,QL,C
COMMON /CRIT/MMFCAL,PHASE
BETA = SQRT(1.+(2.*D)**2)
PL = F*SQRT((BETA+1.)/2.)/BETA
QL = F*SQRT((BETA-1.)/2.)/BETA
SNHQ = SINH(QL)
CSHQ = COSH(QL)
SNP = SIN(PL)
CSP = COS(PL)
CS = CSHQ*SNP
SC = SNHQ*CSP
SS = SNHQ*SNP
CC = CSHQ*CSP
CSSC = -PL*CS + QL*SC
SSCC = -PL*SS + QL*CC
SCCS = PL*SC + QL*CS
CCSS = PL*CC + QL*SS
PF2 = P*F**2
A(1,1) = T*F**2
A(1,2) = QL - 2*D*PL
A(1,3) = -ADF*F**2
A(1,4) = PL + 2*D*QL
A(2,1) = -A(1,3)
A(2,2) = -A(1,4)
A(2,3) = A(1,1)
A(2,4) = A(1,2)
A(3,1) = CSSC - 2.*D*SCCS - PF2*CC
A(3,2) = SSCC - 2.*D*CCSS - PF2*SC
A(3,3) = SCCS + 2.*D*CSSC - PF2*SS
A(3,4) = CCSS + 2.*D*SSCC - PF2*CS
A(4,1) = -A(3,3)
A(4,2) = -A(3,4)
A(4,3) = A(3,1)
A(4,4) = A(3,2)
C(1) = 0
C(2) = -1.
C(3) = 0
C(4) = 0
EPS = 1.E-5
NN = 4
CALL GELG(C,A,NN,1,EPS,IER,NN*NN,NN)
U0 = C(1)
V0 = C(3)
RCP 0224
RCP 0225
RCP 0226
RCP 0227
RCP 0228
RCP 0229
RCP 0230
RCP 0231
RCP 0232
RCP 0233
RCP 0234
RCP 0235
RCP 0236
RCP 0237
RCP 0238
RCP 0239
RCP 0240
RCP 0241
RCP 0242
RCP 0243
RCP 0244
RCP 0245
RCP 0246
RCP 0247
RCP 0248
RCP 0249
RCP 0250
RCP 0251
RCP 0252
RCP 0253
RCP 0254
RCP 0255
RCP 0256
RCP 0257
RCP 0258
RCP 0259
RCP 0260
RCP 0261
RCP 0262
RCP 0263
RCP 0264
RCP 0265
RCP 0266
RCP 0267
RCP 0268
RCP 0269
RCP 0270
RCP 0271
RCP 0272
RCP 0273
RCP 0274
RCP 0275
RCP 0276
RCP 0277
RCP 0278
RCP 0279
RCP 0280
RCP 0281
RCP 0282
RCP 0283
RCP 0284
RCP 0285
RCP 0286
RCP 0287
RCP 0288
RCP 0289
RCP 0290
RCP 0291
RCP 0292
RCP 0293
RCP 0294
RCP 0295
RCP 0296
RCP 0297
RCP 0298

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AMPL0 = SQRT(U0**2 + V0**2)
PHASE0 = ATAN2(V0,U0)
IF(PHASE0.LT.0.) PHASE0 = PHASE0 + 6.283185
UL = C(1)*CC + C(2)*SC + C(3)*SS + C(4)*CS
VL = C(3)*CC + C(4)*SC - C(1)*SS - C(2)*CS
AMPLL = SQRT(UL**2 + VL**2)
PHASEL = ATAN2(VL,UL)
IF(JPA.EQ.0) VFCN = PHASE0 - 3.141593
IF(JPA.NE.0) VFCN = PHASEL
IF(JPA.EQ.0) AMP = AMPL0
IF(JPA.NE.0) AMP = AMPLL
MMFCAL = AMP*F**2
PHASE = VFCN
RETURN
END
C*****
SUBROUTINE RTM12(X,F,FCT,XLI,XRI,EPS,IEND,IER)
C*****
COMMON /ALARM/KALARM
IER=0
XL=XLI
XR=XRI
X=XL
TOL=X
F=FCT(TOL)
IF(KALARM.EQ.1) RETURN
IF(F)1,16,1
1 FL=F
X=XR
TOL=X
F=FCT(TOL)
IF(KALARM.EQ.1) RETURN
IF(F)2,16,2
2 FR=F
IF(SIGN(1.,FL)+SIGN(1.,FR))25,3,25
3 I=0
TOLF=100.*EPS
I=I+1
DO 13 K=1,IEND
X=.5*(XL+XR)
TOL=X
F=FCT(TOL)
IF(KALARM.EQ.1) RETURN
IF(F)5,16,5
5 IF(SIGN(1.,F)+SIGN(1.,FR))7,6,7
6 TOL=XL
XL=XR
XR=TOL
TOL=FL
FL=FR
FR=TOL
7 TOL=F-FL
A=F*TOL
A=A+A
IF(A-FR*(FR-FL))8,9,9
8 IF(I-IEND)17,17,9
9 XR=X
FR=F
TOL=EPS
A=ABS(XR)
IF(A-1.)11,11,10
10 TOL=TOL*A
11 IF(ABS(XR-XL)-TOL)12,12,13
12 IF(ABS(FR-FL)-TOLF)14,14,13
13 CONTINUE
IER=1
14 IF(ABS(FR)-ABS(FL))16,16,15
15 X=XL
F=FL
16 RETURN
17 A=FR-F
DX=(X-XL)*FL*(1.+F*(A-TOL)/(A*(FR-FL)))/TOL
XM=X
FM=F
X=XL-DX
RCP 0299
RCP 0300
RCP 0301
RCP 0302
RCP 0303
RCP 0304
RCP 0305
RCP 0306
RCP 0307
RCP 0308
RCP 0309
RCP 0310
RCP 0311
RCP 0312
RCP 0313
RCP 0314
RCP 0315
RCP 0316
RCP 0317
RCP 0318
RCP 0319
RCP 0320
RCP 0321
RCP 0322
RCP 0323
RCP 0324
RCP 0325
RCP 0326
RCP 0327
RCP 0328
RCP 0329
RCP 0330
RCP 0331
RCP 0332
RCP 0333
RCP 0334
RCP 0335
RCP 0336
RCP 0337
RCP 0338
RCP 0339
RCP 0340
RCP 0341
RCP 0342
RCP 0343
RCP 0344
RCP 0345
RCP 0346
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RCP 0348
RCP 0349
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RCP 0351
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RCP 0356
RCP 0357
RCP 0358
RCP 0359
RCP 0360
RCP 0361
RCP 0362
RCP 0363
RCP 0364
RCP 0365
RCP 0366
RCP 0367
RCP 0368
RCP 0369
RCP 0370
RCP 0371
RCP 0372
RCP 0373

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TOL=X
F=FCT(TOL)
IF(KALARM.EQ.1) RETURN
IF(F)18,16,18
18 TOL=EPS
A=ABS(X)
IF(A-1.)20,20,19
19 TOL=TOL*A
20 IF(ABS(DX)-TOL)21,21,22
21 IF(ABS(F)-TOLF)16,16,22
22 IF(SIGN(1.,F)+SIGN(1.,FL))24,23,24
23 XR=X
FR=F
GO TO 4
24 XL=X
FL=F
XR=XM
FR=FM
GO TO 4
25 IER=2
RETURN
END
C*****
SUBROUTINE GELG (R,A,M,N,EPS,IER,MM,MN)
C*****
DIMENSION A(MM), R(MN)
IF(M)23,23,1
1 IER=0
PIV=0.
MM=M*M
NM=N*M
DO 3 L=1,MM
TB=ABS(A(L))
IF(TB-PIV)3,3,2
2 PIV=TB
I=L
3 CONTINUE
TOL=EPS*PIV
LST=1
DO 17 K=1,M
IF(PIV)23,23,4
4 IF(IER)7,5,7
5 IF(PIV-TOL)6,6,7
6 IER=K-1
7 PIVI=1./A(I)
J=(I-1)/M
I=I-J*M-K
J=J+1-K
DO 8 L=K,NM,M
LL=L+I
TB=PIVI*R(LL)
R(LL)=R(L)
8 R(L)=TB
IF(K-M)9,18,18
9 LEND=LST+M-K
IF(J)12,12,10
10 II=J*M
DO 11 L=LST,LEND
TB=A(L)
LL=L+II
A(L)=A(LL)
11 A(LL)=TB
12 DO 13 L=LST,MM,M
LL=L+I
TB=PIVI*A(LL)
A(LL)=A(L)
13 A(L)=TB
A(LST)=J
PIV=0.
LST=LST+1
J=0
DO 16 II=LST,LEND
PIVI=-A(II)
RCP 0374
RCP 0375
RCP 0376
RCP 0377
RCP 0378
RCP 0379
RCP 0380
RCP 0381
RCP 0382
RCP 0383
RCP 0384
RCP 0385
RCP 0386
RCP 0387
RCP 0388
RCP 0389
RCP 0390
RCP 0391
RCP 0392
RCP 0393
RCP 0394
RCP 0395
RCP 0396
RCP 0397
RCP 0398
RCP 0399
RCP 0400
RCP 0401
RCP 0402
RCP 0403
RCP 0404
RCP 0405
RCP 0406
RCP 0407
RCP 0408
RCP 0409
RCP 0410
RCP 0411
RCP 0412
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RCP 0419
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RCP 0438
RCP 0439
RCP 0440
RCP 0441
RCP 0442
RCP 0443
RCP 0444
RCP 0445
RCP 0446

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        IST=II+M
        J=J+1
        DO 15 L=IST,MM,M
        LL=L-J
        A(L)=A(L)+PIVI*A(LL)
        TB=ABS(A(L))
        IF (TB-PIV)15,15,14
14      PIV=TB
        I=L
15      CONTINUE
        DO 16 L=K,NM,M
        LL=L+J
16      R(LL)=R(LL)+PIVI*R(L)
17      LST=LST+M
18      IF (M-1)23,22,19
19      IST=MM+M
        LST=M+1
        DO 21 I=2,M
        II=LST-I
        IST=IST-LST
        L=IST-M
        L=A(L)+.5
        DO 21 J=II,NM,M
        TB=R(J)
        LL=J
        DO 20 K=IST,MM,M
        LL=LL+1
20      TB=TB-A(K)*R(LL)
        K=J+L
        R(J)=R(K)
21      R(K)=TB
22      RETURN
23      IER=-1
        RETURN
        END
C*****
        SUBROUTINE RTMI(X,F,FCT,XLI,XRI,EPS,IEND,IER)
C*****
        IER=0
        XL=XLI
        XR=XRI
        X=XL
        TOL=X
        F=FCT(TOL)
        IF (F)1,16,1
1      FL=F
        X=XR
        TOL=X
        F=FCT(TOL)
        IF (F)2,16,2
2      FR=F
        IF (SIGN(1.,FL)+SIGN(1.,FR))25,3,25
3      I=0
        TOLF=100.*EPS
4      I=I+1
        DO 13 K=1,IEND
        X=.5*(XL+XR)
        TOL=X
        F=FCT(TOL)
        IF (F)5,16,5
5      IF (SIGN(1.,F)+SIGN(1.,FR))7,6,7
6      TOL=XL
        XL=XR
        XR=TOL
        TOL=FL
        FL=FR
        FR=TOL
7      TOL=F-FL
        A=F*TOL
        A=A+A
        IF (A-FR*(FR-FL))8,9,9
8      IF (I-IEND)17,17,9
9      XR=X
        FR=F
        TOL=EPS
RCP 0447
RCP 0448
RCP 0449
RCP 0450
RCP 0451
RCP 0452
RCP 0453
RCP 0454
RCP 0455
RCP 0456
RCP 0457
RCP 0458
RCP 0459
RCP 0460
RCP 0461
RCP 0462
RCP 0463
RCP 0464
RCP 0465
RCP 0466
RCP 0467
RCP 0468
RCP 0469
RCP 0470
RCP 0471
RCP 0472
RCP 0473
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RCP 0514
RCP 0515
RCP 0516
RCP 0517
RCP 0518
RCP 0519
RCP 0520
RCP 0521

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A=ABS(XR)	RCP 0522
IF(A-1.)11,11,10	RCP 0523
10 TOL=TOL*A	RCP 0524
11 IF(ABS(XR-XL)-TOL)12,12,13	RCP 0525
12 IF(ABS(FR-FL)-TOLF)14,14,13	RCP 0526
13 CONTINUE	RCP 0527
IER=1	RCP 0528
14 IF(ABS(FR)-ABS(FL))16,16,15	RCP 0529
15 X=XL	RCP 0530
F=FL	RCP 0531
16 RETURN	RCP 0532
17 A=FR-F	RCP 0533
DX=(X-XL)*FL*(1.+F*(A-TOL)/(A*(FR-FL)))/TOL	RCP 0534
XM=X	RCP 0535
FM=F	RCP 0536
X=XL-DX	RCP 0537
TOL=X	RCP 0538
F=FACT(TOL)	RCP 0539
IF(F)18,16,18	RCP 0540
18 TOL=EPS	RCP 0541
A=ABS(X)	RCP 0542
IF(A-1.)20,20,19	RCP 0543
19 TOL=TOL*A	RCP 0544
20 IF(ABS(DX)-TOL)21,21,22	RCP 0545
21 IF(ABS(F)-TOLF)16,16,22	RCP 0546
22 IF(SIGN(1.,F)+SIGN(1.,FL))24,23,24	RCP 0547
23 XR=X	RCP 0548
FR=F	RCP 0549
GO TO 4	RCP 0550
24 XL=X	RCP 0551
FL=F	RCP 0552
XR=XM	RCP 0553
FR=FM	RCP 0554
GO TO 4	RCP 0555
25 IER=2	RCP 0556
RETURN	RCP 0557
END	RCP 0558

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