Fire Research Note No. 746

VIBRATION TESTING OF FIRE DETECTORS

by

M. J. O'DOGHERTY

January 1969

FIRE RESEARCH STATION

Fire Research Station,
Borehamwood,
Herts.
Tel. 01-953-6177

F.R. Note No. 746
January, 1969.

VIBRATION TESTING OF FIRE DETECTORS

by

M.J. O'Dogherty

SUMMARY

This note discusses the requirements for vibration tests for automatic fire detectors. The physical basis for the revised tests of B.S. 3116 is considered, together with that for a test suggested by the Institute for Telecommunications Engineering of the Technical University, Aachen, West Germany. The principles underlying the two tests are examined in detail, and the similarities and differences enumerated.

KEYWORDS: Building, Detector, Fire, Tests, Vibration.

MINISTRY OF TECHNOLOGY AND FIRE OFFICES' COMMITTEE
JOINT FIRE RESEARCH ORGANIZATION

VIBRATION TESTING OF FIRE DETECTORS

by

M.J. O'Dogherty

1. INTRODUCTION

Fire detectors used in buildings are generally fixed in some way to the building structure, and can, therefore, be subjected to vibrations which arise in the structure from a variety of causes. The vibrations may excite resonance in the sensitive elements of the detector which can give rise to false alarms. Alternatively failure of components by fatigue, or the loosening or detachment of components, can make the detector fail to operate in the event of a fire. For these reasons a vibration test is required for fire detectors which is representative of the range of amplitudes and frequencies of vibration known to occur in buildings. This note discusses the information available on building vibrations[1] in relation to the tests proposed in the revision of British Standard 3116 : 1959[2], and the proposed test set out in the test schedule proposed by the Institut Elektrische für Nachrichtentecknik (I.E.N.T.) of the Technische Hochschule, Aachen, West Germany[3].

2. UNITS OF VIBRATION INTENSITY

A number of units have been suggested for defining the intensity of vibration[1,3], most of which are of German origin. These units have been related to the physiological effects of vibration, and to the effects on building structures. Most of the units are based on energy considerations, and one of these is Zeller's power of vibration, Z, defined as:-

$$Z = \frac{\hat{\alpha}_o^2}{f} = 16\pi^4 a_o^2 f^3 \qquad (1)$$

where $\hat{\alpha}_o$ is the maximum acceleration ($= 4\pi^2 a_o f^2$).

f is the frequency of vibration

a_o is the maximum amplitude of vibration.

The "vibrar" unit is a useful one for making comparisons between the effects of vibrations having different amplitudes and frequencies. The unit is derived in terms of Zeller's power, i.e.

$$\text{Strength of vibration (vibrars)} = 10 \log_{10} \left(\frac{Z}{Z_o}\right), \qquad (2a)$$

where Z_o has the value 0.1 cm^2/sec^3 in metric units.

$$\therefore \text{ strength in vibrar units} = 10 \log_{10} (10Z)$$

$$= 10 + 10 \log_{10} Z \qquad (2b)$$

3. DAMAGE CRITERIA

Investigations of vibrations of buildings have led to classifications of the intensity of vibration and its possible effects[1]. Such a classification is given in Table 1, in vibrar units, and Figure 1 shows the information plotted as a relationship between amplitude and frequency over the frequency range 1-100 Hz. This relationship can be established by calculating Z for each value of the vibrar strength given, from equation (2), and then using equation (1), from which it can be seen that

$$a_o \propto \frac{1}{f^{3/2}} \; ,$$

so that the slope of the lines in Figure 1 is -3/2 on logarithmic scales.

Table 1.

Vibration Intensity and Probable Damage

Strength of vibration (vibrar)	Classification of vibration	Possible damaging effect
10-20	Light	None
20-30	Medium	None
30-40	Strong	Light damage (cracks in rendering etc.)
40-50	Heavy	Severe (damage to main walls)
50-60	Very heavy	Destruction

Zeller has also drawn up a table relating the strength of the vibration to its effects[4], and this is given in Table 2, omitting some of the higher ratings which are outside the scope of present considerations.

Table 2.

The Zeller scale of vibration effects.

Zeller's value (Z) (cm^2/sec^3)	Rating or grade	Assessment (i.e. effect on persons or buildings)
1	1	Not perceptible
2	2	Very light
10	3	Light
50	4	Measurable (small cracks in plaster)
250	5	Fairly strong
1,000	6	Strong - beginning of danger zone.
5,000	7	Very strong - serious cracking
20,000	8	Destructive
100,000	9	Devastating

The value of Z = 5,000, which represents the onset of serious damage corresponds to 47 vibrars, and the criterion for a destructive vibration (Z = 20,000) corresponds to 53 vibrars (see Table 1). A further table of damage is given by Koch[5], which suggests a level of vibration which will produce cracks extending to the walls of a building equivalent to 42 to 47 vibrars. The general inference from these criteria is that serious damage will occur to the building structure at a level of vibration intensity in excess of 47 vibrars.

4. TEST PROPOSED BY I.E.N.T.[3]

The test method proposed is based on the principle that the detector should be able to withstand vibrations up to a level at which serious damage to the building begins to occur. The level of vibration intensity chosen is Z = 5,000 cm^2/sec^3 (see Table 2 by Zeller), which corresponds to a level of 47 vibrars.

From equation (1), $$Z = \frac{\hat{\alpha}_o^2}{f} = 5,000$$

$$\therefore \quad \hat{\alpha}_o = \sqrt{5,000\, f}$$

$$\therefore \quad \frac{\hat{\alpha}_o}{g_n} = 0.0721 \sqrt{f}$$

where g_n is the acceleration due to gravity (= 981 cm/s^2).

This test curve is shown in Figure 2, over a range of frequency from 5 to 60 Hz. The I.E.N.T. test proposes an upper limit of frequency on the basis that the building strongly damps out the higher frequency excitations. The test procedure subjects the detector to sinusoidal vibrations over the range 5 to 60 Hz at increments of 5 Hz, for 5 minutes at each increment. The detector is mounted in its normal operating position and connected to its normal control equipment, and false alarms and resonances are recorded. After the test the sensitivity of the detectors is measured, but there are no criteria for specifying an acceptable change in sensitivity. There is no specification in the proposals for any form of endurance test.

5. REVISED B.S. 3116 TEST

The revision of B.S. 3116 : 1959 has resulted in some modification of the original test procedure. The test is now divided into two parts:-

(1) Search for false alarms.
(2) Search for resonance and endurance test.

The range of frequencies chosen was 5-60 Hz because the great majority of building vibrations for joists, beams and floors lie within this range[1]. During tests the detector is mounted in its normal operating position, by its normal fixings.

Search for false alarms.

The detector is vibrated sinusoidally at a constant peak acceleration of 0.1 g_n with a continuous sweep over the frequency range. This level of acceleration was chosen to represent a strong vibration over most of the frequency range but generally below that which would cause structural damage. The amplitude of vibration over the frequency range is plotted in Figure 1 for a peak acceleration of 0.1 g_n. At the lower frequencies (less than about 9 Hz), this level of acceleration represents a heavy vibration. In physiological terms a peak acceleration of 0.1 g_n represents an unpleasant vibration at the lower frequencies, and is annoying at frequencies above 34 Hz (see Appendix 1). The requirement of the standard is that no false alarm be indicated during this test.

Search for resonance and endurance test.

The search for resonance of components is made at a fixed amplitude of 127 μm (0.005 in) over the frequency range 5-60 Hz using a continuous sweep.

The detector is connected to equipment which gives a rapid response to transient detector operation, so that resonance of components inside the detector, which results in momentary closing of contacts, can be detected. Other resonances may be observed visually. The use of a fixed amplitude for the resonance search was adopted because the amplitudes of vibration at the upper end of the frequency range are very small for the peak acceleration of 0.1 g_n used in the search for false alarms (see Figure 1). A component may be excited into resonance, but its amplitude is dependent on the amplitude of the excitation vibration (see Appendix 2), and, in consequence, a situation may arise where the sensitive element of a detector is in resonance but not at sufficient amplitude for contact to be made. Therefore in a closed detector the resonance may not be indicated. Tests conducted by the Fire Research Station on a number of proprietary detectors have shown that in order to produce a sufficient amplitude at resonance, an amplitude of excitation of as much as 127 μm may be required.

An endurance test is carried out at any resonant frequencies observed at a peak acceleration of 1 g_n for a period of 2 hours, or, if no resonances are observed, at a frequency of 60 Hz. The object of this test is to subject the detector components to a high stress level, and indicate where fatigue or other failures are likely to occur.

The requirement of the standard is that no component failure occurs during these tests.

6. DISCUSSION.

The test curves for the revised version of B.S. 3116 and the I.E.N.T. proposals are shown in Figure 2, in which peak acceleration is plotted against frequency. Figure 1 shows the same information but with peak amplitude plotted against frequency.

The I.E.N.T. test curve is a more severe vibration than that used in the B.S. search for false alarms, with a peak acceleration ranging from 0.16 to 0.56 g_n over the frequency range, compared with 0.1 g_n. This is because the I.E.N.T. test is intended to represent conditions for which serious structural damage to the building would be expected, whereas the B.S. test represents a search for the possibility of false alarms for strong vibrations, but at a level below the damage intensity.

The peak accelerations required in the B.S. 3116 proposals for the resonance search are greater than those of the I.E.N.T. test for frequencies above 27 Hz, ranging up to 1.84 g_n at 60 Hz. The B.S. 3116 endurance test, which is conducted at a peak acceleration of 1 g_n, represents higher peak accelerations than the

I.E.N.T. test over the whole frequency range. The high peak accelerations of the B.S. search for resonance arise from the use of a fixed amplitude of 127 μm over the frequency range. This was considered necessary in order to detect resonance at the higher frequencies, for which the amplitudes of the exciting vibration are very small for the false alarm search conducted at 0.1 g_n (see Section 5 and Appendix 1). Although the acceleration levels rise above that likely to cause building damage (at frequencies higher than 27 Hz), the method is only used as a technique for detecting resonances within the detector which may otherwise not be found. The endurance test of the proposed B.S. 3116 represents a level of acceleration above that to which a detector is likely to be subjected in a building. The object of this test, however, is to subject the detector components to a level of stress above that which they would ever experience, so as to reveal weaknesses in design. A test of this kind, which represents stress levels above those ever likely to be encountered in service, is a common practice in the testing of engineering components.

The tests differ in that there is a continuous sweep of the frequency range in the proposed B.S. 3116 test, but the I.E.N.T. test is carried out at discrete increments of 5 Hz. While it may be unlikely that a resonant frequency will be so sharp that it will not be found by the method of using discrete steps, the continuous sweep method is necessary to determine the exact resonant frequency.

The revised version of B.S. 3116 lays down requirements for sensitivity of the detectors following vibration testing, but the I.E.N.T. proposals are not specific on this point.

7. CONCLUSIONS

The tests proposed for B.S. 3116 and by the I.E.N.T. both cover the same range of frequencies of vibration, viz. 5 to 60 Hz.

The I.E.N.T. test subjects the detector to vibration intensities which would result in severe building damage. False alarms and resonances are recorded together with their causes, but no endurance test is specified. Additionally, there is no criterion given for any change which may occur in detector sensitivity following the test as in the B.S. 3116 proposals.

The proposals for the revision of B.S. 3116 : 1959 suggest a search for false alarms at a vibration intensity representative of strong vibrations but below a destructive level for buildings. The resonance search produces higher peak accelerations than the I.E.N.T. test, but it is considered that the fixed amplitude of 127 μm is necessary to reveal resonances at the higher frequencies. There is also an endurance test, which is at a vibration intensity above destructive conditions in a building, on the basis that the detector should be subjected to a stress level well above any possible service conditions so as to reveal design weaknesses. There is no equivalent endurance test in the I.E.N.T. proposals.

REFERENCES

(1) STEFFENS, R.J., Some aspects of structural vibration, Building Research Station, Ministry of Technology, Engineering Series 37.

(2) British Standard 3116 : 1959, Heat sensitive detectors for automatic fire alarm systems in buildings, British Standards Institution.

(3) A test schedule for automatic fire alarm systems, Institute for Telecommunications Engineering, Technical University, Aachen, West Germany, 1968.

(4) DAWANCE, G. Measurement and effects of vibration in houses and industrial buildings, Ann. Inst. Batim, 10, 115-6, 713-28, 1957.

(5) KOCH, H. W. Determining the effects of vibrations in buildings, V.D.I.Z., 95 21, 744-7, 1953.

(6) REIHER, A. J. and MEISTER, F. J. Human sensitivity to vibration, Forsch. auf den Geb. des. Ing., 2 11, 381-6, 1931.

(7) DIECKMANN, D. A study of the influence of vibration on man, Ergonomics, 1, 4, 347-55, 1958.

(8) MITTELMANN, G. Vibrations in buildings near building works, Bauingenieur, 37 (6), 217-20, 1962.

Appendix 1

Physiological effects of vibration

Investigations into the susceptibility of humans to vibrations have been conducted by Reiher and Meister[6], and by Dieckmann[7]. These investigations have examined the physiological effects of the vibrations, and have covered intensities from the lower limit of perception to the upper limit of endurance for average subjects. The investigations have enabled the results to be classified into a number of distinct regimes when the amplitude of the vibration is plotted against frequency. Figure 4 shows the human sensitivity to vibration based on the work of Reiher and Meister. The curves show that for a peak acceleration of 0.1 g_n the vibration would be unpleasant below 34 Hz and annoying above this frequency. Other criteria, such as those of Dieckmann, and those put forward in D.I.N. 4025 (1958)[1,8], show that such a level of acceleration is very unpleasant at the lower frequencies and strongly evident at the higher frequencies of the range.

The intensity of vibration suggested for the I.E.N.T. test would represent a painful vibration on the Reiher-Meister scale, and extremely unpleasant effects at the lower frequencies according to Dieckmann's criteria, which means the vibration is not endurable for more than 1 min. This would be expected for a vibration of sufficient intensity to cause structural building damage.

Appendix 2.

Dynamic response of detector components to a forced vibration

Consider a detector component of mass M which is attached to part of the detector casing by a fixing which has a spring stiffness, k, and a linear damping coefficient c (see Figure 3). Let the casing of the detector be subjected to a forced sinusoidal vibration, such that the amplitude y_o is given by:-

$$y_o = a_o \sin p\, t \tag{1}$$

where a_o is the maximum amplitude, p is the circular frequency (rads/s) and t is time.

Let the absolute displacement of the detector element at any time be y_1, so that its displacement relative to the casing is $y_o - y_1 = z$ say. Then the equation of motion of the component of mass M is:-

$$M \frac{d^2 y_1}{dt^2} = kz + c\frac{dz}{dt} \tag{2}$$

or $$M\left(\frac{d^2 y_o}{dt^2} - \frac{d^2 z}{dt^2}\right) = kz + c\frac{dz}{dt}, \text{ since } y_1 = y_o - z$$

$$\therefore M\frac{d^2 z}{dt^2} + c\frac{dz}{dt} + kz = M\frac{d^2 y_o}{dt^2} \tag{3}$$

$$= -Ma_o\, p^2 \sin p\, t$$

The solution of this equation is:-

$$z = a_o \frac{p^2}{\omega^2} F \sin(pt + \pi - \phi) \tag{4}$$

where $\omega = \sqrt{\frac{k}{M}}$, which is the natural circular frequency of the system.

F is the dynamic magnification = $\sqrt{\dfrac{1}{\left(1 - \left(\frac{p}{\omega}\right)^2\right)^2 + \left(2\beta\frac{p}{\omega}\right)^2}}$

and $\tan\phi = \dfrac{2\beta\omega p}{\omega^2 - p^2}$

The factor $\beta = \frac{c}{c_1}$, where c_1 is the critical damping factor of the system. The value of β can be expressed as $\frac{c}{2M\omega}$

At the resonant frequency of the component we have $p = \omega$, and therefore $F = \frac{1}{2\beta}$

and $\pi - \phi = \frac{\pi}{2}$

$$\therefore \quad z = \frac{a_o}{2\beta} \sin \left(pt + \frac{\pi}{2}\right) \tag{5}$$

This expression for z represents the displacement of a component within the detector relative to the casing. If a contact was mounted on one end of the component, and another was mounted on the case, the value of z would have to reach that of the initial contact gap. For example, if the initial gap was 4.8 mm ($^3/_{16}$ in), and if the value of $\beta = 0.005$ is taken, which is representative of damping in metals such as mild steel, than from equation (5) the value of $a_o = 0.048$ mm (0.00188 in), so an amplitude of about 0.051 mm (0.002 in) is required to achieve contact closure. For frequencies above 22 Hz, at a peak acceleration of 0.1 g_n, the peak amplitude would be less than this value.

The example given has only one degree of freedom, and an analysis of the behaviour of a strip, for example, is more complex because it has an infinite number of degrees of freedom and the amplitude at any point is compounded of contributions from different vibrational modes. The analysis indicates, however, that there is a minimum amplitude of the existing vibration to produce closure of contacts, and that at lower amplitudes resonance may occur but not be recorded.

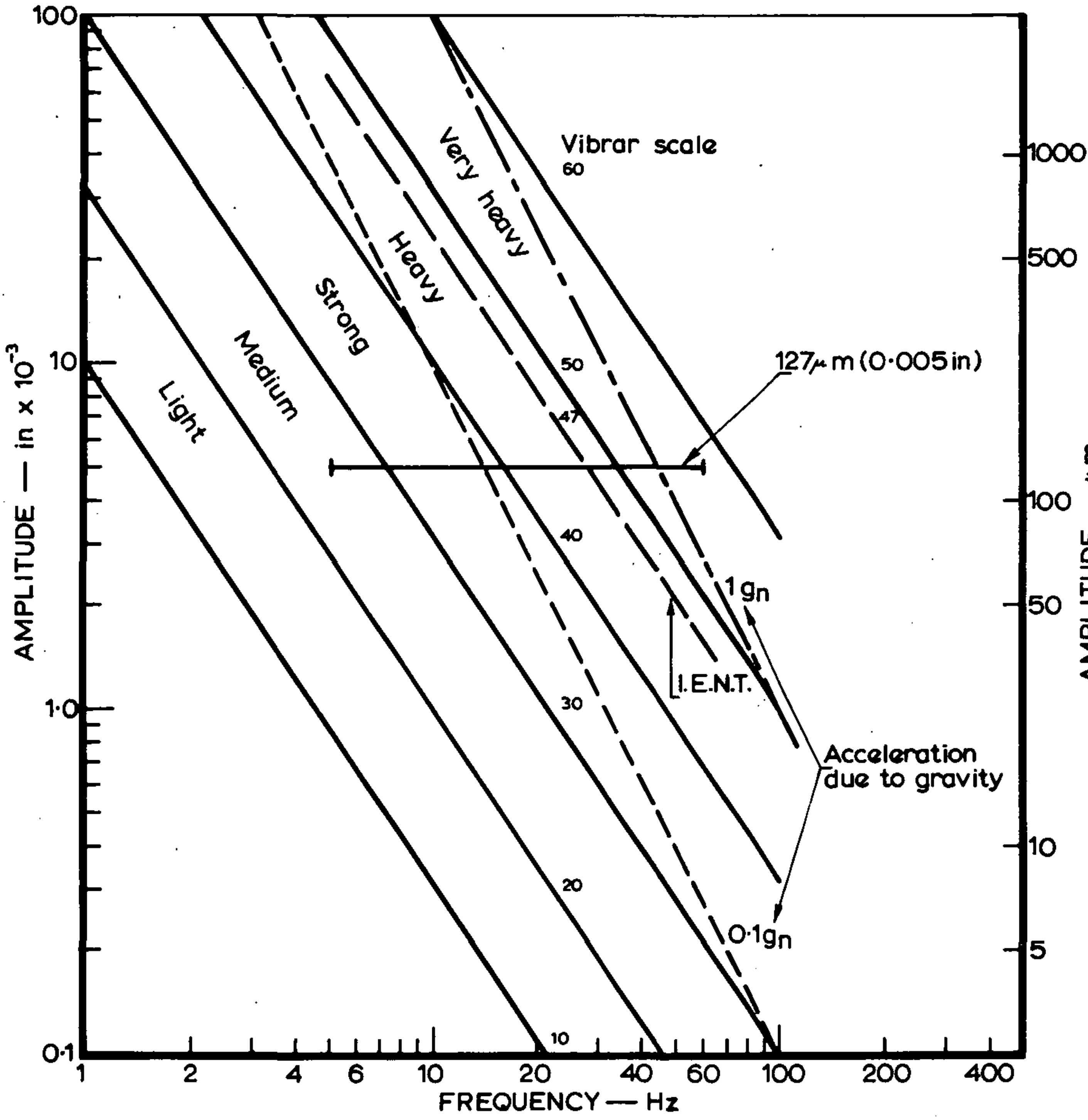


FIG. 1. CLASSIFICATION OF VIBRATION INTENSITY

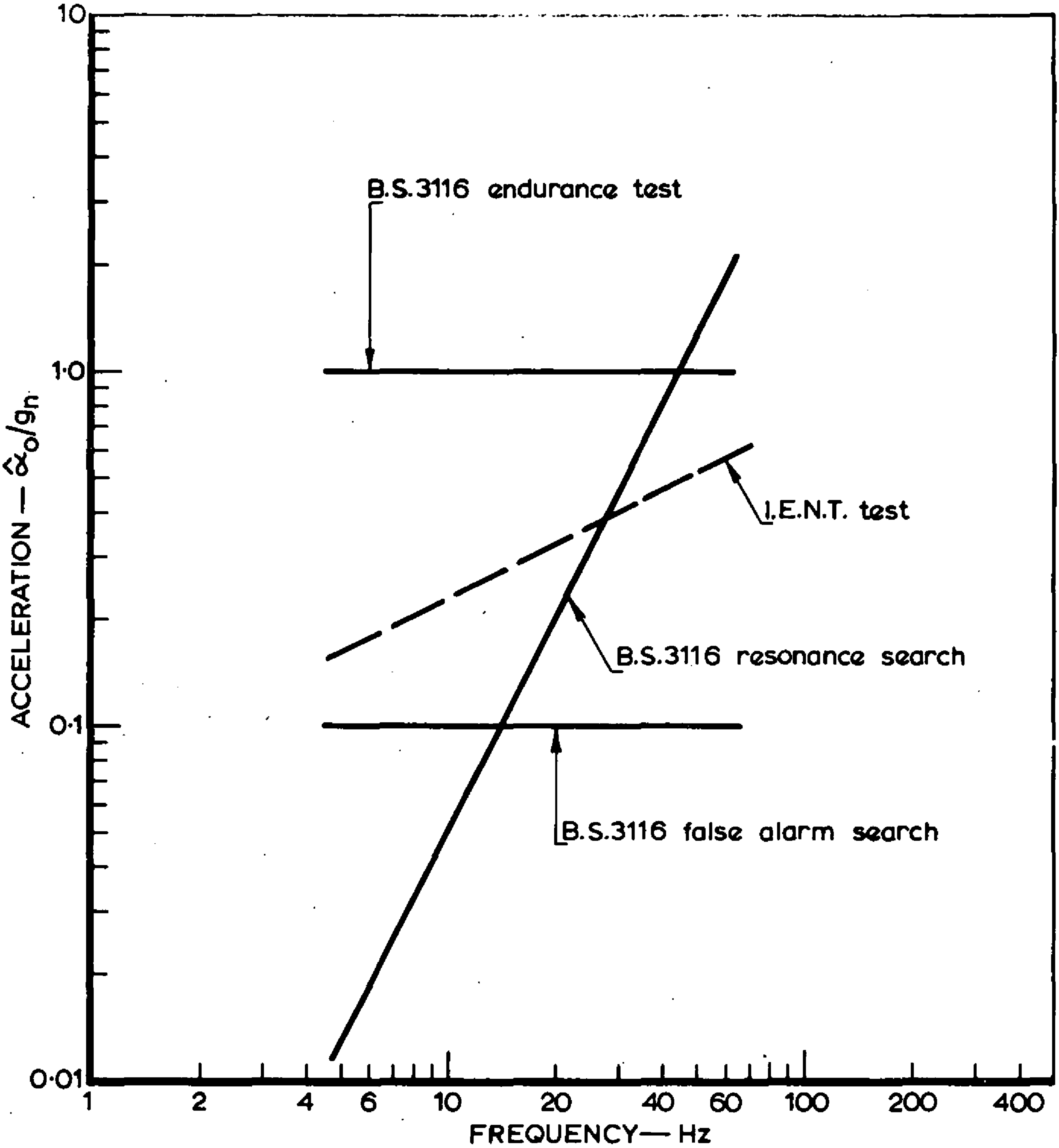
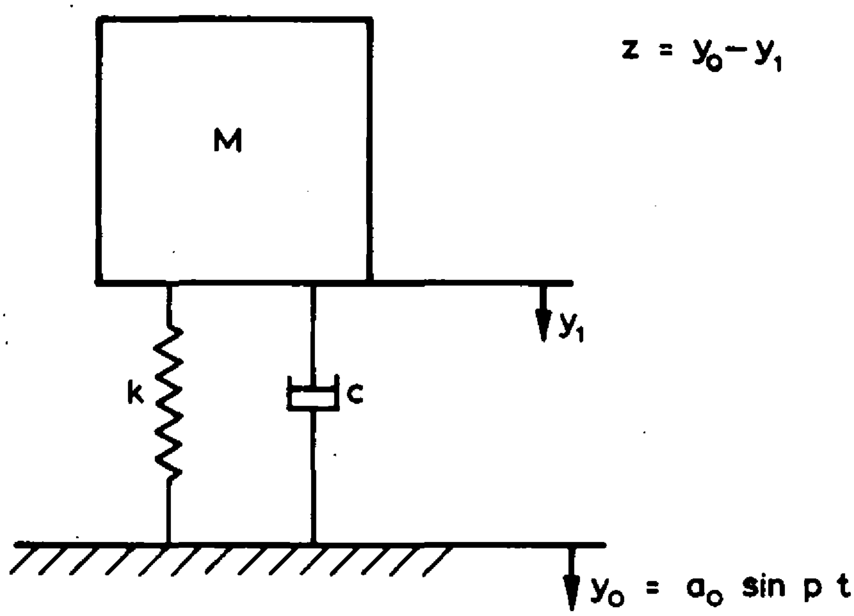


FIG. 2. PROPOSED VIBRATION TEST CURVES



Spring force = kz

Damping force = $c \frac{dz}{dt}$

FIG. 3. SPRING AND MASS SYSTEM WITH DAMPING

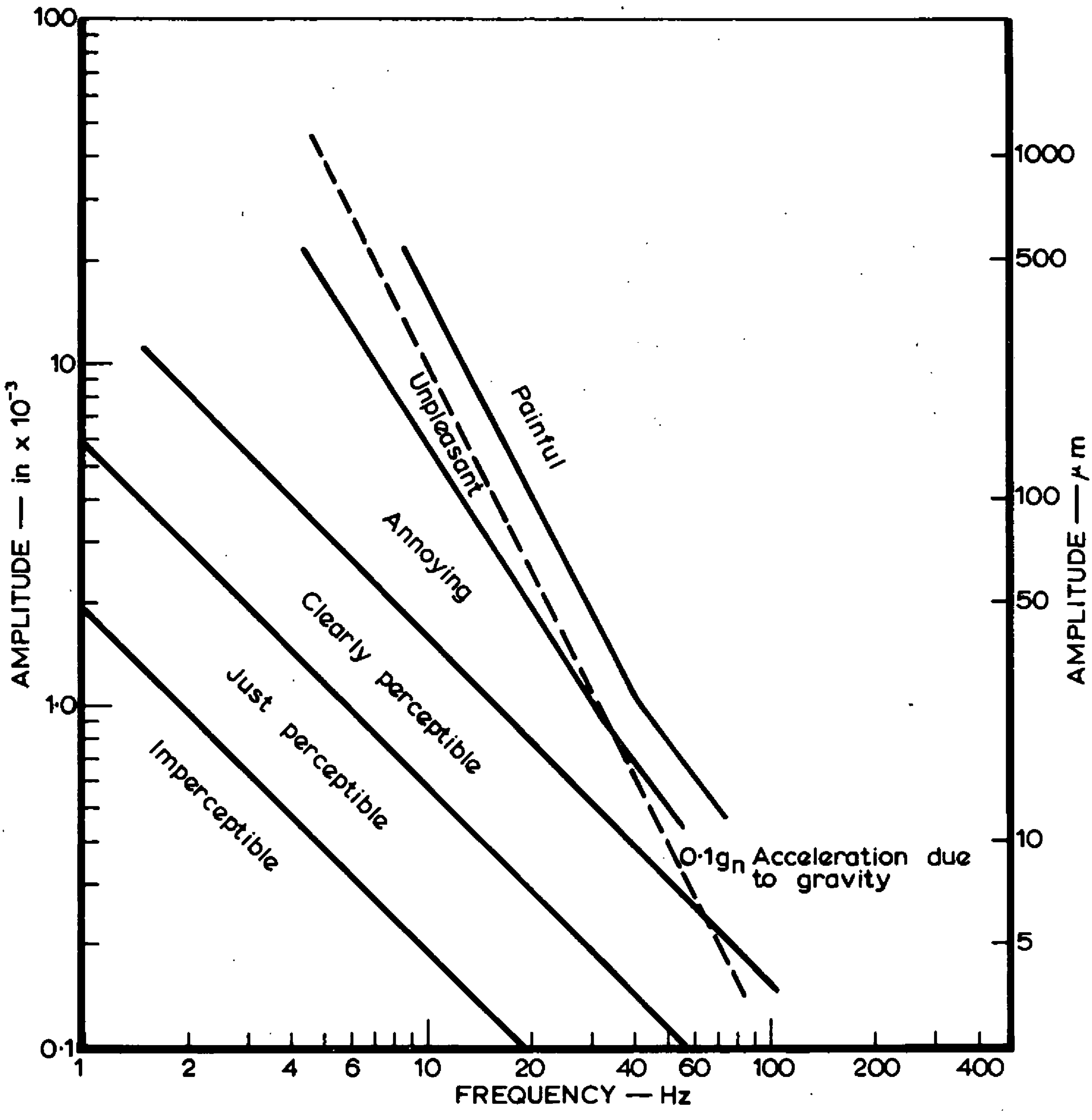


FIG. 4. PHYSIOLOGICAL EFFECTS OF VIBRATION (REIHER-MEISTER)

1/8710 F.R. 746