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U.S. DEPARTMENT OF COMMERCE / National Bureau of Standards

Correlation of Floor Vibration to Human Response

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CORRELATION OF FLOOR VIBRATION TO HUMAN RESPONSE

James R. Shaver

A new approach to the problem of perceptible floor vibrations is presented based on the assumption that human activity, which produces the vibration, and human response to vibration are random variables. Techniques for data reduction are discussed and a detailed description of one approach is given along with the associated computer programs. Data from floor vibrations is compared with current criteria for human response.

Key words: Analysis; experimental; floor systems; human response; random process; spectral analysis; vibration.

1. INTRODUCTION

Historically, the design of floor systems for serviceability has been based on limiting the deflection that can occur for a given design load to prevent structural damage. It was believed by most engineers that this design procedure indirectly accounted for the effect of human activity on floor systems which could produce quite perceptible and annoying vibrations for other human occupants. Research and state-of-the-art studies [1,2,3][1/] conducted during the past decade on the various aspects of vibrating floor systems have increased the awareness of the engineering community to the fact that the traditional serviceability design procedure does not necessarily lead to floor systems with satisfactory dynamic characteristics which prevents objectionable vibrations from the occupant viewpoint when the floor is subjected to human activity.

Recent efforts [4.5] to study the problem of perceptible floor vibrations have primarily employed experimental techniques. Results from these studies have been inconclusive as to what constitutes objectionable floor vibration from an occupant viewpoint. Questions have been raised about the proper forcing function to be used in the test to simulate human activity [2,5] and the lack of information on the human response to this type of vibration [4]. The experimental procedures used have been based on the assumption that both human activity which produces vibration and occupant response to vibration of a floor system are deterministic variables. However most scientific studies which deal with human activity and human response as variables treat them as a random variable rather than a deterministic one.

[1/] Numbers in brackets refer to literature references.

This report describes a new approach to the problem of perceptible floor vibrations based on the assumption that human activity and human response to vibration are random variables. Presented is a random variable methodology[2/] based on physical testing and subsequent analysis of the dynamic response of floor systems subjected to human activity.

2. BACKGROUND

In order to understand why both human activity and occupant response should be characterized as random variables, it is necessary to understand the difference between a deterministic variable and one that is random. A deterministic variable is one whose value can be calculated or determined from knowledge of its behavior at any previous instant in time, while a random variable is one whose instantaneous value cannot be predicted with complete certainty for any given instant in time. This means that the instantaneous value for a random variable can only be specified by a probability distribution function which gives the probable fraction of the total time that the instantaneous value lies within a specified range.

If one considers all the possible parametric variations that can affect the instantaneous value of the dynamic loading that occurs from human activities such as walking, running, jumping, it becomes clear that each activity is, in itself, a random process composed of many variables. For example, considering footfall or walking since it is the most prevalent activity that occurs on a floor system, variations in weight, gait, heel-to-ball of foot contact and foot wear of individuals will all affect the instantaneous value of the dynamic loading that occurs.

It appears, from an examination of the literature, that no definitive study has been made to determine the statistical data needed for characterization of footfall as a random variable. However, a 1961 English floor abrasion study [4] made some quantitative measurement of the forces applied to the floor by walking and does give some insight into the nature of footfall from a static viewpoint. A typical plot of the vertical force component for a footfall, obtained in this 1967 study, appears in Figure 1. Figure 1 shows two peaks and a trough. As pointed out by the authors, the first and second peaks will vary in time of occurrence from initial contact and there is often, although not always, a discontinuity in the curve as it rises to the first peak. The study also indicated that if the vertical force component was considered in relation to the weight of the person, it appeared

[2/] This methodology was developed as part of a larger research effort into the nature of structural deflection limitations sponsored by the Department of Housing and Urban Development.

that the trough in the curve is always less than body weight while the peaks may be either above or below depending on the manner in which the body trunk is accelerated. Additional information is needed on the duration of footfall, its frequency content and probability of peak values in order to describe it as a random dynamic forcing function.

The human response to vibration involves many variables: vibration input where intensity, frequency, direction and duration must be considered; psychological influences in the form of mental state, motivation and experience; and physical influences from sound and sight. Given this multiplicity of parameters, it is reasonable to classify human response as a random process.

It should be pointed out that the structural floor systems are not considered to be a random variable. Although there are several types of floor systems, their dynamic properties can be described deterministically from an engineering viewpoint. Rather it is the forcing function (human activity) and the human response to this activity which must be considered as random processes. This makes the overall problem of human response to floor vibration induced by human activity a random vibration problem. This can be stated in functional form as:

$$F(t) \rightarrow G(t) \rightarrow Y(t) \Longrightarrow D(t)$$

where F(t) is the random forcing function, G(t) is the deterministic floor system characteristics, Y(t) is the random response of the floor system and D(t) is the random human response to the floor vibration, Y(t).

3. APPROACH TO PROBLEM

The dynamic response of a floor system subjected to human activity represents a random physical phenomenon which cannot be described by an explicit mathematical relationship because any given observation will represent only one of the many possible results which might have occurred. A single time history representation or observation of the random phenomenon is called a sample function (a sample record when observed over a finite time interval). Then the collection of all possible sample functions which the random phenomenon might have produced is called a random process. From a given sample function it is possible to estimate statistical parameters necessary to describe the random process.

Four main types of statistical functions are used to describe the basic properties of random data: (a) mean square values, (b) probability density functions, (c) autocorrelation functions, and (d) power spectral

density functions. The mean square value furnishes a rudimentary description of the intensity of the data. The probability density function furnishes information concerning the properties of the data in the amplitude domain. The autocorrelation function and the power spectral density function furnish similar information in the time domain and frequency domain, respectively.

While it is possible to determine the required parameters directly from the time history under certain simplifying assumptions, the majority of the techniques used to date perform the analysis in the frequency domain. Analysis in this domain is usually termed spectral decomposition.

There are three reasons for selecting spectral decomposition over time history to represent one's data. First, spectral decomposition presents data in a form that is related to quantities familiar to engineers. Many physical systems (including the human body) have been modeled with a fair degree of success in this domain. Most models, for example, consist of a set of simple second order oscillators connected in a manner which simulates the various components of the particular physical systems. Such a model is shown in Figure 2. Each oscillator has its own oscillatory or resonant frequency which, in turn, is dependent upon the size, shape and material of the component it is simulating. Since each oscillator will be excited primarily by energy at its resonant frequency, the knowledge of the frequency content of the response provides the key to the determination of the system response to impulse or shock, such as that produced by footfall. Generally, the response of a floor system at resonant frequencies will predominate in the total response. The second reason for utilizing spectral decomposition is the independence of each frequency component from all others. This independence in the frequency domain greatly simplifies analysis. By comparison, the determination of a response in the time domain at some instant in time is dependent not only on the value of the excitation at that time but on all previous values of the excitation. Third, this type of analysis can be used to describe input data, F(f), response data, Y(f), or, if the input and response are measured simultaneously, it can be used to describe the frequency response function, G(f), of the system as shown in Eq. 3.1. Specifically, given any two of the above items, the third can be determined.

$$Y(f) = |G(f)|^2 F(f) \qquad (3.1)$$

The primary approach to obtaining a meaningful dynamic response of a floor system subjected to human activity is to first obtain a time history and then transform this time history into the frequency domain using Fourier

techniques. In addition, the mean square value and probability density function should be obtained. It does not appear at this time that the autocorrelation function or the power spectral density function will provide any useful information.

4. DATA REDUCTION AND ANALYSIS

Spectral decomposition or analysis using Fourier techniques consists of decomposing a time history in terms of trigonmetric functions. The magnitude and phase of each trigonometric term needed to reconstruct the time history are plotted as a function of frequency. This technique is simply the evaluation of the finite, Fourier transform of the time history as expressed by Equation 4.1 where the time history x(t) is multiplied by the Fourier kernel, a complex exponential containing both the frequency and time variables, and then integrating this product over the record length;

$$X(f) = \int_{-T/2}^{T/2} x(t)e^{-j2\pi ft}dt \tag{4.1}$$

Using Euler's transformation, the kernel may be expanded so that Eq. 4.1 may be rewritten as,

$$X(f) = \int_{-T/2}^{T/2} x(t) \cos 2\pi ftdt - j\int_{-T/2}^{T/2} X(t) \sin 2\pi ftdt \tag{4.2}$$

This equation shows how spectral analysis can be considered as a decomposition of the time history in terms of sine and cosine components.

In order to evaluate this integral by digital techniques, one must solve the discrete, finite Fourier transform which is given as

$$X(k\Delta f) = \Delta t \sum_{i=o}^{N-1} X_i \; e^{-j2\pi k\Delta fi\Delta t} \tag{4.3}$$

where X_i is the digital representation of the time history obtained by sampling the continuous record at Δt intervals and the natural frequency spacing for the complete transform is

$$\Delta f = \frac{1}{N\Delta t} \tag{4.4}$$

Then $k\Delta f$ is defined by

$$k\Delta f = \frac{k}{N\Delta t}, \; k = 0, 1, 2..., N/2 \tag{4.5}$$

Equation 4.3 may then be rewritten as

$$X_k = \Delta t \sum_{i=o}^{N-1} X_i \; e^{\frac{-j2\pi ik}{N}} \quad k = 0, 1, 2,..., N/2 \tag{4.6}$$

Employing Euler's formula again and rewriting, Eq. 4.6 becomes

$$X_k = A_k - jB_k \quad k = 0, 1, 2, \ldots, N/2 \tag{4.7}$$

where

$$A_k = \Delta t \sum_{i=o}^{N-1} X_i \cos \frac{2\pi ik}{N} \tag{4.7a}$$

$$B_k = \Delta t \sum_{i=o}^{N-1} X_i \sin \frac{2\pi ik}{N} \tag{4.7b}$$

A computer program can be written which will evaluate Eq. 4.7 directly. However, this program would require a rather large amount of running time particularly when large volumes of data are being analyzed. Although the most efficient techniques known to date for evaluating Eq. 4.6 are the Fast Fourier Transform (FFT) methods, they were not used because these methods are not straight forward in their application and do require some special knowledge and experience for proper utilization.

The evaluation procedure employed to evaluate Eq. 4.7, was first derived by Goertzel [5] and is believed to be the most efficient of the pre-FFT methods. The method requires the generation of an auxiliary variable Q as follows:

$$Q_o = 0$$

$$Q_1 = X_{N-1}$$

$$Q_i = (2 \cos \frac{2\pi k}{N}) Q_{i-1} - Q_{i-2} + X_N - i, \quad i = 2, 3, \ldots, N-1 \tag{4.8}$$

Then, A_k and B_k in Eqs. 4.7a and 4.7b become

$$A_k = \Delta t \left[(\cos \frac{2\pi k}{N}) Q_{N-1} - Q_{N-2} + X_o \right]$$

$$B_k = \Delta t (\sin \frac{2\pi i}{N}) Q_{N-1}, \quad k = 0, 1, \ldots, N-2 \tag{4.9}$$

This technique was utilized in the spectral analysis of the 40 second walking record obtained using the test procedure given in Appendix A and required less than 3 seconds for 12,000 data points on a UNIVAC 1108 with an EXEC 8 system. The computer program is given in Appendix B. It should be remembered that the evaluation of X_k by Eqs. 4.8 and 4.9 would require generally unacceptable amounts of computer running time when extremely large volumes of data are to be analyzed.

The most useful output from the Fourier spectrum is the modulus. This modulus is obtained by realizing that the Fourier spectrum can be represented by a complex expression.

$$X(f) = |X(f)| \, e^{-j\theta(f)} \tag{4.10}$$

where $|X(f)|$ is the modulus and $e^{-j\theta(f)}$ is the phase.

From Eq. 4.7, the expression for the finite Fourier transform, the modulus is,

$$|X_k| = (A_k^2 + B_k^2)^{1/2} \tag{4.11}$$

The modulus dimensionally represents a pseudovelocity and it can be shown [6] that this is identical to the relative velocity of the residual response for a linear undamped single degree-of-freedom system when the system response is a pure sinusoid. In general, the two will be in close agreement for any undamped system with the pseudovelocity lower at low frequencies and higher at high frequencies than the relative velocity because of its frequency dependence.

The phase presentation of the spectrum may prove to be useful in determining damping in the system. Again from Eq. 4.7, the phase angle is given by

$$\Theta = \tan^{-1} \frac{B_k}{A_k} \tag{4.12}$$

Figure 3 is a plot of the modulus of the spectral decomposition of the 40 second walking record. The values of this modulus are in mg-s which is a pseudovelocity in feet per second. This graph is also called an energy density curve in random data analysis. Due to filters in the acceleration signal conditioning equipment all input above 25 Hz has been removed thus accounting for the low energy content above this value.

The acceleration record was sampled every 160 ms which is equivalent, because of a difference in record and playback speed of the analog data tape, to a 10 ms sampling rate in real time. At the 10 ms real time sampling rate, 1191 samples were taken thus producing a natural frequency spacing of 0.084 Hz in the Fourier transform. The modulus of the spectral decomposition has been plotted at every 0.5 Hz.

An examination of Figure 3 indicates that significant amounts of energy occurs in the range of 15-25 Hz with a pronounced peak at 18 Hz which is the fundamental frequency for the floor tested. The existence of

energy in this range indicates that a vibrating floor system is capable of inducing a human response to vibration at frequencies other than the lowest natural frequency of the system. Thus, test procedures which determine the vibration level only at the fundamental frequency for the floor system may exclude significant energy levels at other frequencies.

The missing link at this time is a means of transforming the energy level at these frequencies to a corresponding root-mean-square (rms) acceleration at the same frequency thereby permitting a comparison with the current human response criteria. However, it is possible to determine the rms acceleration for the record and associate it with the lowest natural frequency for comparison purposes. This is done in section 6.

5. DAMPING

Damping in floor systems is a very complex quantity yet its measurement is important since it effects the level and duration of vibration. In addition, it has been suggested that in the case of a single pulse input the occupants will perceive motion at a lower threshold if the vibration of the floor does not decay rapidly. Although the scope of the study did not permit an investigation into more effective means of determining damping and relating its effect to human response a brief discussion will be given because of the significant role damping plays in any dynamic problem.

Structural damping that occurs in floor systems is composed of three primary components: (1) material damping which is the ability of the materials themselves to dissipate energy, (2) interlayer slip which is energy dissipation through friction between the subfloor and joist and (3) end conditions which may damp motion by inducing support vibration or dissipate energy through friction. Generally, the energy loss from material damping is small as compared to the amount dissipated by slip and support effects.

There are six generally accepted mathematical means of representing damping: (1) logarithmic decrement, (2) amplification factor, (3) quality factor, (4) equivalent dashpot constant, (5) complex modulus and, (6) bandwidth. For the simple case of a linear single degree of freedom system, a relationship can be established between all six definitions, but for other cases this is no longer necessarily true. When structural damping is of primary interest any one of the six representations could be used with some degree of success depending upon the end result desired. Logarithmic decrement or decay rate is the simplest to measure experimentally but

is difficult to use in design or analysis. The most useful form of presentation for the designer is specific damping energy, in inch-pounds per cycle, while for purposes of analysis the equivalent dashpot constant is most useful.

However, from the viewpoint of the present approach taken in this methodology and its emphasis on spectral techniques, the use of either the bandwidth method or quality factor in characterizing the damping of structural floor systems should lead to a better means of describing the damping quality of floors as it relates to human response to vibration. While it appears feasible at this time to obtain these damping characteristics from a spectral decomposition, this derivation is beyond the scope of this report.

6. HUMAN RESPONSE TO VIBRATION

Human body vibration is usually treated as an externally-applied condition, although it is often self-induced such as during walking or running. The spectrum of human reaction to vibration is extremely wide encompassing both "pleasant" effects which range from relaxation to stimulation and "unpleasant" effects which span from discomfort to injury. Much of the information and literature concerning the effects of vibration on man is of a provisional, specialized or contradictory nature. This is particularly true in the area of human response to floor vibrations where only in the past decade have attempts been made to quantify this response. Thus, there does not exist, at this time, a consensus standard for determining whether or not floor vibration induced by human activity is acceptable from the occupant viewpoint.

This section will present the current state of knowledge on human reaction to externally applied vertical transient vibration against which the results of the proposed floor vibration methodology already given might be compared.

The current state of knowledge on human reaction to externally-applied vertical transient vibration is based on a limited number of studies and represents a wide range of thresholds. However, as basic as it is, this knowledge is currently the only information on which to base a judgement of whether or not a floor is acceptable from a human response viewpoint.

The ISO Guide for the Evaluation of Human Exposure to Whole-Body Vibration ISO/DIS 2631 [7] provides allowable rms accelerations at different

frequencies for various levels of exposure time. It is primarily intended for periodic (sinusoidal) vibrations in the frequency range from 1 Hz to 80 Hz but does cover narrow-band or wide-band vibration within this frequency range. In the case of either wide- or narrow-band random vibration, the allowable accelerations are based on the limit given for the center frequency in each third octave band.

Splittgerber [8] has proposed a standard based on the ISO Guide which provides vibration and shock limits for occupants of buildings. This proposed standard differentiates between continuous or intermittent vibration and impulsive shock excitation during either a day or night environment. It also contains vibration limits for different types of occupancy such as hospital, residential, office, etc.

A standard acceleration level is specified for each direction of vibration and then permissable acceleration levels are obtained for the different types of vibration input, occupant classification, and time conditions by applying an appropriate weighting factor to the standard.

Figure 4 shows the ISO Guide's standard acceleration curve for vertical vibrations and Splittgerber's permissable acceleration level for intermittent vibration in residences during the daytime hours. This daytime level is based on minimum complaints from the occupants and was obtained by applying a weighting factor of two to the standard curve.

Plotted on Figure 4 for purposes of comparison is Lenzen's [9] modification of the original Reiher and Meister work [10] on steady state vibrations for transient vibration. Lenzen's modification considers transient vibration as a vibration which may last only a few seconds but is characterized by a buildup to a level which is maintained for several cycles. Realistically, Lenzen's definition fits the vibration produced by a single footfall or someone jumping with Splittgerber's definition fitting the vibration produced by walking or running. The dashed lines on Figure 4 denote the slightly perceptible range for Lenzen's modification which is again believed to represent a minimum complaint level.

Also plotted in Figure 4 is Splittgerber's rms acceleration limit for daytime impulsive shock in residences which he characterizes as a rapid buildup to a peak followed by decay. It is comparable to Lenzen's definition for transient vibration. This acceleration limit was obtained by weighting the standard curve by sixteen. As can be seen from Figure 4 there is good agreement between these two criteria for $f > 8$ Hz with a divergence of the two below this frequency. No definite conclusion can be drawn at this time on the reason for this divergence in the low frequency range.

Plotted as a triangle on Figure 4 is the peak rms acceleration of 0.95 mg as determined from the 40 second continuous walking test record. This value was obtained using analog techniques with the time constant of the rms meter and scan rate of the data adjusted so that the uncertainty is less than 2% and is the peak rms value associated with maximum acceleration. Since the major energy component in the frequency spectrum occurs at 18 Hz, in accordance with the ISO Guide, this rms value is plotted at a frequency of 16 Hz as this is the center frequency for the third octave band in which 18 Hz falls.

A reinterpretation of this rms acceleration with regard to frequency and type of excitation was also made in order to compare the results with Lenzen's criteria. Lenzen's criteria would consider it to be a single pulse at the predominate floor frequency which in this case is 18 Hz. The maximum rms acceleration is found from the expression:

$$A_{rms} = \frac{1}{\sqrt{2}} \quad A_{peak}$$

and is 1.2 mg. This value is plotted as a circle on the figure.

From the figure it can be seen that the treatment of the walking record as an intermittent vibration gives a resulting rms acceleration slightly below the standard curve and well below the minimum complaint level. Treating the data as being comparable to single footfall or an impulsive shock which is the case for the plot of the peak rms acceleration it is obvious that the results are not realistic.

An interview with the occupants of the dwelling where the test data were obtained indicated that the vibrations produced by walking were not considered annoying although at times they were perceptible. It is interesting to note that a deaf couple living in this housing project used floor vibrations (which are, in this case, quite low) as a means of sensing the presence of someone in the room.

7. SUMMARY

In this report a new approach to the treatment of perceptible floor vibrations is presented based on the concept that human activity and human response to this activity are random variables. The reasons for choosing the random process approach to this floor vibration problem are given along with an overview of the method in functional form. A description of the random process and the statistical functions used to treat random data is presented.

Spectral analysis is chosen over time, history, as the method for analyzing floor vibration data. A computationally efficient procedure for obtaining the Fourier spectrum is given along with the associated computer software.

The current state of knowledge on human reaction to externally applied vertical transient vibration is discussed. One record of human activity obtained in a field test is analyzed using the techniques presented in this report and the results compared with a proposed standard for vibration and shock limits for occupants of buildings.

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9. APPENDIX A Field Test Procedure

The physical test procedure to be used must be designed for field application. Because of this requirement, the instrumentation must be simple and require a minimum of set-up time with little inconvenience to the occupants where the test is being made. A transducer which has the required sensitivity and response time and measures acceleration is preferred since it directly measures the quantity generally considered by most to be related to human response. Velocity transducers may also satisfy the above requirements but the subsequent differentiation needed to produce acceleration is often difficult to achieve without loss of information. Displacement transducers are difficult to satisfactorily employ in the field for this type of test, due to physical restraints of installation and reference datum. In addition, these transducers generally do not have the proper time response. Transformation of the displacement data to acceleration would also result in a considerable amount of lost information.

A displacement transducer was used in addition to an accelerometer in the field test.

Description of Test Site

The site selected for application of this methodology was a single family attached house (townhouse) with a wood-joist floor system located in Gaithersburg, Maryland. The house was occupied at the time of the test and furnished as shown in Figure 5. The floor system was typical of that found in many houses and consists of 2 x 8 wood joists spaced 16 in on center overlaid with 1/2-in plywood. The joists have a clear span of 12 feet 10 inches with diagonal bridging at mid-span. A synthetic wood floor tile is attached to the plywood subfloor by an adhesive. The floor construction is shown in Figures 6 and 7.

Floor response measurements were obtained from both an accelerometer and linear variable differential transformer (LVDT). The range of the accelerometer is from 10 mg to 0.001 mg. Figure 6 shows the location of this instrumentation. The LVDT was positively attached to the joist at mid-point of the clear span and the accelerometer set on the floor directly above the LVDT. Output from the LVDT and accelerometer were recorded as analog signals. While the frequency response of the electronic equipment was adequate to reproduce the time histories, the signal conditioning equipment for the accelerometer has a cut-off frequency of 25 Hz. This is generally considered satisfactory for most wood-joist floor systems.

Test Procedure

A series of tests were made using two procedures: (1) human activity represented by a 170-lb man walking in a normal traffic pattern, and (2) dropping a 25-lb bag from several heights. The first procedure is typical of a minimum human activity on a floor system while the second one has been used in the past as a method to assess the adequacy of floor systems from a vibrational viewpoint.

During the activity test, the walker utilized a path which was considered typical of the traffic patterns in that room. This path was followed for approximately 40 seconds.

The bag was dropped from heights of 7, 6, 5 and 4 inches. Several tests were made for drop heights greater than 7 in and, in each instance, the accelerometer raised from the floor in a rebound action.

Test Results

The walking test is the most significant data obtained since it is representative of the human activity that most frequency occurs on floor systems. In addition, it is a minimum type of activity as compared to running, jumping, etc. The accelerometer is a representative measure of the human response as its output is that which is preceived by a human standing or sitting in an unpadded chair at the location of the transducer. A typical segment of this record is given in Figure 8.

10. APPENDIX B Computer Program

The computer program developed to perform the spectral decomposition of a digitized time history is presented. The main program acquires a channel of digitized data, called data counts, from tape and then converts this to data in engineering units. The program assumes that the data is going to be either a record of displacement measurements or acceleration and makes the conversion upon being given the appropriate conversion factor and displacement or acceleration identification. Following the conversion, the data is made available to a subroutine which, using the Fourier techniques described in section 4.0, performs the spectral decomposition. The program is written in Fortran V and is operational on a UNIVAC 1108 system equipped with Exec 8. Only minor modification needs to be made to the main program for operation on any computer with a Fortran V compiler assuming the input data tape is compatible with the one for which the program was written. However, the subroutine can be used, without any modification, on a system with a Fortran V compiler.

```
      DIMENSION IHEAD(12), ITIME(4), IMUXT(12), IGAIN(12), CNVFC(12),
     1          IBUF(12000), X(12000), TIME(12000), IDCD(12), IOP(12)
      DIMENSION  RELVEC(6000), EMGVEC(6000), FREQ(6000)
      EQUIVALENCE (IHEAD(1),ID),(IHEAD(2),IRUN),(IHEAD(3),NSCPRC),
     1        (IHEAD(4),NRCPFL),(IHEAD(5),NSMIN),(IHEAD(6),NSSEC),
     1        (IHEAD(7),NSMSEC),(IHEAD(8),ITIME(1)),(IHEAD(9),ITIME(2)),
     1        (IHEAD(10),ITIME(3)),(IHEAD(11),ITIME(4)),(IHEAD(12),NCHSN)
C*****READ PROGRAM AND CHANNEL CARDS*********************************
      READ(5,600) NDCH, TPSDFC
  600 FORMAT(I5,E12.4,I5)
      DO 5 I=1,NDCH
    5 READ(5,600) IDCD(I), CNVFC(I),IOP(I)
      NDCHRD = 0
C*****READ HEADING RECORD AND CHANNEL NOS. WITH GAIN*****************
      CALL NTRAN(7,2,12,IHEAD,L,22)
      IF ( L+1 .LT. 0 ) GO TO 90
      CALL NTRAN(7,2,NCHSN,IMUXT,L,22)
      IF ( L+1 .LT. 0 ) GO TO 90
      CALL NTRAN(7,2,NCHSN,IGAIN,L,22)
      IF ( L+1 .LT. 0 ) GO TO 90
C*****WRITE HEADING AND CHANNEL NOS. WITH GAIN***********************
      WRITE(6,601) ID, IRUN, NSCPRC, NRCPFL, NSMIN, NSSEC, NSMSEC,
     1  (ITIME(I), I=1,4 ), NCHSN
  601 FORMAT( )H1,, 14X, 'SITE ID ', I5 / 15X, 'RUN NO.', I5 / 15X,
     1     'SCANS / RECORD =', I5/ 15X, 'RECORDS / FILE =', I5 /
     1    )5X, 'SCAN INTERVAL  MN=',I4,3X,'SC=',I4,3X,'MS=',I4 /
     1    15X, 'TIME =',I3,':',I2,':',I2,':',I2 / 15X,
     1     'NO. CHANNELS SCAN =', I4 // )
      WRITE(6,602) (IMUXT(J),IGAIN(J), J=1,NCHSN )
  602 FORMAT( 15X, 'CHANNEL', I3, 2X, 'GAIN', I3 )
C*****READ AND WRITE CHANNEL OF DATA COUNTS**************************
  500 CALL NTRAN(7,2,12000,IBUF,L,22)
      IF ( L+1 .LT. 0 ) GO TO 90
      NDCHRD = NDCHRD + 1
      NDTPCH = NSCPRC * NRCPFL
      WRITE(6,603) IMUXT(NDCHRD), ( IBUF(I), I=1,NDTPCH )
  603 FORMAT( 1H1, 4X, 'CHANNEL', I3, 15I7 / ( 15X, 15I7 ) )
C*****IF DATA IS DISPLACEMENT ( CODE = 1 ) REMOVE OFFSET*************
      IF ( IDCD(NDCHRD) .EQ. 0 ) GO TO 100
      DO 10 I=1,NDTPCH
   10 IBUF(I) = IBUF(I) - IBUF(1)
C*****CONVERSION FROM DATA COUNT TO ENGINEERING UNITS****************
  100 DO 20 I=1,NDTPCH
   20 X(I) = ( 10 * IBUF(I) ) / ( 2048 * IGAIN(NDCHRD) * CNVFC(NDCHRD) )
C*****FILL TIME ARRAY************************************************
      DELTAT = ( NSMIN * 60 + NSSEC + NSMSEC * 0.001 ) * TPSDFC
      TIME(1) = 0.
      DO 30 I=2,NDTPCH
   30 TIME(I) = TIME(I-1) + DELTAT
C*****WRITE CONVERTED DATA*******************************************
      IF ( IDCD(NDCHRD) .EQ. 0 ) GO TO 200
      WRITE(6,604) IMUXT(NDCHRD)
  604 FORMAT( 1H1, 4X, 'CHANNEL', I3, ' IS DISPLACEMENT IN INCHES' )
      GO TO 300
  200 WRITE(6,605) IMUXT(NDCHRD)
  605 FORMAT( 1H1, 4X, 'CHANNEL', I3, ' IS ACCELERATION IN MG' )
  300 WRITE(6,606) (TIME(I), X(I), I=1,NDTPCH)
  606 FORMAT( 10( F8.3, E12.4 ) )
C*****SPECTRAL ANALYSIS ( CODE = 1 )*********************************
      IF ( IOP(NDCHRD) .EQ. 0 ) GO TO 400
      CALL FOURTR(X,NDTPCH,DELTAT,EMGVEC,RELVEC,FREQ)
  400 IF ( NDCHRD - NDCH ) 500
      CALL NTRAN(7,10)
      GO TO 205
   90 WRITE(6,607)
  607 FORMAT('******* L =',I3,' *******')
  205 STOP
      END
```

SUBROUTINE FOR SPECTRAL DECOMPOSITION

```
      SUBROUTINE FOURTR(X,N,DELTAT,EMGVEC,RELVEC,FREQ)
      DIMENSION RECFOR(3), RELVEC(6000), EMGVEC(6000), FREQ(6000),
     1    X(12000)
      L = N - 1
      M = N / 2
      DO 100 K = 0,M
      OMEGA = 6.2831853 * K / N
      CSOMEG = COS(OMEGA)
      SNOMEG = SIN(OMEGA)
C***** EVALUATE RECURRSION FORMULA ************************************
      RECFOR(1) = X(N)
      RECFOR(2) = X( N-1 )
      RECFOR(3) = X( N-2 ) + 2. * CSOMEG * RECFOR(2) - RECFOR(1)
      DO 200 I = 3,L
      RECFOR(1) = RECFOR(2)
      RECFOR(2) = RECFOR(3)
  200 RECFOR(3) = X( N-I ) + 2. * CSOMEG * RECFOR(2) - RECFOR(1)
C***** COMPUTE REAL AND IMAGINARY VECTORS ****************************
      FREQ(K) = K / ( N * DELTAT )
      EMGVEC(K) = RECFOR(3) * SNOMEG * DELTAT
  100 RELVEC(K) = ( X(0) + RECFOR(3) * CSOMEG - RECFOR(2) ) * DELTAT
C***** COMPUTE ABSOLUTE VALUE ****************************************
      DO 300 K=0,M
  300 X(K) = SQRT( RELVEC(K)**2 + EMGVEC(K)**2 )
      WRITE(6,201) ( FREQ(K), RELVEC(K), EMGVEC(K),X(K), K=0,M )
  201 FORMAT(1H1, 4X, 4F16.8 / ( 5X, 4F16.8 / ) )
      RETURN
      END
```

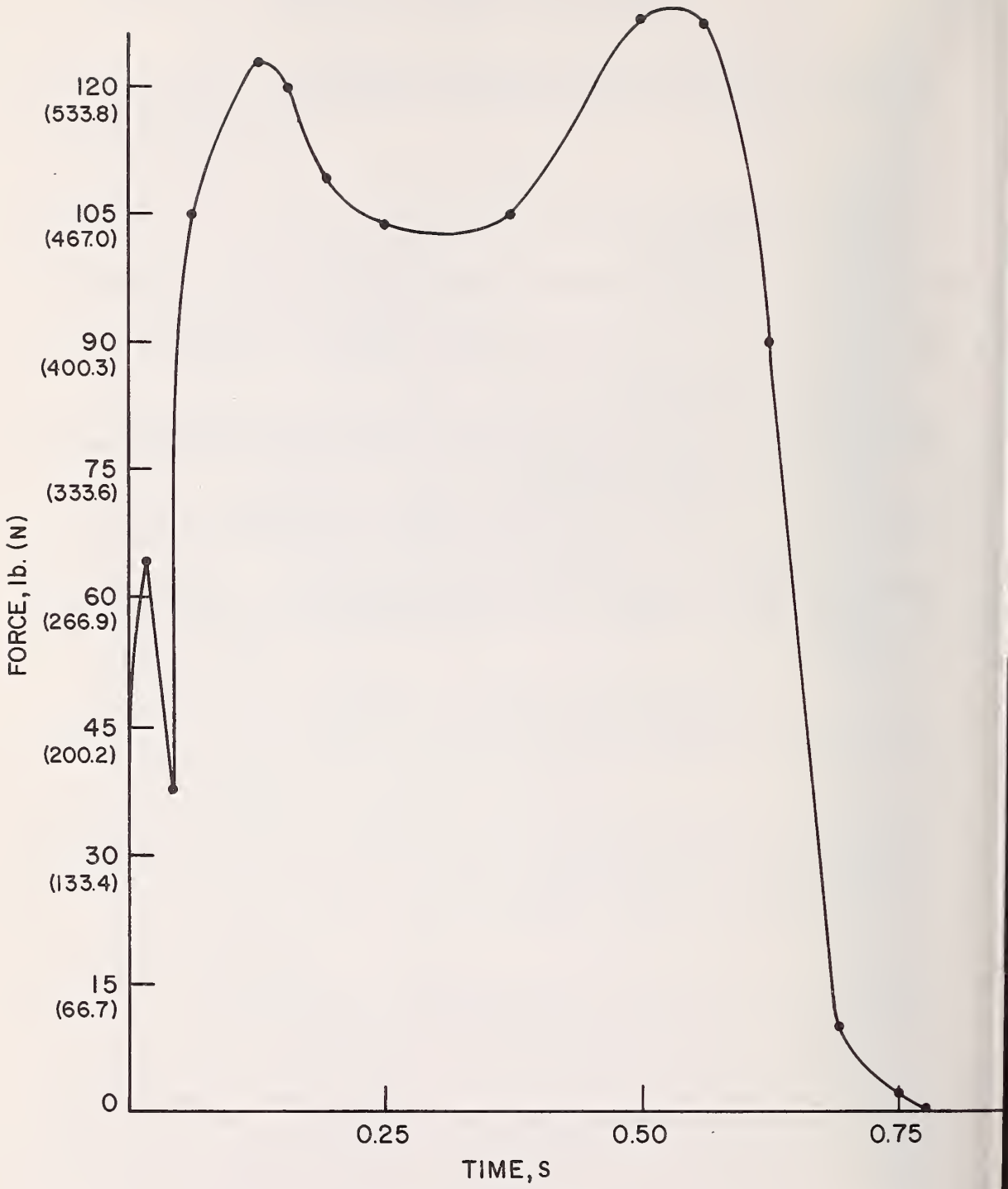

Figure 1 VERTICAL LOAD FROM FOOTFALL [4]

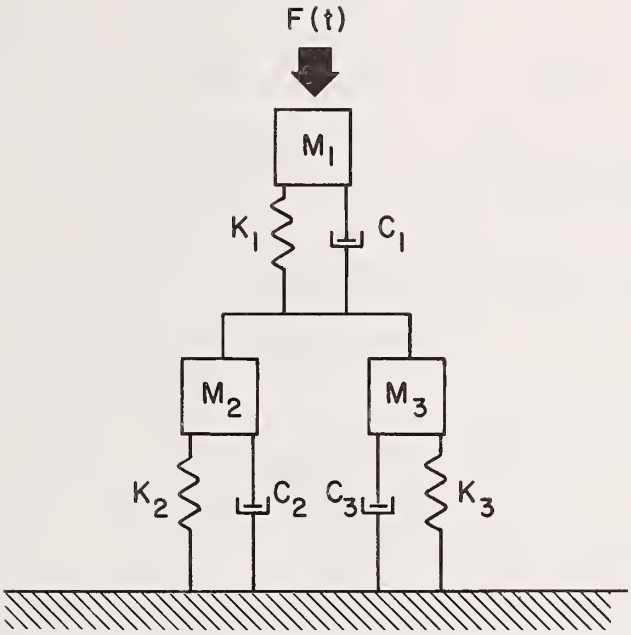

Figure 2 ENGINEERING VIBRATION MODEL

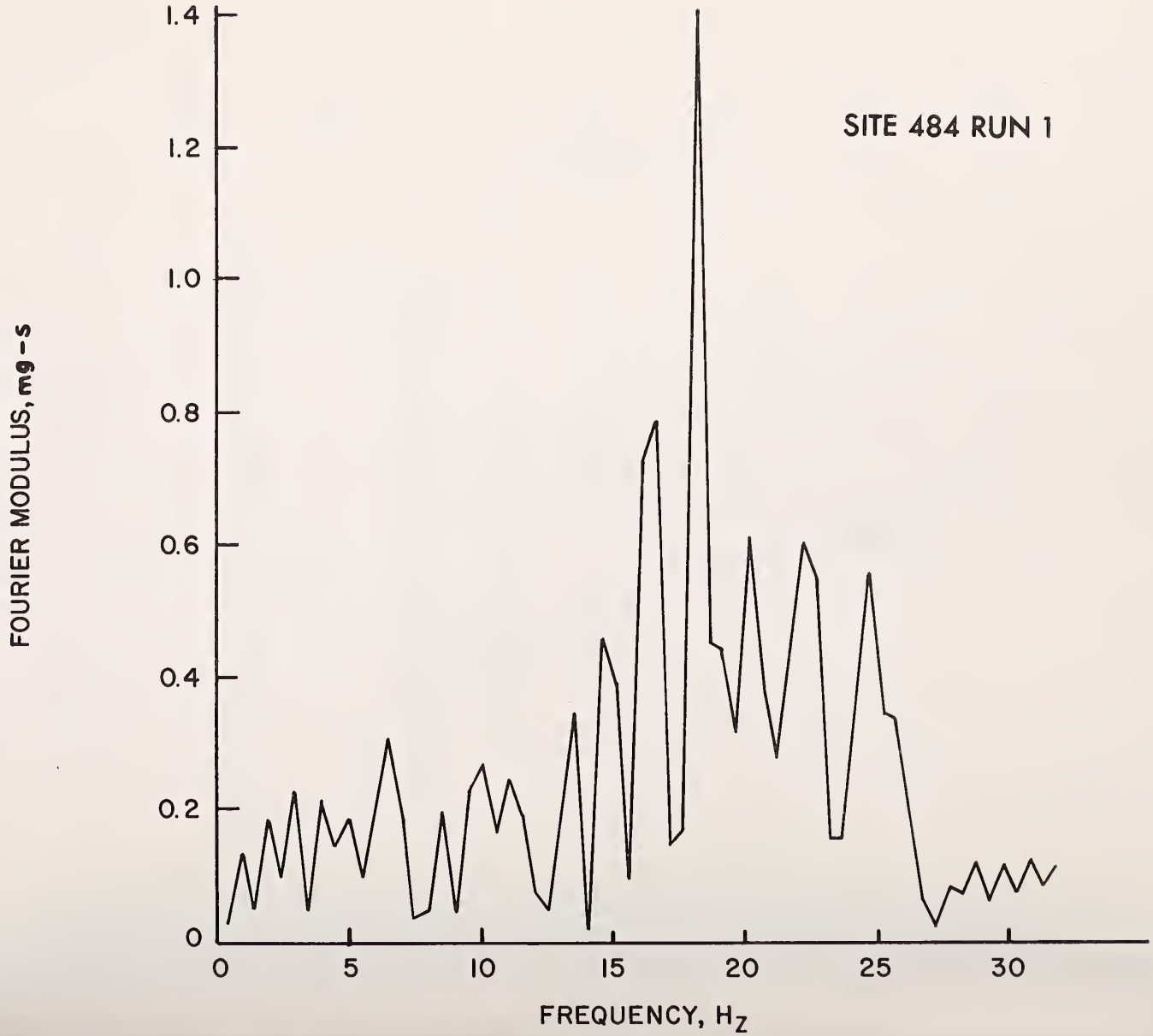

Figure 3 ENERGY DENSITY

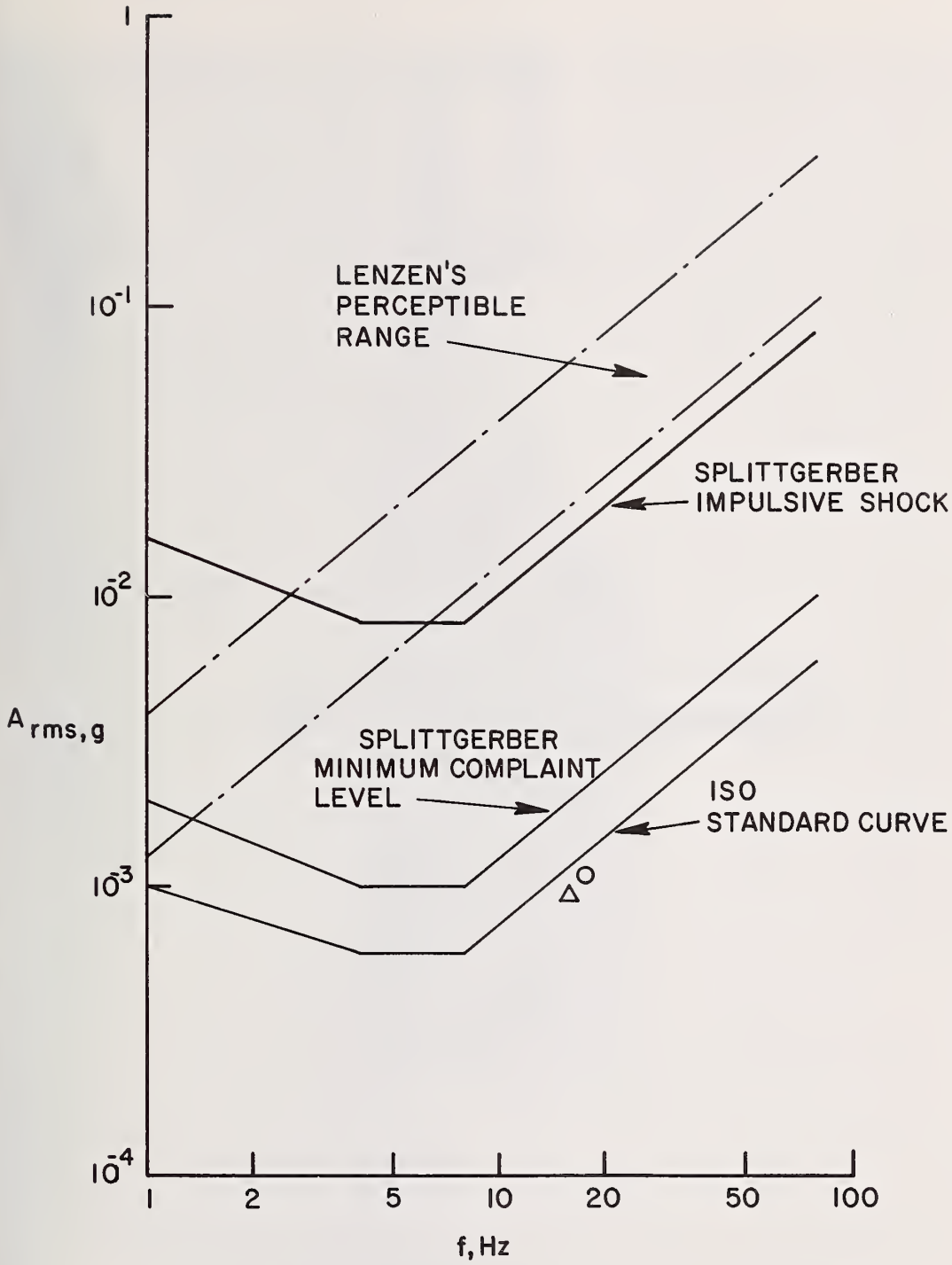

Figure 4 HUMAN RESPONSE THRESHOLDS TRANSIENT VERTICAL VIBRATION

FIGURE 5 TEST FLOOR SURFACE

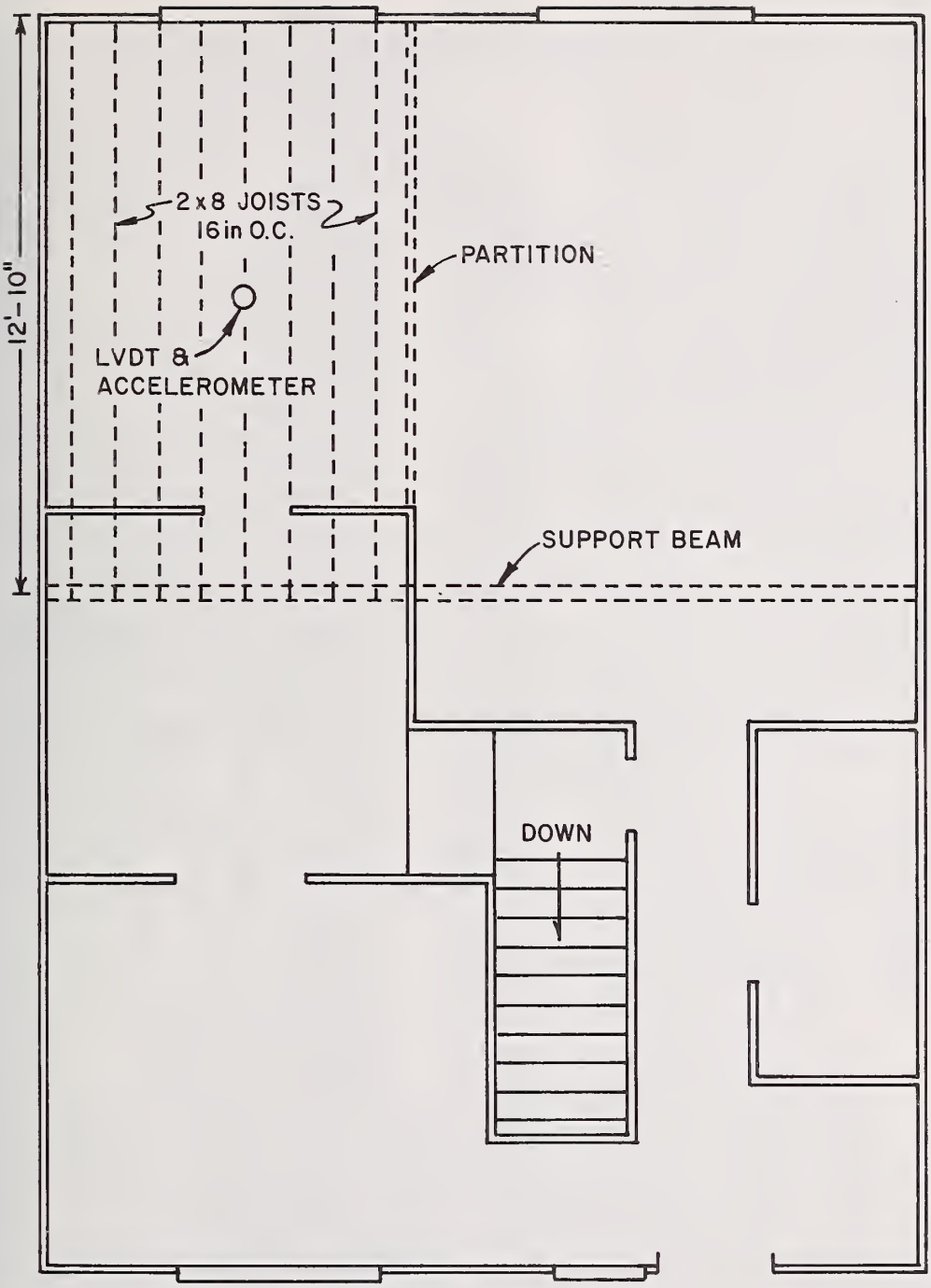

Figure 6 FLOOR PLAN OF TEST FLOOR

a) LVDT OUTPUT

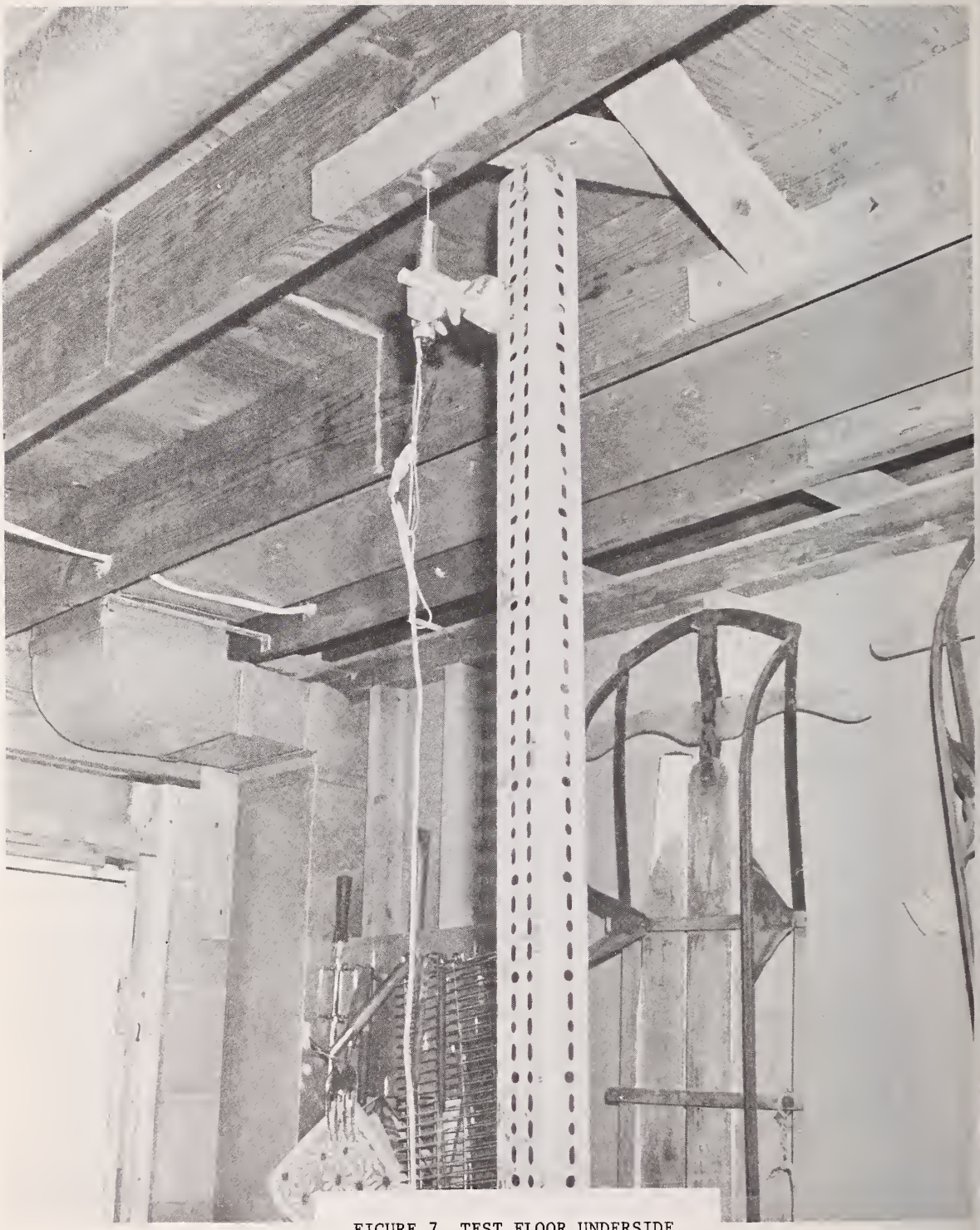

FIGURE 7 TEST FLOOR UNDERSIDE

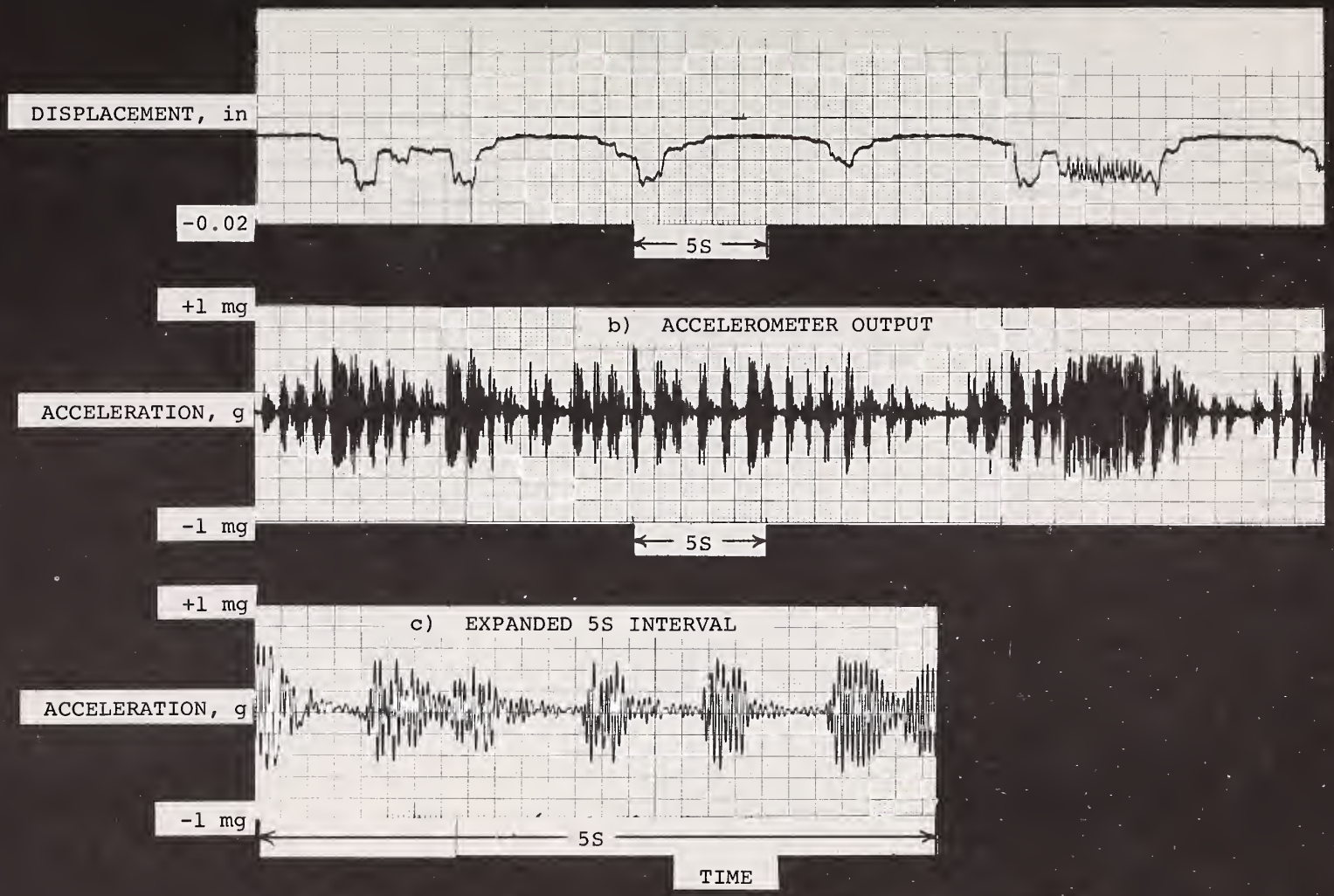

FIGURE 8 TYPICAL FLOOR VIBRATION INDUCED BY WALKING

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16. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)

A new approach to the problem of perceptible floor vibrations is presented predicated on the realization that human activity and human response to this activity are random variables. Techniques for data reduction are discussed and a detailed description of one approach is given along with the associated computer program. Data from floor vibrations is compared with current criteria for human response to vibration.

17. KEY WORDS (six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons) Analysis; experimental; floor systems; human response; random process; spectral analysis; vibration.

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