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IMPACT NOISE ON FLOORS

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ABSTRACT

Some of the criticisms aimed at the International Standard Tapping machine and its use in rating floors against impacts are discussed in this note. Possible alternate test procedures offer some advantages, but the use of the hammer itself has unsatisfactory aspects. Further basic research is necessary and in this note two studies are described. One is an objective examination of the impulses created by the standard hammer when it strikes various resilient coverings placed on a concrete floor. The second is an attempt to define the parameters on which subjects base their evaluation of footstep noise.

LE BRUIT DES CHOCS SUR UN PLANCHER

SOMMAIRE

On examine quelques-unes des critiques de l'appareil international standard servant à évaluer le comportement d'un plancher sous l'effet d'un choc. D'autres méthodes d'essai offrent des avantages, mais l'utilisation du marteau lui-même n'est pas toujours satisfaisante. Il faut poursuivre la recherche fondamentale, et deux études sont décrites ici. La première est un examen objectif des impulsions produites par le marteau standard sur un plancher de béton recouvert de différents matériaux élastiques. La deuxième cherche à définir les paramètres sur lesquels les personnes fondent leur évaluation du bruit de pas.

NATIONAL RESEARCH COUNCIL OF CANADA
DIVISION OF BUILDING RESEARCH

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R.D. Ford and A.C.C. Warnock

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PREFACE

The transmission of structure-borne sounds, particularly impact noises such as footsteps, constitutes the most serious sound insulation problem in multi-family buildings. The Division, therefore, has given considerable attention to this topic. Of particular concern has been the lack of a satisfactory test procedure to assess the performance of structures from the viewpoint of impact noise. The project was interrupted for a time because of staff shortages, and before resuming research it seemed timely to make a fundamental reassessment of the problem. The Division was very pleased to have Dr. R. D. Ford of Salford University, Salford, England, spend the summer of 1971 in the Building Physics Section during which time he produced this report that not only provides a critical review of the impact problem but that also includes experimental work that answers several major questions. Dr. A. C. C. Warnock, who assisted in this exploratory phase, is continuing the Division's work on the project.

Ottawa
June 1974

C.B. Crawford
Director

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1. INTRODUCTION.

The criticisms of the International Standard Tapping Machine and its use in evaluating floors for impact insulation are many and varied but, in spite of this, many countries have adopted the machine as the impact source, comparing the resultant noise spectrum with a national criterion that is regarded as acceptable. The United States has been slower than many countries in this respect although a proposed standard is now being considered by the American Society for Testing and Materials which uses the standard machine (1).

The chief criticisms of the machine are that the force spectrum has a greater high frequency content than have footsteps and that the forces involved are much greater than those applied in walking. Footstep noise is, in itself, difficult to define. It depends primarily on the shoes being worn but also on the individual walker. Five or six years ago the major source of irritation could easily be defined as a female wearing 'spike' heels with steel or hard plastic tips. Nowadays flatter softer heels are worn and females make no more noise walking than males. The general consensus is that the harder the heels the more intrusive the noise. In comparing hammer noise with hard heeled footsteps, spectral analysis shows that the footsteps produce substantially lower sound pressure levels with a greater proportion at low frequencies. This might not in itself be important if the subjective evaluation of floors correlated well with results obtained by the tapping machine method but several authors have demonstrated that there can be an appreciable variance and that the results depend on the type of impact (2,3, 4, 5, 6, 7, 8).

Proposals for changing the test procedure to give better results fall essentially into three groups. One school of thought suggests that the machine should be left unaltered and that the grading or specification curves should be changed so that less importance is given to the high frequency content. Rating contours currently in use are all more severe at high frequencies than at low frequencies. Because the tapping machine produces an excessive amount of high frequency noise, compared with footsteps, it is argued that the rating curves should be made more tolerant at high frequencies. Several publications (3, 9, 10) have shown that the use of a flat or nearly flat rating curve does indeed give better agreement with subjective evaluation than, for example, the I.S.O. contour. This approach has the great attraction that national and international standards can remain unaltered at least so far as the machine is concerned. On the other hand the criticism concerning force remains unanswered and this can be very important when testing resilient surfaces that usually have non-linear elastic properties.

A more radical line of thought is that either the existing machine should be modified or that a completely new machine should be designed. Suggestions for modification are that rubber tips could be used on the hammers which would give a more realistic spectral content and that a lower fall height could be used which would alleviate the non-linearity problem (11). Unfortunately, both of these modifications result in appreciably lower noise levels, which makes measurement more difficult, particularly in the field. There seems to be no simple solution to these contradictory requirements, although it has been suggested that electrodynamic excitation could be a satisfactory compromise (12). Even then there would be difficulties over the size of the vibrator and there would be an enormous psychological barrier in that an impact source was not obviously being used for the test. Totally new machines have been designed and built (13, 14) with which walking conditions are simulated quite closely. The actual process of walking has been carefully studied and the masses and stiffnesses of the various parts of the leg and foot have all been included. Although the machines can wear any shoe desired, they are somewhat bulky and there seems to be little enthusiasm for such a device outside the designer's own laboratory.

Finally there are those who argue that if footsteps are required as an impact source then people should walk on the floor. One criticism is that a human source is more variable than a machine although proponents of the idea claim that there is very little variation between individuals - it is the type of shoe that is important, not the wearer. Nevertheless, one is still faced with the problem of finding a standard walker for a test and another, perhaps more serious, criticism is that the noise levels produced in the room below are very low for measurement purposes.

More fundamental work on the physical processes of noise production, transmission and radiation starts with a study of the force-time history of the impulse. One of the first attempts to measure the force impact from a foot (15) was more concerned with the wearing of floor coverings than noise and the method consisted of a rather elaborate floor section that measured vertical and horizontal forces and torque when stepped upon. The interest was in the maximum forces produced rather than the initial force resulting from the heel strike which is responsible for the noise.

More recently, in designing a mechanical walker (13, 14), the initial heel strike has been studied in some detail. Force-time histories measured with a floor transducer for a variety of shoes and floor coverings have been recorded and it is evident that the rise time of the impulse is related to the resilience of the shoe and the floor covering, i.e., the sharper the impact the greater the high frequency content of the resulting noise. A more detailed study (16) utilized force transducers in the heel of a lady's shoe and in one hammer of an I.S.O. standard tapping machine. The force-time histories were transformed to give the power spectrum of the force input.

Once the force input is defined the theory for the production and transmission of impact noise is based largely on the vibrational properties of a concrete slab (16) and the resultant noise from various impacts, varying from hammers to footsteps, can be calculated provided that certain assumptions are made about the point input impedance and the radiation resistance of the concrete slab. The theory is currently being extended to account for floating-floor and timber constructions (17).

If it can be assumed that a floating-floor or a resilient covering has a purely additive effect when laid on the concrete slab, then the improvement can be defined in terms of the mechanical properties of the various components. The basic equations of motion (11) can be simplified to show that there is always a resonance that is a function of the resilience of the supporting layer and of the supported mass. An improvement in impact insulation is only achieved at frequencies above the resonance.

In principle, non-linear behaviour of the resilient layers can be allowed for, although several assumptions are necessary to make the equations tractable. One ingenious practical solution for the case of hammer impacts (18, 19) is to measure the contact time and deduce from this an equivalent linear stiffness for the particular deflection that actually occurs. The calculated improvement based on this measurement agrees well with that measured in practice but it is doubtful whether the effect of any other impact could be deduced.

One area that has received very little attention concerns the subjective evaluation of the quality of a floor. Apart from seeking a method of test that satisfies the physical requirements it must give results that are shown to correlate with subjective judgement. In the broader sense, it might be desirable to evaluate a floor construction entirely theoretically. In order to do any of this it is necessary to know the parameters upon which a subjective evaluation is based. The loudness and the potential hazard to hearing of impulsive noises have been studied and in both cases it appears that it is the mean audible energy content that is important. This makes sense because a purely physical quantity is still being measured. Annoyance, unfortunately, is a bit more complex and there is no reason to suppose that the mean energy level is particularly important. Indeed common sense and experience both suggest that the impulsive nature of the noise matters considerably and any assessment is, at least partially, based upon the peak noise levels that are achieved only momentarily.

This lack of knowledge has been circumvented in a number of ways when correlation has been sought between subjective evaluation and impact test data. The most direct approach is to allow subjects to listen to footstep noise created on several different floors and place them in rank order. Attaching numerical values to the judgements is more difficult but it has been shown that asking a subject to adjust the level of a background masking noise until the impact noise is no longer annoying yields results that are the same as the rank order method (3). The selected level of the masking noise is then taken as a numerical rating of the impact noise. There have been attempts to measure the so-called peak spectrum of the impact noise and to then compute loudness levels in Zwicker or Stevens phons but it is very doubtful whether the peak spectra were ever genuinely measured because it is very easy to obtain incorrect results using conventional analysis equipment.

There are clearly several areas in which useful research can be done and this paper describes two of them.

One is purely objective and is a study of the impulses created by a standard hammer as used in the I.S.O. tapping machine when it strikes various resilient coverings placed on a concrete floor. The object is to test the premise that the improvement obtained by using the resilient covering is additive to the basic behaviour of the floor. This approach should, in time, lead to an understanding of how the mechanical properties of the floor covering relate to its impact behaviour and how to measure and optimize those properties.

The second is subjective and is an attempt to define the parameters of footstep noise upon which subjects base their evaluation. If this can be done it should be possible to predict those parameters and hence predict the evaluation.

2. OBJECTIVE STUDY

2.1. Theory

The most promising theoretical approach to the problem of a concrete floor slab radiating sound as a result of being struck impulsively is outlined in the appendix of Reference 16.

It is argued that energy enters the slab during the impulse and, at the same time, is absorbed due to natural damping processes. The slab is assumed to be a reverberant system and so the energy balance equation yields

$$\overline{V}^2 = \frac{\overline{F}^2 N}{Zy\, 2\pi f\, M.S.} \qquad (1)$$

where $\overline{V}^2$ is the mean square velocity of the slab

$\overline{F}^2$ is the mean square force of one impulse averaged over 1 second

N is the number of impulses per second

Z is the point impedance of the slab

y is the loss factor of the slab (= 1/Q)

f is the frequency considered

M is the mass per unit area of the slab

S is the surface area of one side of the slab

$\overline{V}^2$ and $\overline{F}^2$ usually refer to frequency bands, e.g., 1/3 octaves. Z and y are both functions of frequency.

The radiated sound power is given by $W = R.S\ \overline{V}^2$ where R is the radiation factor and is another function of frequency.

Finally the mean square sound pressure in the room is dependent upon the input sound power and the room absorption, A,

$$\frac{\overline{p}^2}{\rho c} = \frac{4W}{A} \qquad (2)$$

where ρc is the characteristic impedance of air and A is the absorption of the room.

The whole approach to the problem is in terms of energy and, although the original source is impulsive, the energy is averaged out to long-term mean square values. Even this simplified approach is difficult to use in practice because of the uncertainty of defining values for Z, y and R for the slab and $\overline{F}^2$ for the impulse.

The premise here is that for a concrete slab, either alone or with a resilient covering such as vinyl or carpet, Z, y and R are a function of the slab alone and are independent of any resilient layer. The resilient layer, through its material properties, affects $\overline{F}^2$ by modifying the force-time history of the impulse. It should be possible, therefore, to obtain the force spectrum by analysing the impulse.

At low frequencies, Z is greatly coloured by a few major resonances, but at medium and high frequencies its average value, over a frequency band, should tend to

$$Z = 8\sqrt{MB} \tag{3}$$

where B is the cylindrical bending stiffness of the slab. Again, at low frequencies, R is determined by the slab geometry and the resonances, but above the critical frequency its value should tend to that of the characteristic impedance of air ($=\rho c$). The damping depends primarily upon the edge mounting conditions of the slab and must be measured. It could be affected (increased) by a resilient surface covering but, for the moment, this will be regarded as a second-order effect and ignored.

The object, then, is to measure as many of these parameters as is possible and to test the premise that, for a given floor slab, the resulting sound level is directly related to the impulsive forcing function.

2.2 Details of Floor Slab

The particular slab in the Building Physics Laboratories at the National Research Council of Canada is of reinforced concrete 2.4 m square by 100 mm thick. The edges rest on resilient material that isolates the slab from the surrounding structure; the joints are caulked to prevent airborne sound leaks. The fundamental bending resonance of the slab is at about 40 Hz and this is excited quite easily giving rise to relatively high sound pressure levels in the chamber below.

There is no way of measuring properties of the concrete so the following book values are assumed.

Density (ρ) = 2.3×10^3 kg/m^3.

Young's modulus (E) = 3×10^{10} N/m^2.

These may be used to calculate the following parameters

Bending Wave Velocity (CB) = $26.2\ f^{1/2}$ m/s

Critical Frequency (f_c) = 173 Hz

Point Impedance (Z) = 2×10^5 N·s/m

Mass Per Unit Area (M) = 230 kg/m^2

2.3 Force Spectrum of a Hammer Blow

The hammer in a standard tapping machine is made from brass and steel. It weighs 0.5 kg and is allowed to fall freely from a height of 40 mm which gives it a velocity on impact of 0.89 ms^{-1}. Because of its construction the hammer itself is not very elastic and when it falls upon a similarly hard surface such as concrete the impact is short and sharp.

The simplest way of defining the impulse is to suppose that the force, F, imparted by the hammer is constant for the duration of the impulse, T. This is illustrated in Figure 1(1). The power spectrum of the force is obtained by Fourier transforming the pulse, i.e.,

$$F(f) = \int_o^T Fe^{2\pi ft} dt \qquad (4)$$

$$= FT \frac{\sin \pi ft}{\pi ft} \qquad (5)$$

The mean square force in a frequency band is obtained by squaring and integrating, i.e.,

$$\bar{F}^2 = 2\int_{f_1}^{f_2} F^2 T^2 \left(\frac{\sin \pi fT}{\pi fT}\right)^2 df \qquad (6)$$

$f_1 \rightarrow f_2$

At low frequencies (when $\sin \pi fT \simeq \pi fT$) the integration is very simple but at higher frequencies it is necessary to carry out the integration numerically over the frequency band of interest. The numerical approach has advantages in any case, as will be seen later, when the pulse is not a rectangle as is assumed here. Continuing with the argument for the moment, however, and considering a concrete surface, where T is typically 250 μs, it may be assumed that, for frequencies up to about 1000 Hz

$$\bar{F}^2 \simeq 2\int_{f_1}^{f_2} F^2\, T^2\, df \qquad (7)$$

$$\underset{f_1 \to f_2}{} = 2\, F^2 T^2\, (f_2 - f_1). \qquad (8)$$

If the frequency band considered is a 1/3-octave centred on frequency fo, then

$$\bar{F}^2_{1/3} = 0.46\, F^2\, T^2\, fo \qquad (9)$$

The impulse FT must equal the change in momentum of the hammer and the standard theoretical assumption is that a perfect rebound occurs

$$\text{i.e.} \quad FT = 2\, m\, u_o \qquad (10)$$

where m is the hammer mass, and
u_o is its impact velocity.

In the case of the standard hammer

$$FT = 2 \times 0.5 \times 0.89$$
$$= 0.89\ N \cdot s \qquad (11)$$

More generally,

$$FT = (1+k)\, m\, u_o \qquad (12)$$

where k is the coefficient of restitution.

Since k can vary between 0 and 1, the force impact can vary by 6 dB and it is obviously important to know the correct value of this factor.

The 1/3-octave band spectrum for a short impulse with perfect rebound is illustrated in Figure 2.

If the impulse is of longer duration then the term $\frac{\sin \pi f T}{\pi f T}$ cannot be neglected. To illustrate its effect another rectangular impulse of 0.89 N·s has been selected but with a duration of 5 ms. Its force spectrum has been calculated by numerical integration and is also shown in Figure 2. Compared with the short sharp impulse the band level decreases markedly above about 100 Hz.

The rectangular impulse is theoretically attractive but bears little relation to a real impulse. A closer approximation is a half sine-wave of half period T. This is illustrated in Figure 1(3). For comparison the spectrum has again been calculated for an impulse of 0.89 NS and duration 5ms, and this is shown in Figure 2.

Finally, because the pulse shape actually observed experimentally is not really a half sine-wave but is more like the pulse shown in Figure 1(4), that also has been transformed to give its force spectrum, which is also shown in Figure 2. Although this pulse shape is based on experimental observation it has been found expedient to describe its shape by the expression

$$F = \hat{F} \sin(\pi t/T)\, e^{-\frac{\alpha \pi^2}{T^2}\left(t - \frac{T}{2}\right)^2} \qquad (13)$$

In fact this expression is difficult to deal with analytically but presents no problems numerically and can be made to fit observed pulse shapes by suitable selection of the constants $\hat{F}$, T and α. It does assume symmetry about the time t=T/2 and thus may be found too restrictive for very lossy surfaces such as carpeting.

Considering the spectra of the three impulses of equal area and duration but of different shape illustrated in Figure 2, it may be observed that at frequencies below 1/2T, the band levels are dependent on the pulse area but not on the shape. However, at frequencies above 1/2T, it is the shape which is all-important. This may not be very significant for a hammer striking a hard concrete surface but if there is a resilient floor-covering then, for any useful calculations to be made, it is clearly essential for the pulse shape to be known reasonably accurately.

In order to obtain the force-time history of hammer blows on various surfaces a special hammer was made for the B & K tapping machine that contains an accelerometer. The idea is that the hammer is essentially a rigid body and the force it imparts is equal to its mass times its acceleration. The system does not operate down to D.C. but cuts off at about 2 Hz. This means that the normal acceleration existing when the hammer is not in contact with the floor is not measured but the error is small because the accelerations incurred during impact are relatively large. For example the peak acceleration is of the order of 800g when the hammer strikes concrete and of the order of 40g when it strikes carpet.

Such high accelerations, coupled with an accelerometer sensitivity of about 50m V/g, produce voltages that are too large for the pre-amplifiers to cope with, an unusual measurement difficulty. The problem is easily resolved by putting a capacitance in parallel with the piezo-electric accelerometer. A .02 μF capacitor effectively reduced the sensitivity to 2.4 mV/g. The sensitivity can be checked by dynamically calibrating the hammer with its associated electronics on a controlled shaker table.

The simplest way of observing the pulse is to photograph an oscilloscope screen. Typical pulses obtained by dropping the hammer from the standard height of 40 mm onto 5 different surfaces are shown in Figures 3(1) to (5). Generally there is a tendency for the hammer to bounce, more so on the bare concrete than on the resilient coverings. The time between bounces may be observed by using a much slower time base on the oscilloscope. This may be used to calculate the rebound velocity of the hammer and hence the coefficient of restitution k, if it is assumed that the strike velocity is 0.89 ms^{-1}. Alternatively, k may be calculated from the area under the initial impulse. The coefficients calculated by both methods are listed in Table I.

The value of k for concrete is consistent with both methods but the discrepancies for the resilient surfaces are inexplicable. Visual observation suggests that the true value is somewhere between the two measured values but there is clearly room for improvement here.

Attempts to analyse the impulses into 1/3-octave band spectra using conventional analogue equipment failed because the duration of each pulse is so short. Consideration was given to tape loop recording techniques to increase the mark-space ratios but, apart from technical difficulties, harmonics of the pulse repetition frequency would be introduced which should not in reality be present. Altogether the problem seemed more suited to digital than analogue methods.

An SDS 920 computer (in Building M3 at NRC) with analogue peripheral equipment, although not ideal because of its slow speed, can be used for analogue to digital conversion of pulses and subsequent computation of their 1/3-octave band spectra. The fastest practicable sampling rate for the conversion is 250 samples/second. In order to obtain sufficient samples of the shortest pulses, the magnetic tape recordings were slowed down by a factor of 128. Four pulses on each of the five surfaces were analysed and the mean force spectra are shown in Figure 4. Disadvantages of the method were that the process was very tedious, the first part of the pulse was always missed because of triggering difficulties, and sampling errors led to distortions of the pulse shape that do not affect the low frequency spectral content but probably do affect the high frequency content. It has already been pointed out that the precise pulse shape is very important if the band levels at frequencies above the peak in the spectrum are to be correct.

After experiencing the difficulties of analogue to digital conversion, it seemed worthwhile investigating other methods. One obvious method is to fit an equation to the pulse and then carry out the calculations. The equation selected in this study is Equation 13, which is illustrated in Figure 5. There is no theoretical justification for this equation and possibly a better one could be found. Certainly its chief disadvantage must be that it assumes symmetry while Figures 3(4) and 3(5) indicate that the pulse shape for carpet is asymmetrical.

Values for $\hat{F}$, T and α for each of the five surfaces were determined from the visual inspection of polaroid photographs and each set is based on the mean of four pulses. These values are summarized in Table II.

These impulses have been transformed and integrated to give the force band levels, which are shown in Figure 6. In fact these spectra are very similar to those obtained by the analogue to digital conversion method (Figures 4 and 6) and the method of representing the pulses by a reasonably accurate equation seems to be quite satisfactory.

2.4 Damping in the Concrete Floor Slab

Initially, attempts were made to measure the decaying response of the floor slab to impact excitation but, while it was easy to excite the fundamental resonance at 40 Hz, it was difficult to obtain a measurable decay at higher frequencies. A more successful method was to excite the floor in a particular frequency band by means of a Goodmans V50 Vibrator and then to measure the decaying signal from an accelerometer fixed to the floor when the excitation was stopped. The method is exactly analogous to measuring the reverberation time of a room except that the reverberation times of the floor are very short, particularly at high frequencies, and the B and K Level Recorder is only just able to cope. The reverberation times of the floor were measured in octave bands at the standard centre frequencies varying from 31 to 4000 Hz. The vibrator simply rested on the floor and the coil was loaded with a 1 kg mass to provide some reactance.

The damping of the floor is described by the loss factor, y, where

$$y = \frac{\text{energy dissipated per cycle}}{2\pi \times \text{peak energy stored during the cycle}}$$

$$= \frac{2.2}{f\ T^1} \qquad (14)$$

where T^1 is the reverberation time of the floor, defined as the time taken for the energy to decay by 60 dB, and f is the frequency at which T^1 is measured.

The results are summarized in Table III.

2.5 Transfer Function of Concrete Slab

The transfer function of the floor is defined as the ratio of the radiated sound power to the mean square input force

i.e.,
$$G = \frac{W}{F^2 N} = \frac{R}{Zy\, 2\pi f\, M} \tag{15}$$

The supposition is that G is independent of the floor covering, the effect of which is contained in the force spectrum.

Although G can be broken down into smaller parts, e.g., the radiation factor R and the velocity response of the floor can both be considered separately, from the experimental point of view it may be more useful to measure the transfer function directly.

The force spectrum is already available from Section 2.3 (p. 7). The radiated sound power may be obtained by conducting a normal impact test on the floor using the tapping machine which gives 10 impacts/second. Ordinarily the sound level is measured in 1/3-octave bands and corrected to that which it would be if there were 10 m^2 of absorption in the reverberation room. The reverberant sound level is derived from Eq. 2, substituting ρc = 410 $N \cdot s/m^2$ and A = 10 m^2, viz.

$$\frac{\overline{p}^2}{410} = \frac{4W}{10} \tag{16}$$

Expressing sound pressure and sound power as levels relative to 2 x 10^{-5} N/m^2 and 10^{-12} watts, respectively,

$$\left(\frac{\overline{p}}{2 \times 10^{-5}}\right)^2 = \frac{W}{10^{-12}} \times 0.410 \tag{17}$$

$$\therefore \quad \text{ISPL} = \text{PWL} - 4 \text{ dB} \tag{18}$$

where ISPL is the impact sound pressure level normalised to

10 m^2 of absorption

and PWL is the power level re 10^{-12} watts.

Now

$$\frac{G}{10^{-12}} = \frac{W}{10^{-12}} \cdot \frac{1}{F^2 N} \tag{19}$$

$$\begin{aligned} \therefore \quad 10 \log_{10} \left(\frac{G}{10^{-12}} \right) &= \text{PWL} - 20\log_{10} F - 10 \log_{10} N \\ &= \text{ISPL} - \text{FL} - 6 \text{ dB} \end{aligned} \tag{20}$$

The bare concrete floor is to be used as the standard or reference floor and its impact sound pressure levels are shown in Figure 7. The corresponding transfer function, using the force spectrum given in Figure 6, is shown in Figure 8.

At frequencies above 200 Hz (above the critical frequency) it may be assumed that the radiation factor, R, is simply equal to the characteristic inpedance of air, ρc. At these frequencies it may also be assumed that $Z = 8\sqrt{MB}$. The damping has been measured, so a theoretical value for G may be obtained in the frequency range 250 to 4000 Hz. This also is shown in Figure 8 and lies about 3 dB above the measured value.

To investigate this discrepancy further, the velocity response of the bare concrete floor was measured when it was excited by the hammer machine in the usual manner. The velocity was obtained by integrating the acceleration measured on the underside of the slab. The velocity distribution across the surface was uneven and altogether measurements were made at 13 locations in order to obtain a reasonably good mean value. The four positions recommended in the standard impact test (1) were used for the tapping machine. The velocity spectrum is shown in Figure 9 together with the theoretical spectrum obtained from the force levels in Figure 6. There is good agreement at the higher frequencies and better agreement than might have been expected at the lower frequencies where individual resonances should predominate in the response. The radiation factor R may be obtained from the measured velocity levels and impact sound pressure levels. This is shown in Figure 10 together with the high frequency theoretical value of ρc. From 315 to 2500 Hz the measured radiation factor is consistently low by about 3 dB and so it appears that the discrepancy between the measured and theoretical values of the transfer function is in the radiation term.

2.6 Impact Sound Pressure Levels

Impact tests on the bare concrete floor and on the same concrete floor with the four different resilient coverings were carried out in the normal way. The four recommended positions for the tapping machine were used together with three microphone positions. The vanes in the room were rotated during measurement. The standard deviation was generally of the order of 2 to 3 dB below 200 Hz and less than 2 dB above 200 Hz except at 50 Hz where the standard deviation was 10 dB on one occasion. Measurement of levels below 100 Hz did present difficulties and really more than three microphone positions should be used. Difficulties were also experienced in measuring reverberation times at these low frequencies and it is even doubtful whether reverberation time has much real meaning for this region. Some sort of correction has to be made however to a standard room absorption of 10 m^2. The recommendations only suggest that measurements should be made down to 50 Hz, but this was extended down to 31 Hz in these tests because it is possible that there is a comparatively large amount of radiated sound energy at low frequencies, particularly around 40 Hz, when a carpet covers the floor. This is accentuated more by footsteps than hammers and may make an important contribution to the subjective evaluation of floors under footstep excitation.

All of the measured levels have been normalized to 10 m^2 of room absorption and are shown in Figure 7 and 11 to 14. Also shown are the IIC ratings and the straight line ratings using the same method of determination as IIC, that is a total adverse deviation not exceeding 32 dB or a single adverse deviation not exceeding 8 dB in the frequency range 100 to 3150 Hz.

Also shown in Figures 11 to 14 are the calculated levels based on the force spectra from Figure 6 and the transfer function from Figure 8. The agreement between the measured and theoretical spectra for the two vinyl coverings is remarkably good and is still acceptable for the two carpets. Some variation is to be expected at frequencies below 100 Hz because of the difficulties in measuring the sound pressure levels in a room of only 65 m^3 volume, and at frequencies above the peak in the force spectrum the calculated values are consistently below the measured values, presumably because of the shape of the measured force impulse not being sufficiently well defined.

In terms of IIC or straight line ratings the agreement is quite good and these results do show what can be achieved in terms of predicting the impact levels by knowing the floor transfer function and measuring the force spectrum on, perhaps, just a small sample of resilient covering using an instrumented hammer with no acoustic facilities at all. Such an approach could be useful for initial screening of several types of floor covering or even quality control in the same way that a small impedance tube is used for screening or control of acoustically absorbent materials.

3. SUBJECTIVE STUDY

3.1 Introduction

Earlier attempts to rate floors subjectively have indicated that one of the most convenient and meaningful methods is to ask subjects to adjust the level of a masking noise until the impact noise to which they are exposed is no longer intrusive. To many subjects "no longer intrusive" appears to mean inaudible, but, in subjective work, the terminology can rarely be so explicit as to mean the same thing to everybody. The problem here is the old chestnut of differentiating between loudness and annoyance. Several papers have been written on the loudness of impact noises and the general conclusion is that the mean audible energy content is the significant parameter. In terms of annoyance, however, other parameters are significant such as the location and occupation of the subject and the peak levels of the noise which may only occur for a short period about the time of the impact. In a subjective test procedure little can be done about the circumstances of the subject because the situation is almost always going to be artificial. On the other hand, the objective parameters of the noise may be varied and certainly it would be useful to learn a little more about their significance.

In this study it will be assumed that asking a subject to adjust the level of a masking noise until the impact noise is no longer intrusive is a meaningful way of obtaining a subjective parametric measure of the impact noise. Correlation between this subjective measure and various objective parameters will then be sought in an attempt to define the basis on which the subjective judgements are made.

In particular it seems quite possible that the judgement is based on the peak rather than on the mean audible energy levels. If this is so, it means that the room conditions may have to be carefully controlled since reverberation time affects peak levels much less than mean energy levels.

As a trial study, in order to check on the room effect, recordings of footstep noise were made in the reverberation room both in its usual condition with a reverberation time of 2 to 4 seconds and with several square metres of absorbent material effectively reducing the reverberation time to between 0.5 and 2 seconds, which is more typical of domestic conditions.

3.2 Recording of Footstep Noise

In a reverberant or semi-reverberant room it is impossible to make measurements of sound pressure levels at just one point because of standing wave effects; it is usual to measure at several points and so obtain an average value. In order to reduce the number of measuring points it is also common to have rotating vanes in the room that serve to modify the standing waves. In making recordings of footstep noise the vanes could not be operated because they created too much background noise and it was concluded that the best method for measurement purposes is to survey the room, select a representative position and then correct any levels measured at this position to give the average room value. In these particular tests, the absolute levels were of no significance and so the microphone could be located in any position.

One female, wearing shoes having cork heels with a plastic surface, and five males all wearing shoes with rubber or rubber-tipped heels, were used in the tests. Each walked for approximately one minute on the bare concrete floor while a recording was made. It had been intended that they should also walk on a carpet but the signal level was too low to provide usable recordings. To provide another type of input the tapping machine was modified so that only one hammer would operate at a rate of 2 impacts/second. This machine created far too much noise when operating on the bare concrete but when operating on the carpet it produced levels about 15 dB greater than did the walkers on the bare concrete.

Two separate sets of recordings were made, first with the reverberation room in its usual condition having a reverberation time between 2 and 4 seconds and then with the room deadened by means of 14 4-ft x 2-ft x 2-in. thick glass fibre batts that reduced the reverberation time to between 0.5 and 1 second above 200 Hz and between 1 and 2 seconds below 200 Hz.

3.3 Subjective Evaluation of Impact Noise

Subjective evaluation was carried out in an anechoic room. The reproduction system was of reasonable fidelity and the subject sat approximately 3 m from the loudspeaker. The levels of the impact noises were adjusted to be the same as during the original recording in order that they should be truly representative of footstep noise.

The masking noise was adjusted so that its spectral content followed the NC40 contour from 80 to 8000 Hz. The over-all level of this noise could be changed in 1 dB steps by the subject. The masking noise was added to the impact noise so that it came through the same loudspeaker.

Each subject was given a 1-minute practice run so that he could familiarize himself with the operation of the stepped attenuator box and then he listened to the fourteen different recordings. During each 30-second recording he was asked to adjust the over-all level of the masking noise until the impact noise was just no longer intrusive, to note the attenuator setting and then wait for the next recording. Nine subjects were used. The full set of results is listed in Table IV. The numbers are all in dB re the true NC40 level, e.g., -5 indicates that the subject attenuated the NC40 noise spectrum uniformly by 5 dB to obtain the desired masking level.

Table IV has been included because it gives rise to one or two interesting points. The mean subjective evaluation is the most important feature because this will be used for correlation with the objective parameters. Recordings 1 and 8 were of the tapping machine, which is why the corresponding evaluation is comparatively high. The remainder are of footsteps and yet a range of 9 dB is still required for their evaluation, implying that there is no such thing as a standard or average walker. The standard deviation of the mean is not very meaningful since this partially reflects the fact that different subjects have different standards for judgement. The one thing that the standard deviation does show is that subjects found the first recording particularly difficult to judge, suggesting that one practice run was not enough. The variation of individual judgement is shown in the last but one row which lists the mean deviation from the mean. There is apparently a spread of nearly 7 dB between the least concerned subject (-3.7) and the most concerned (+ 3.1). The standard deviation of any one subject's judgement varies between 0.9 and 2.2 dB.

3.4 Objective Evaluation of Impact Noise

The General Radio Real Time Analyser was used for obtaining the long-term R.M.S. 1/3-octave band spectra of the recordings used for the subjective work. These are shown in Figures 15 to 21. As would be expected, the levels are generally lower in the 'dead' room conditions and, if the walkers walked in exactly the same manner on each occasion, the difference would be a direct function of the two sets of reverberation times.

In addition to obtaining the spectra, the long-term A-weighted R.M.S. levels were also measured because it was felt that this would be a good estimate of the mean audible energy content of the noise.

In reality of course the noise is a series of exponentially decaying pulses with a repetition rate of about 2 per second, as illustrated in Figure 22, (1) and it is interesting to study the variation with time of the mean square value of the signal integrated over a time of about 30 ms.

This particular time is desirable for two reasons: firstly it corresponds approximately to the time constant of the human ear; secondly it is short compared with the impact repetition period but longer than the period of the lowest frequency of interest. If the signal is A-weighted, squared and integrated with a time constant of 30 ms, the variation with time is of the form shown in Figure 22, (2). The peak values will be referred to as the peak R.M.S. A-weighted levels. In practice they were obtained for each recording by passing the weighted squared integrated signal through a logarithmic amplifier and then onto a UV recorder. The mean peak R.M.S. level for each recording is shown together with the long-term R.M.S level in Table V.

Attempts to obtain the peak spectrum by passing the signal through 1/3-octave filters before squaring and integrating were thwarted by filter-ringing which upset the integration time. No immediate solution could be seen for this difficulty and so an indirect method was devised for calculating the peak R.M.S. level in each frequency band from the long-term R.M.S. level and the reverberation time at that frequency.

It is assumed that energy decays exponentially between impulses and that the repetition rate is 2 per second. The situation is depicted in terms of both energy and sound pressure level in Figure 23. The mean energy level is obtained by integrating over 0.5 secs.

i.e.,

$$\overline{E} = \frac{Eo}{0.5} \int_{o}^{0.5} e^{-2\alpha t} \, dt$$

$$= \frac{-Eo}{\alpha} \left(e^{-2\alpha t} \right)_{0}^{0.5}$$

$$= \frac{Eo}{\alpha} \left(1 - e^{-\alpha} \right) \qquad (21)$$

So the ratio of peak mean energy to mean energy is given by

$$\frac{Eo}{\overline{E}} = \frac{\alpha}{1 - e^{-\alpha}} \qquad (22)$$

By definition $\alpha = 6.91/T$ where T is the reverberation time.

The ratio is more usefully expressed in decibels and the difference between the peak R.M.S. level and the long-term R.M.S. level as a function of reverberation time is shown in Figure 24.

The long-term R.M.S. levels obtained from the fourteen recordings used for the subjective work have all been corrected using the above expression to give the peak R.M.S. spectra and these are shown in Figures 25 to 31. It might be hoped that each pair of spectra obtained with the same source but with the two different room conditions would now be almost identical because the peak energy level is almost independent of reverberation time, and there is a fair degree of similarity. The remaining differences reflect measurement errors and the walking inconsistencies of any one person.

It is now necessary to give a single figure value to the spectra for correlation with the subjective evaluations. The NC40 spectrum was chosen for the masking noise and so the obvious course is to compare the spectra with the NC40 contour. This has been done for each of the spectra shown in Figures 15 to 21 and 25 to 31, and the figures quoted in Table VI show the amount in decibels by which the NC40 contour must be uniformly adjusted from its true position in order that no more than three individual 1/3-octave band levels should exceed the contour levels. Three bands are chosen as the criterion because the use of NC contours to define spectra is more commonly applied to octave band spectra and because it was felt that using only one band would be more susceptible to the influence of measurement errors.

3.5 Correlation Between Subjective Evaluation and Objective Parameters.

The subjective evaluations are summarized in Section 3.3. For comparison with the objective A-weighted levels it is more convenient to express the chosen masking level in terms of A-weighted decibels. This is easily done since the NC40 spectrum has a level of 48 dB(A). Thus all the mean subjective judgements are in dB re 48 dB(A).

The subjective evaluation exists, therefore, in terms of the masking level expressed in either dB(A) or the spectrum level re NC40. The objective evaluation is in terms of the long-term R.M.S. levels or the peak R.M.S. levels again expressed in terms of dB(A) or the spectrum level re NC40. Consequently, it is possible to draw four graphs to show the degree of correlation: two between subjective evaluation and the long-term R.M.S. levels and two between the subjective evaluation and the peak R.M.S. levels. This is done in Figures 32 and 33.

It is clear that there is better correlation with the peak levels than with the long-term levels, but it seems to make little difference whether the measurement is in terms of dB(A) or re NC40, except that the regression line for the NC method almost passes through the zero-zero point. This implies that the chosen masking spectrum almost exactly equals the noisier bands of the peak impact spectrum in level thus adding further weight to the argument that the intrusiveness of impact noise is a function of the short-term peak R.M.S. levels rather than the long-term R.M.S. levels.

4. CONCLUSIONS.

The first part of this study shows that, to a close approximation, the effect of a resilient covering can be considered additive to the transfer function of a bare concrete slab. There are some discrepancies, more marked with carpets than with vinyl, and these could be due to the resilient layer changing the over-all damping of the floor. Measurements of this type should obviously be extended to a greater variety of resilient floor coverings and to different basic floor constructions including concrete of different thickness and area. Previous papers have suggested that a resilient layer does give an additive improvement above a certain frequency and, in general, this has been confirmed. A very important point that has emerged from the study of the pulse shape, however, is that the resilient layer can, presumably through its internal lossiness, reduce the amount of rebound and therefore the over-all impulse. This provides a bonus improvement over the whole frequency range. There is clearly a great deal of research that needs to be done into measuring and optimizing the mechanical properties of floor coverings.

The concept of a constant transfer function for a particular floor has only been established in the case of hammer impacts. It should be extended to include other impact sources, notably footsteps, and to do this the footstep has to be carefully measured and analyzed to obtain the force spectrum.

The transfer function itself has one puzzling feature which is that the radiation resistance appears to be some 3 dB less than expected. It is possible that the radiating area is less than the total area although the velocity measurements indicate that the whole slab is moving. Predicting the transfer function for a floor is clearly very difficult particularly at frequencies below the critical frequency where the radiation factor is uncertain and floor resonances tend to be few and far between. This is particularly unfortunate since footsteps, the common impact source, predominantly excite low frequencies.

The second part of the study has shown that, if the masking noise concept is a valid measure for subjectively evaluating the intrusiveness of impact noise, then subjective judgement is based on the short-term peak

R.M.S. levels rather than on the long-term R.M.S. levels. In fact it appears that the masking noise is adjusted so that it is approximately equal in level to the noisier bands of the peak R.M.S. impact noise spectrum. No way has been devised for obtaining this peak R.M.S. spectrum directly because filter-ringing tended to blur the sharpness of the impulsive rise and there is need for a more direct method than has actually been used. Confirmation of the main conclusion should be obtained by repeating the experiment with, say, a variety of floor coverings and perhaps a different floor.

Another important step that is needed is a comparison of the objective ratings of a variety of floors measured by using the tapping machine with their subjective evaluations. This has been done before and has given birth to the concept of the straight line rating but knowledge of the spectral content and the basis of subjective evaluation should make it possible to explain why some floors still do not conform. For example, it may be that very low frequencies are important for footsteps on carpet and discounting all frequencies below 100 Hz for rating purposes simply overlooks this possibility.

REFERENCES

1. Tentative method of laboratory measurement of impact sound transmission through floor ceiling assemblies using the tapping machine. American Society for Testing and Materials, E492-73T.

2. Mariner, T. Technical problems in impact noise testing. Building Research, Jan.-Feb. 1964, p. 53.

3. Olynyk, D. and T.D. Northwood. Assessment of footstep noise through wood-joist and concrete floors. J. Acoust. Soc. Am., Vol. 43, No.4, April 1968, p. 730-733.

4. Olynyk, D. and T.D. Northwood. Subjective judgements of footstep-noise transmission through floors. J. Acoust. Soc. Am., Vol. 38, No. 6, December 1965, p. 1035-1039.

5. Mariner, T. and H.W.W. Hehmann. Impact noise rating of various floors. J. Acoust. Soc. Am., Vol. 41, No. 1, 1967, p. 206-214.

6. Gösele, K. On the control of walking noise. Gesundheits-Ingenieur. Vol. 80, Heft 1, 1959.

7. Sound transmission through floor-ceiling structures. 1. Evolution of new impact test method. Geiger and Hamme Laboratories, Ann Arbor, Michigan. Report No. IBI-1-I, November 1965.

8. Coblentz, A. and R. Josse. A propos des bruits d'impact. Cahiers du Centre Scientifique et Technique du Bâtiment, No. 92, June 1968.

9. Fasold, W. Investigation of the shape of the requirement curve for the impact noise insulation in dwellings. Acustica, Vol. 15, 1965, p. 271-284.

10. Schwirtz, W. A. M. Interpretation of impact sound transmission measurements. Technisch Physische Dienst, T.N.O. - T.H., Delft. Report No. 706. 102. 11-4-67.

11. Lindblad, S. Impact sound characteristics of resilient floor coverings. Division of Building Technology, Lund Institute of Technology, Bulletin 2, Lund, Sweden, 1968.

12. Cremer, L. and J. Gilg. The problem of appropriate test method of impact sound excitation of floors. Acustica, Vol. 23, Heft 2, 1970, p. 53-62.

13. Feasibility study on impact and surface noise. Kodaras Acoustical Laboratories, New York. Report No. KAL. -286-2 (Part 2), March 1966.

14. Josse, R. Study of heavy impacts in the interior of dwellings. A machine simulating real footsteps for acoustic tests of floors. Centre Scientifique et Technique du Bâtiment, Paris, 1 February 1969.

15. The forces applied to the floor by the foot in walking. National Building Studies Research Paper 32, H. M. S. O., London, 1961.

16. Watters, B. G. Impact-noise characteristics of female hard-heeled foot traffic. J. Acoust. Soc. Am., Vol. 37, No. 4, 1965, p. 619-630.

17. Ver, I. L. Impact noise isolation of composite floors. J. Acoust. Soc. Amer., Vol. 50, 1971, p. 1043-1050.

18. Zaborov, V. I. and L. P. Tyumentseva. Allowance for local deformation in the analysis of impact noise insulation. Soviet Physics-Acoustics. Vol. 11, No. 1, July-Sept. 1965, p. 46-49.

19. Zaborov, V. I., G. S. Rosin and L. P. Tyumentseva. Reduction of impact noise by flooring materials. Soviet Physics-Acoustics. Vol. 12, No. 3, Jan.-Mar. 1967, p. 263-265.

TABLE I

COEFFICIENT OF RESTITUTION, k

Surface	Obtained by measuring time between bounces	Obtained from area under impulse
Bare concrete	0.67	0.64
Permapolish vinyl on concrete	0.35	0.09
Permapolish vinyl on 2-mm cork on concrete	0.43	0.22
Green carpet on concrete	0.60	0.13
Rubber-backed carpet on concrete	0.52	0.0

TABLE II

VALUES OF CONSTANTS IN EQUATION 13

Surface	$\hat{F}$	T	α
Bare concrete	4360 N	0.34 ms	0.661
Permapolish vinyl on concrete	800	1.25	0.715
Permapolish vinyl on 2-mm cork on concrete	532	2.05	0.621
Green carpet on concrete	180	7.25	1.55
Rubber-backed carpet on concrete	268	3.85	1.10

TABLE III

DAMPING MEASUREMENTS IN CONCRETE SLABS

Frequency, f.	Mean Value of T'	Loss factor y	yf.
31 Hz	1.42 s	0.050	1.55
63	0.63	0.055	3.49
125	0.44	0.040	5.0
250	0.44	0.020	5.0
500	0.29	0.015	7.6
1000	0.28	0.008	7.9
2000	0.13	0.008	17.0
4000	0.10	0.006	22.0

TABLE IV

NOISE LEVELS (RE NC40) SET BY SUBJECTS TO MASK IMPACTS JUST TO THE NON-INTRUSIVE POINT

	Recording	Subject 1	2	3	4	5	6	7	8	9	Mean subjective evaluation	Standard deviation
'Live' Room	1	0	10	6	2	10	8	16	12	12	8	4.8
	2	- 4	- 4	-1	3	2	-2	2	4	3	0	3.0
	3	- 3	- 4	0	-1	3	0	2	2	2	0	2.3
	4	- 7	- 9	-3	-4	0	-2	-4	-1	1	-3	3.0
	5	-12	-11	-7	-9	-3	-8	-7	-4	-7	-8	2.8
	6	- 5	- 3	-2	-4	0	-3	-2	-1	-1	-2	1.5
	7	-15	-11	-9	-9	-7	-8	-8	-4	-7	-9	2.9
'Dead' Room	8	9		11	6	14	13	11	14	10	11	2.5
	9	- 3		2	-1	1	1	0	3	1	0	1.8
	10	- 6	-10	-3	-9	-3	-4	-5	-2	-3	-5	2.7
	11	- 8	- 7	-4	-8	-3	-4	-6	-3	-6	-5	1.9
	12	-10	- 9	-4	-9	-4	-6	-6	-3	-3	-6	2.6
	13	- 7	- 4	1	-6	0	-3	-3	1	3	-2	3.2
	14	- 8	- 9	-3	-9	-3	-6	-6	-2	-7	-6	2.5
	Mean deviation from the mean	-3.7	-2.7	+0.8	-2.2	+2.4	+0.2	+0.8	+3.1	+1.8		
	Standard deviation	1.7	1.4	1.4	2.2	0.9	1.0	2.2	1.0	1.9		

TABLE V

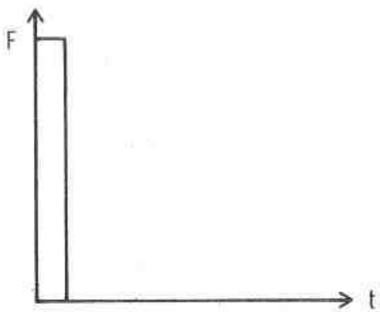
LONG-TERM RMS AND SHORT-TERM PEAK RMS A-WEIGHTED LEVELS MEASURED FOR TEST SIGNALS

	Recording	Long-term RMS	Mean peak RMS
'Live' Room	1	52	56
	2	41	44
	3	38	42
	4	35	39
	5	31	35
	6	36	40
	7	32	35
'Dead' Room	8	44	52
	9	36	42
	10	30	36
	11	30	36
	12	29	37
	13	32	40
	14	29	36

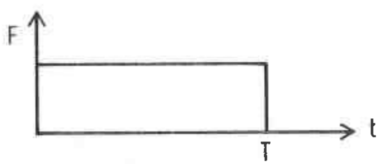
TABLE VI

AMOUNT IN dB BY WHICH THE NC40 CONTOUR MUST BE ADJUSTED TO DESCRIBE THE SPECTRUM

	Recording	Long-term RMS spectra	Peak RMS spectra
'Live' Room	1	9	12
	2	-2	1
	3	-6	-2
	4	-10	-6
	5	-12	-9
	6	-7	-3
	7	-11	-8
'Dead' Room	8	1	10
	9	-9	0
	10	-14	-5
	11	-16	-6
	12	-15	-7
	13	-13	-4
	14	-17	-7

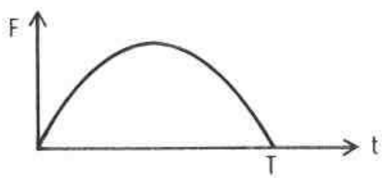


(1) RECTANGULAR PULSE, LARGE FORCE, SHORT DURATION



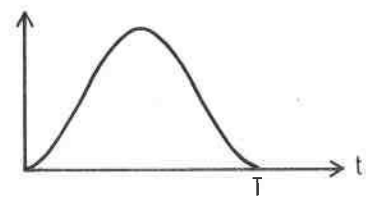
$F = \hat{F} \ (t = 0 \rightarrow T)$

(2) RECTANGULAR PULSE. SMALL FORCE, LONG DURATION



$F = \hat{F} \ \mathrm{SIN} \ \frac{\pi t}{T} \ (t = 0 \rightarrow T)$

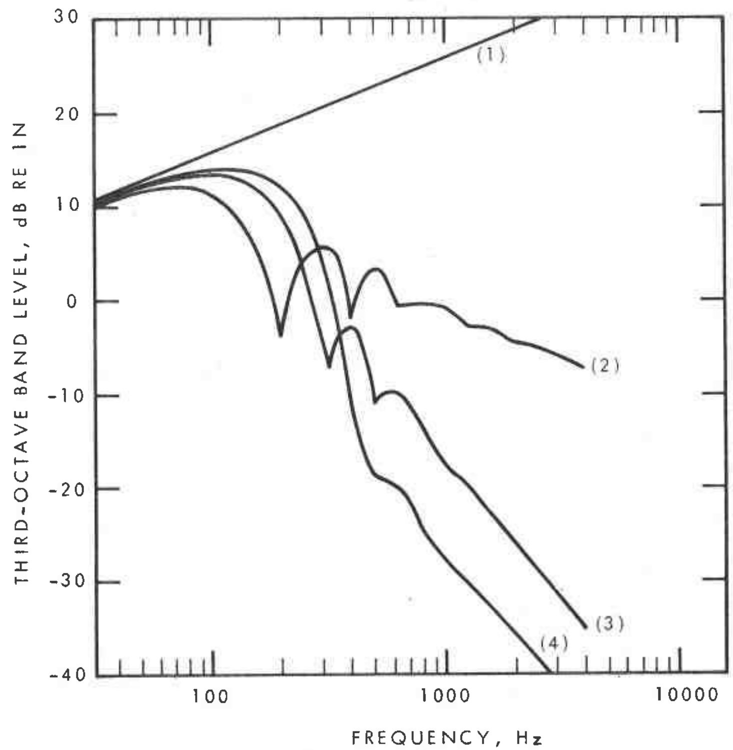
(3) SINUSOIDAL PULSE



$$F = \hat{F} e^{-\alpha \frac{\pi^2}{T^2} \left(t - \frac{T}{2}\right)^2} \mathrm{SIN} \ \frac{\pi t}{T}$$

(4) EXPONENTIAL SINUSOIDAL PULSE

FIGURE 1
THEORETICAL PULSE SHAPES



(1) RECTANGULAR PULSE. LARGE FORCE, SHORT DURATION

(2) RECTANGULAR PULSE. 178N BY 5 MS.

(3) SINUSOIDAL PULSE. 280N PEAK BY 5MS

(4) $e^{-\alpha \frac{\pi^2}{T^2} \left(t - \frac{T}{2}\right)^2} \mathrm{SIN} \ \frac{\pi t}{T}$ 351N PEAK BY 5MS $\alpha = 0.562$

FIGURE 2
FORCE SPECTRA OF HAMMER WITH PERFECT REBOUND
(1 IMPULSE/SEC) FOR VARIOUS THEORETICAL PULSE SHAPES

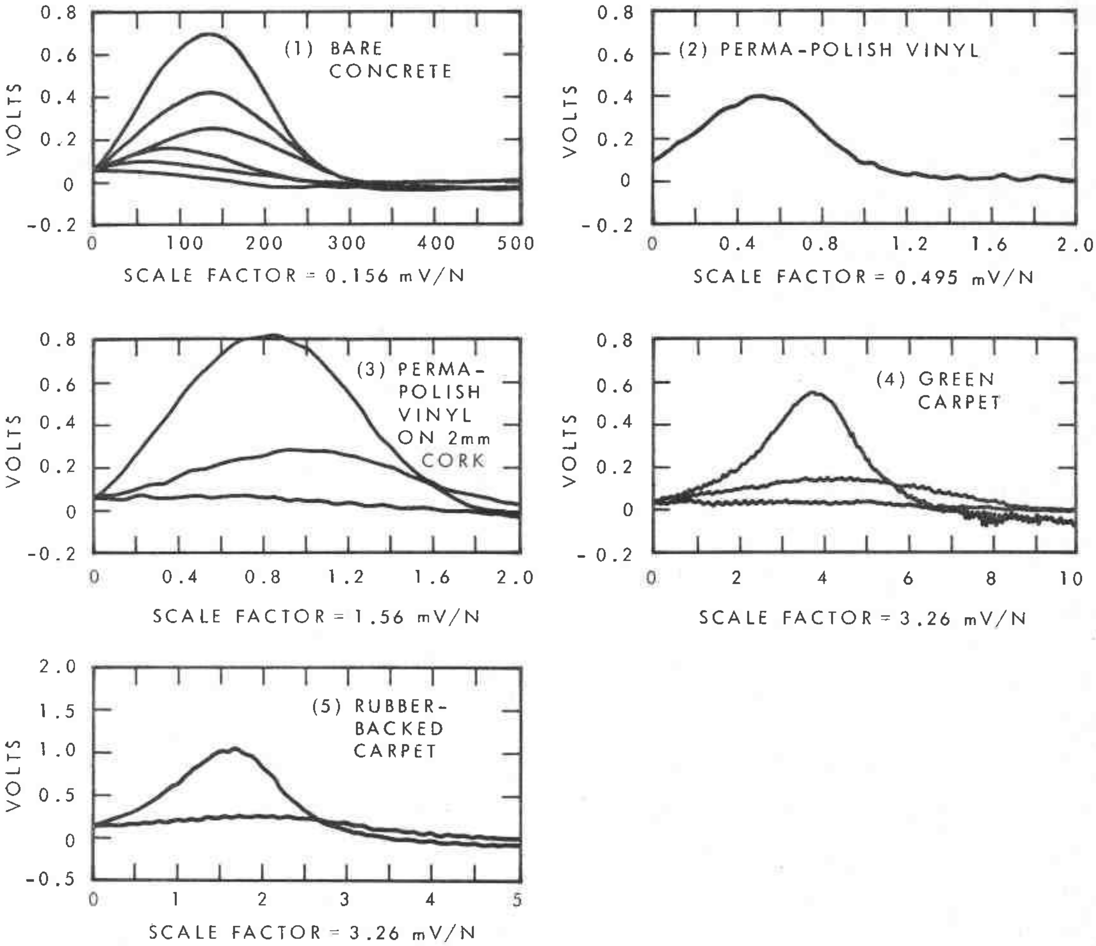


FIGURE 3

HAMMER IMPULSES ON VARIOUS FLOORS

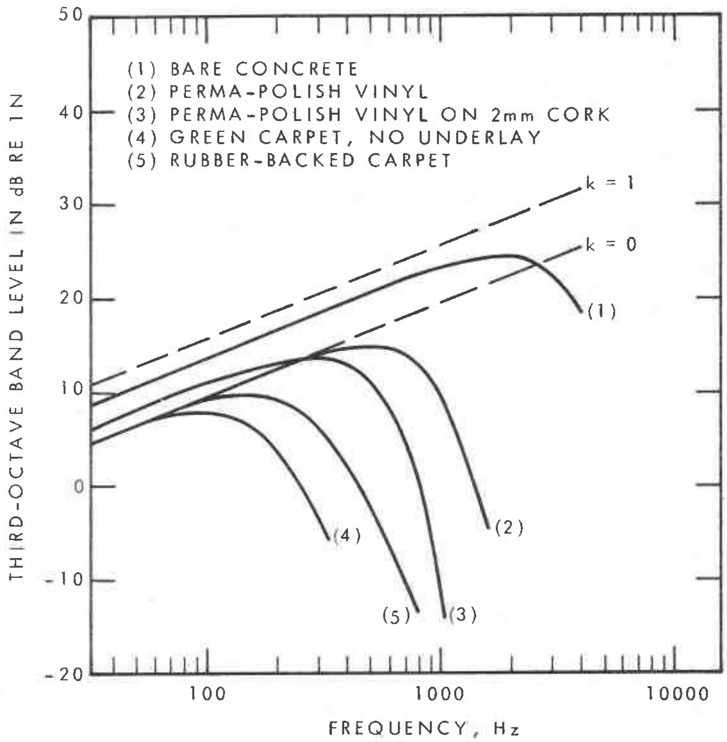
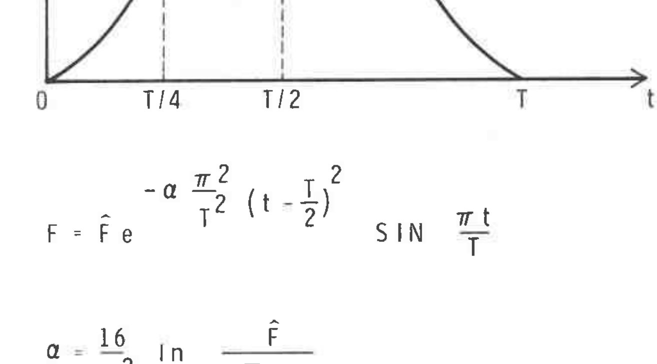


FIGURE 4

HAMMER FORCE SPECTRA (IMPACT/SEC) OBTAINED BY A → D CONVERSION OF PULSES



$$F = \hat{F} e^{-\alpha \frac{\pi^2}{T^2} \left(t - \frac{T}{2}\right)^2} \quad \text{SIN} \quad \frac{\pi t}{T}$$

$$\alpha = \frac{16}{\pi^2} \ \ln \ \frac{\hat{F}}{\sqrt{2} \ F_{\frac{1}{4}}}$$

FIGURE 5

IDEALIZED HAMMER IMPULSE

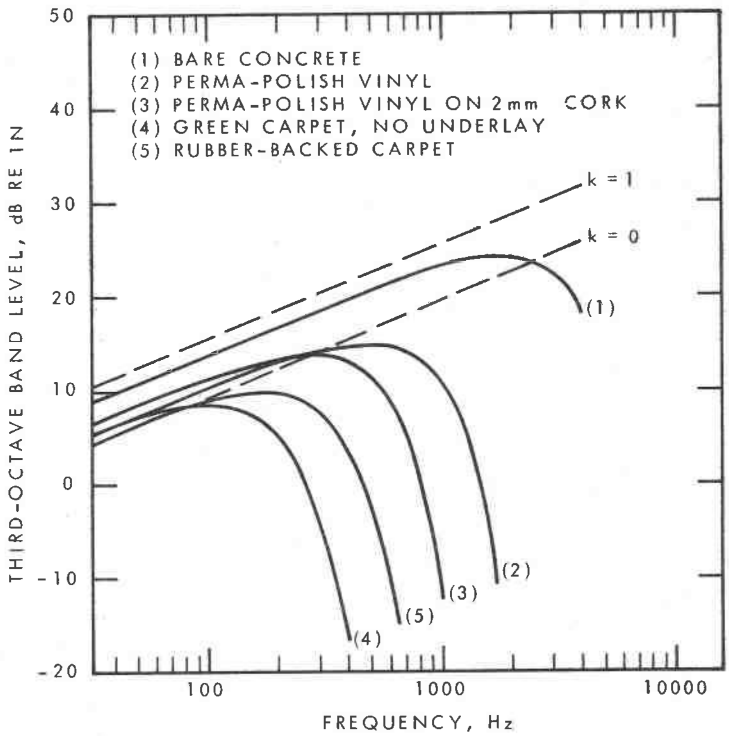


FIGURE 6

HAMMER FORCE SPECTRA (1 IMPACT/SEC) OBTAINED FROM IDEALIZED PULSE SHAPES

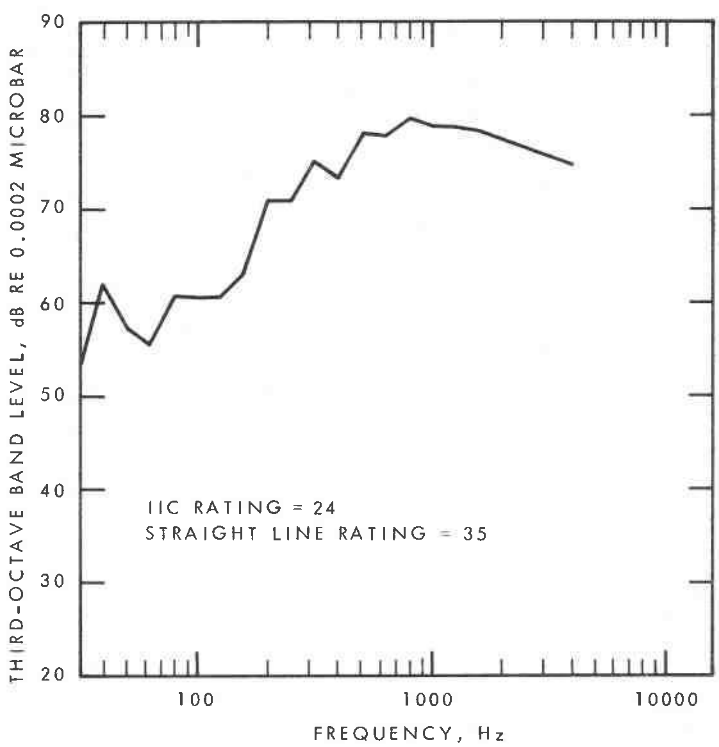


FIGURE 7

IMPACT NOISE LEVELS OF TAPPING MACHINE ON BARE CONCRETE FLOOR NORMALIZED TO 10m² ABSORPTION

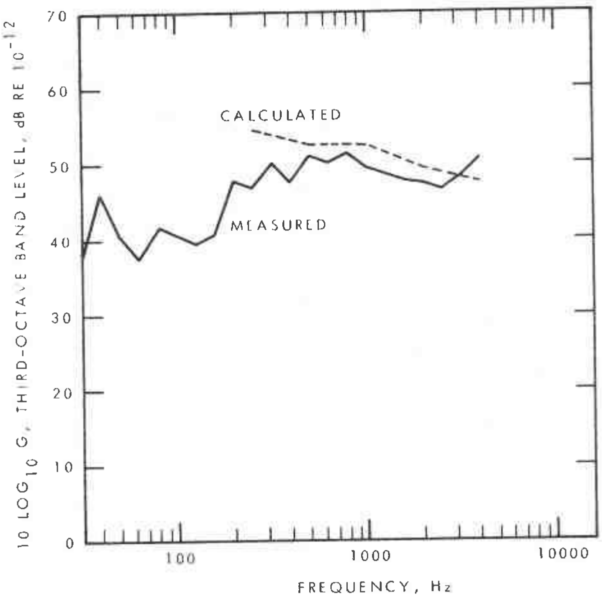


FIGURE 8
TRANSFER FUNCTION OF CONCRETE FLOOR

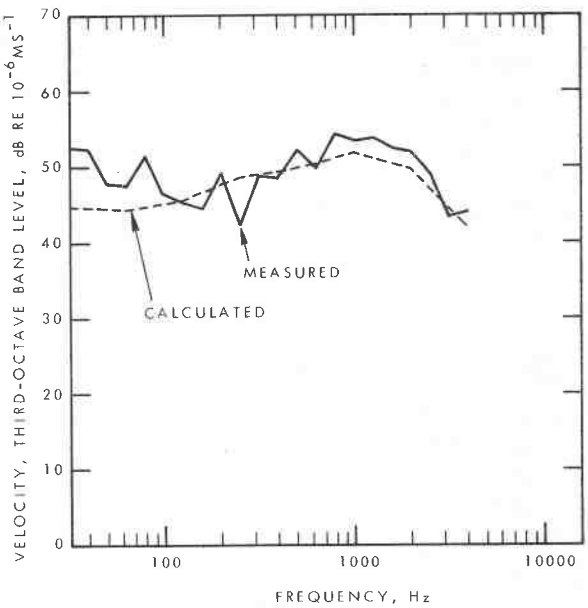


FIGURE 9
VELOCITY OF BARE CONCRETE FLOOR WHEN EXCITED BY THE TAPPING MACHINE

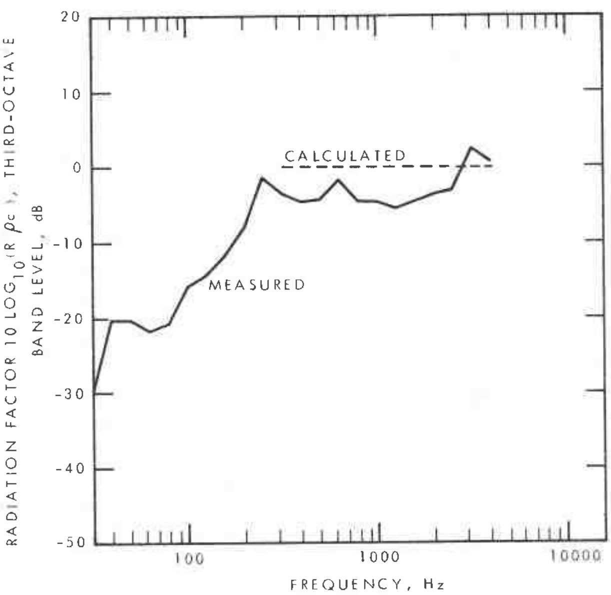


FIGURE 10
RADIATION FACTOR OF CONCRETE FLOOR

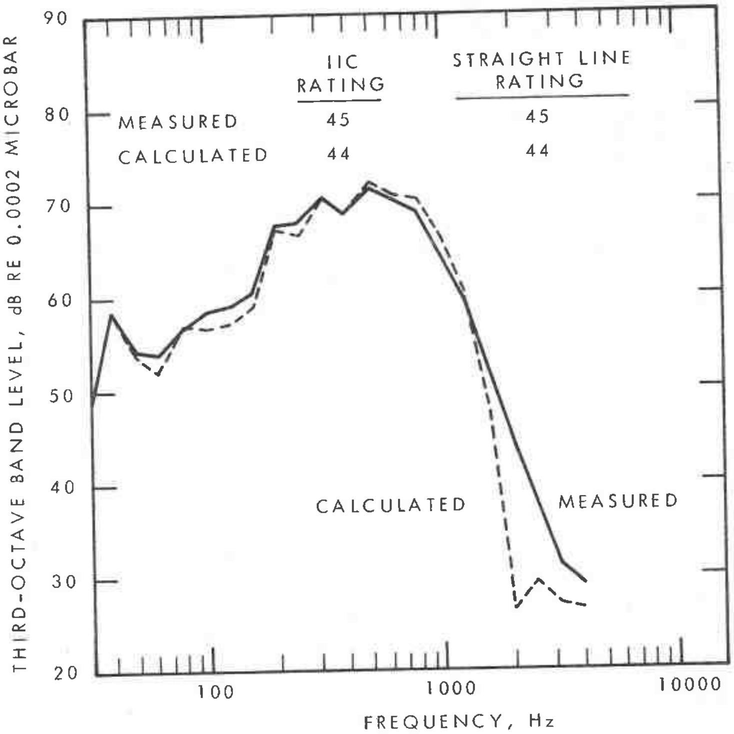


FIGURE 11

IMPACT NOISE LEVELS OF TAPPING MACHINE ON PERMA-POLISH VINYL NORMALIZED TO $10m^2$ ABSORPTION

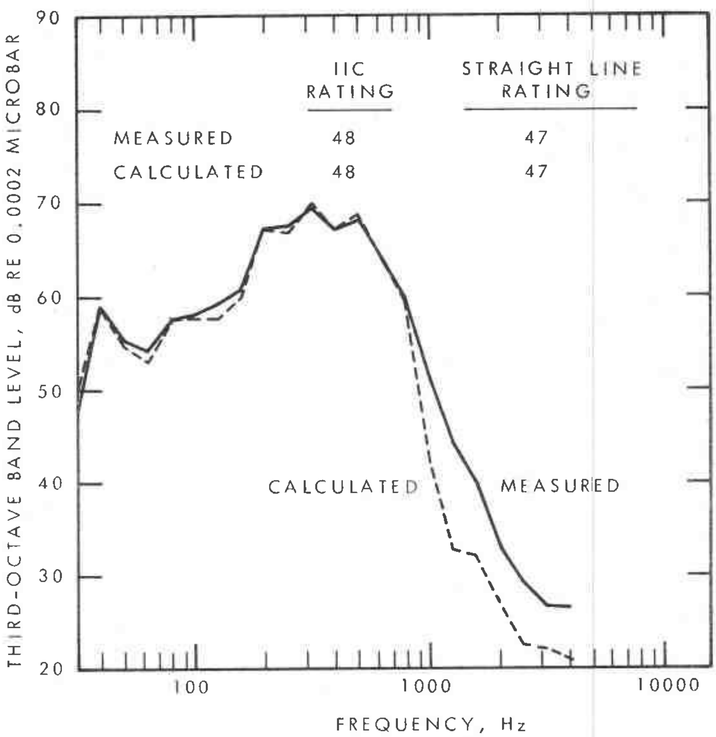


FIGURE 12

IMPACT NOISE LEVELS OF TAPPING MACHINE ON PERMA-POLISH VINYL ON 2MM CORK NORMALIZED TO $10m^2$ ABSORPTION

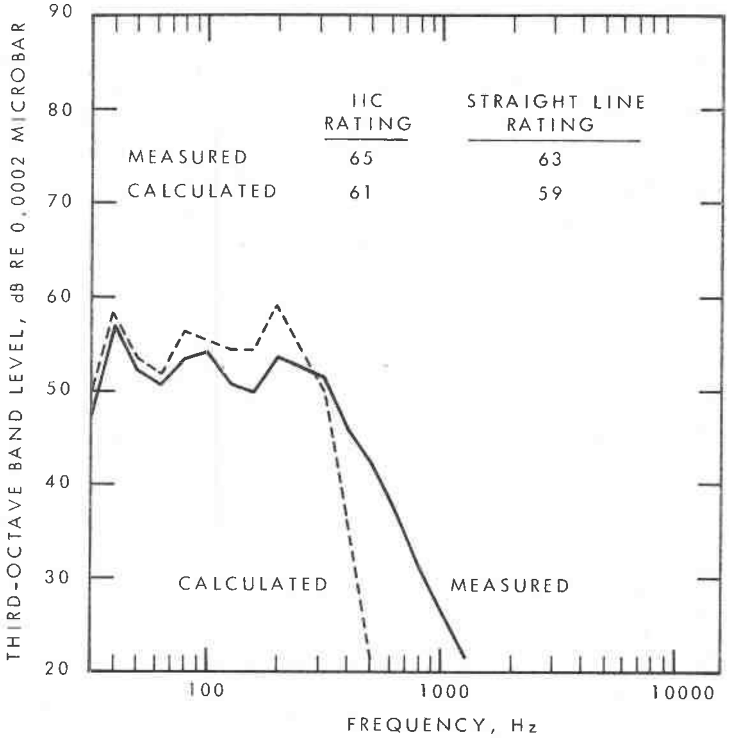


FIGURE 13

IMPACT NOISE LEVELS OF TAPPING MACHINE ON GREEN CARPET NORMALIZED TO $10 m^2$ ABSORPTION

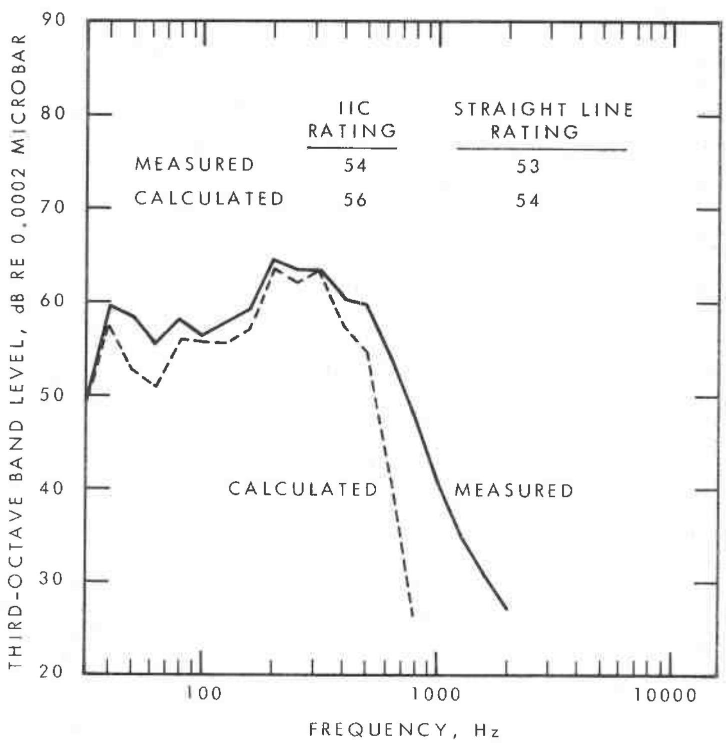


FIGURE 14

IMPACT NOISE LEVELS OF TAPPING MACHINE ON RUBBER-BACKED CARPET NORMALIZED TO $10 m^2$ ABSORPTION

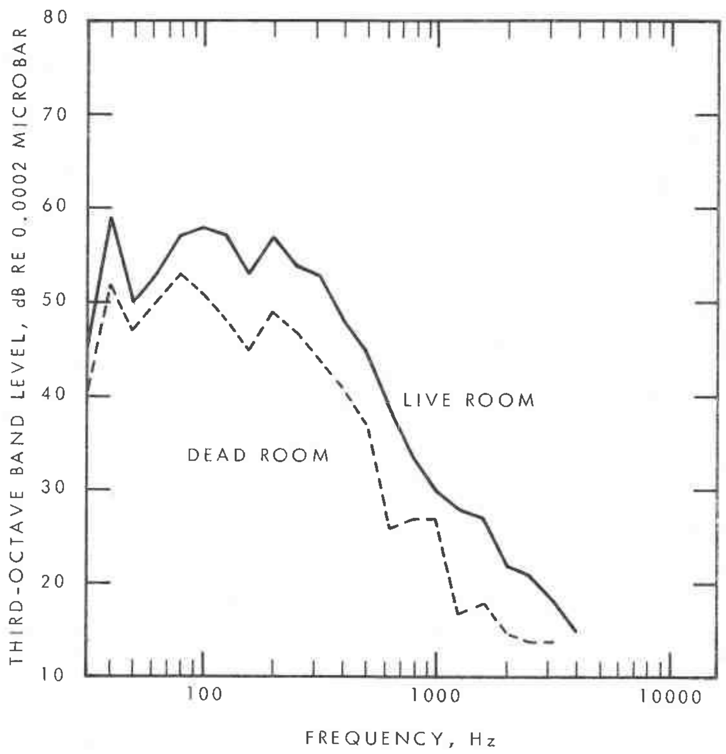


FIGURE 15

TAPPING MACHINE WITH SINGLE HAMMER (2 IMPACTS/SEC) ON GREEN CARPET, LONG TERM RMS LEVELS

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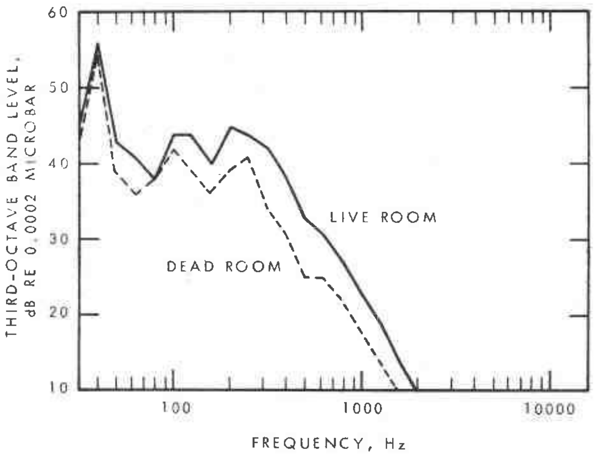


FIGURE 16

WALKER NO. 1 (MALE) ON BARE CONCRETE FLOOR.
LONG TERM RMS LEVELS

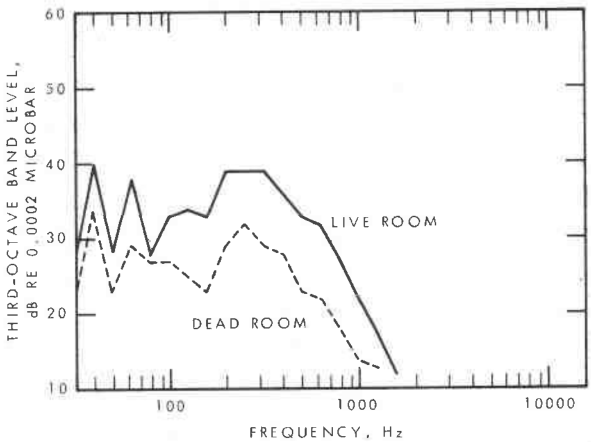


FIGURE 17

WALKER NO. 2 (FEMALE) ON BARE CONCRETE FLOOR.
LONG TERM RMS LEVELS

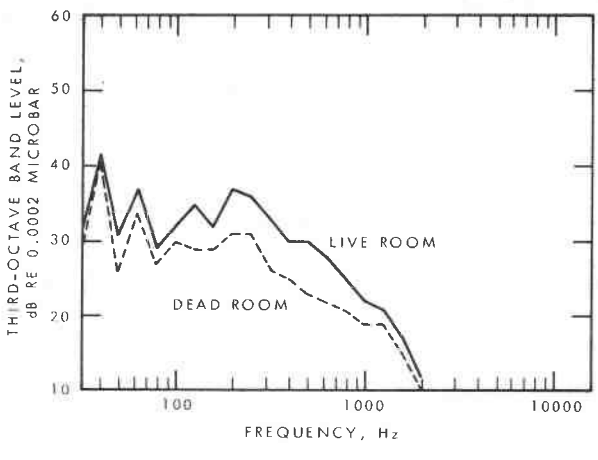


FIGURE 18

WALKER NO. 3 (MALE) ON BARE CONCRETE FLOOR.
LONG TERM RMS LEVELS

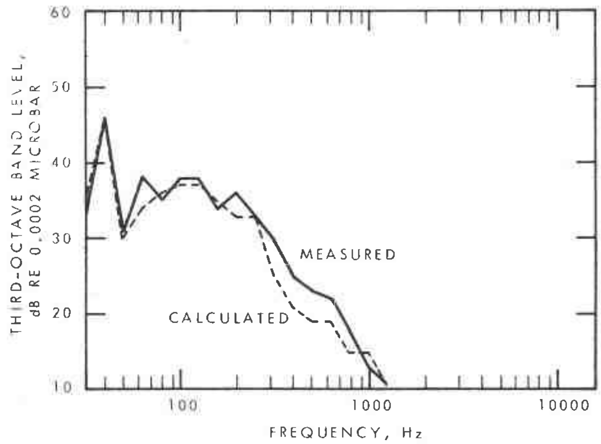


FIGURE 19

WALKER NO. 4 (MALE) ON BARE CONCRETE FLOOR. LONG TERM RMS LEVELS

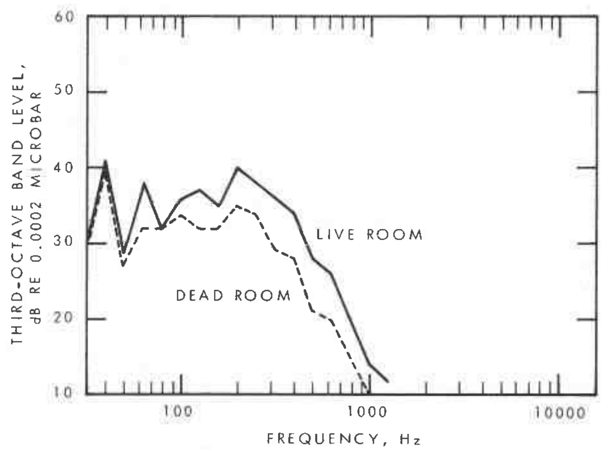


FIGURE 20

WALKER NO. 5 (MALE) ON BARE CONCRETE FLOOR. LONG TERM RMS LEVELS

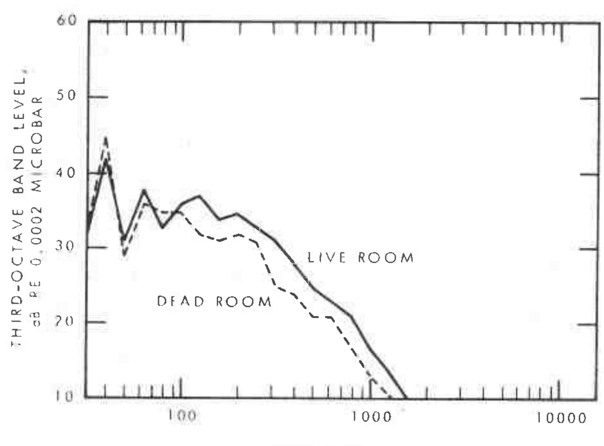
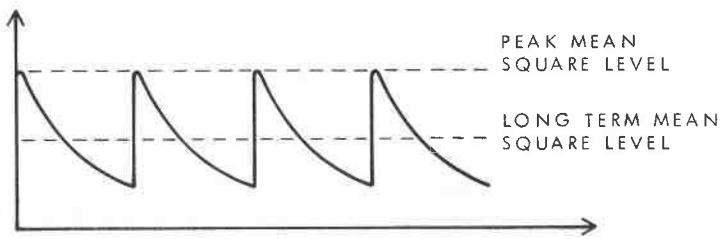


FIGURE 21

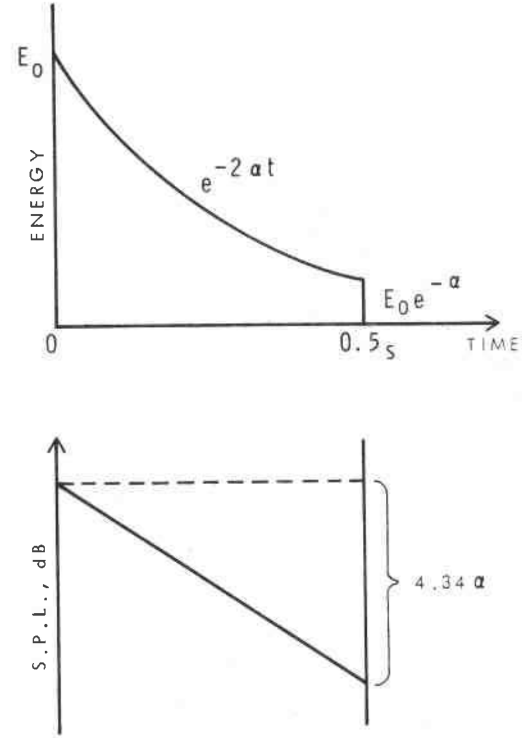
WALKER NO. 6 (MALE) ON BARE CONCRETE FLOOR. LONG TERM RMS LEVELS

(1) PRESSURE WAVEFORM OF IMPACT NOISE



(2) VARIATION OF ENERGY USING A SHORT INTEGRATION TIME

FIGURE 22
TIME VARIATION OF IMPACT NOISE



$\alpha = \frac{6.91}{T}$ WHERE T IS THE REVERBERATION TIME

FIGURE 23
ENERGY DECAY BETWEEN IMPACTS

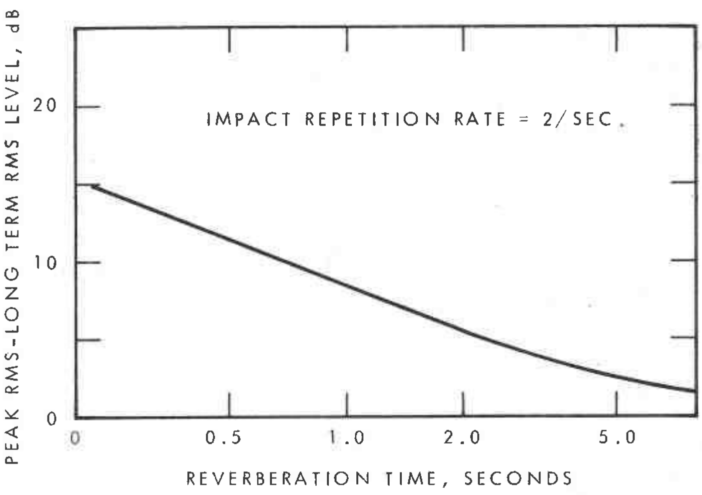


FIGURE 24

DIFFERENCE BETWEEN PEAK AND LONG TERM RMS LEVELS FOR IMPACT NOISE AS A FUNCTION OF REVERBERATION TIME

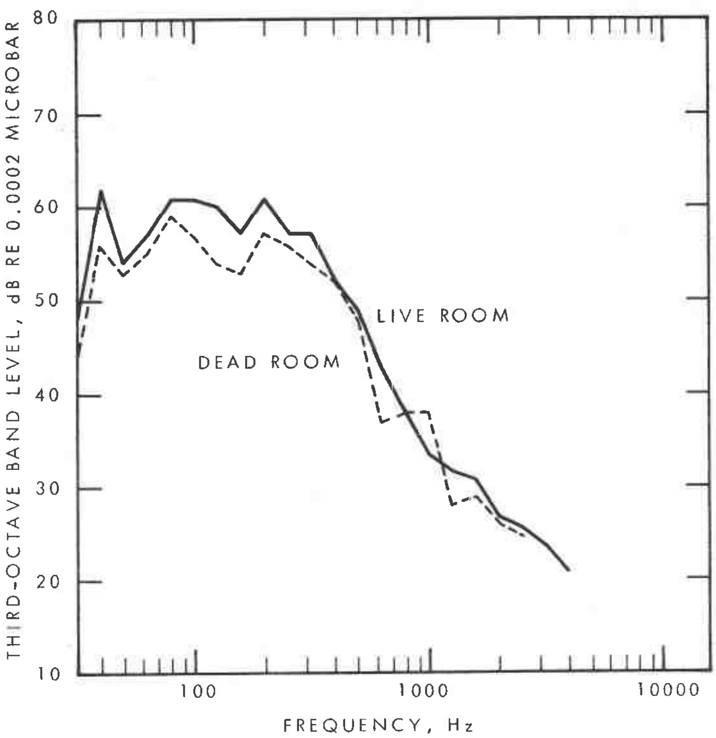


FIGURE 25

TAPPING MACHINE WITH SINGLE HAMMER (2 IMPACT/SEC) ON GREEN CARPET. PEAK RMS LEVELS

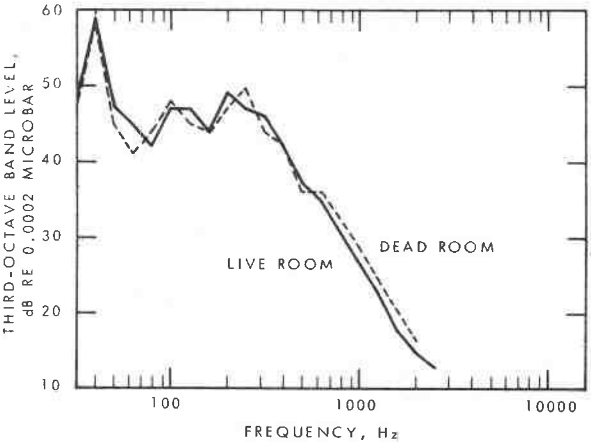


FIGURE 26

WALKER NO. 1 (MALE) ON BARE CONCRETE FLOOR.
PEAK RMS LEVELS

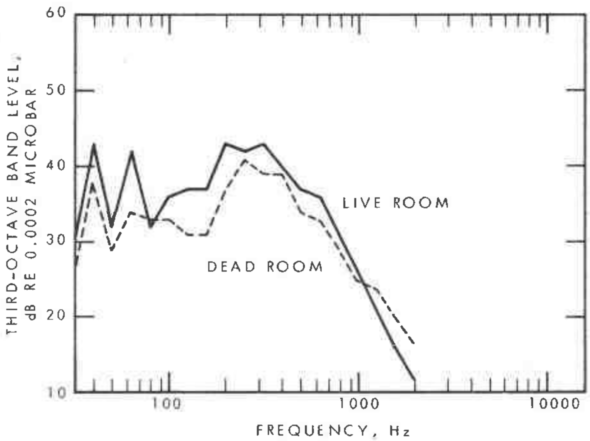


FIGURE 27

WALKER NO. 2 (FEMALE) ON BARE CONCRETE FLOOR
PEAK RMS LEVELS

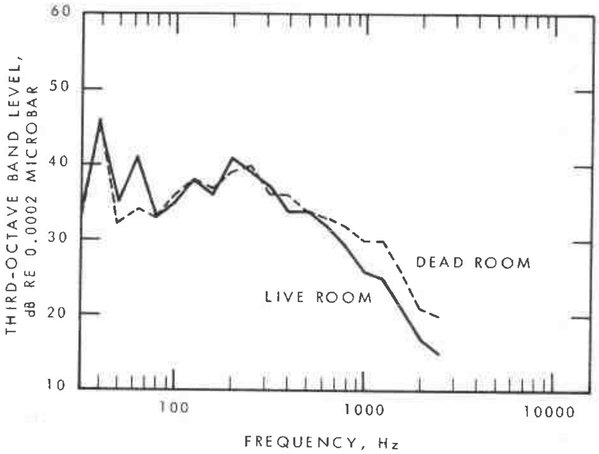


FIGURE 28

WALKER NO. 3 (MALE) ON BARE CONCRETE FLOOR.
PEAK RMS LEVELS

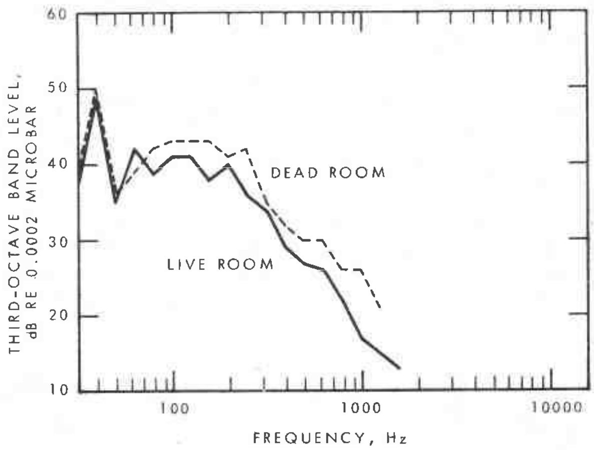


FIGURE 29

WALKER NO. 4 (MALE) ON BARE CONCRETE FLOOR.
PEAK RMS LEVELS

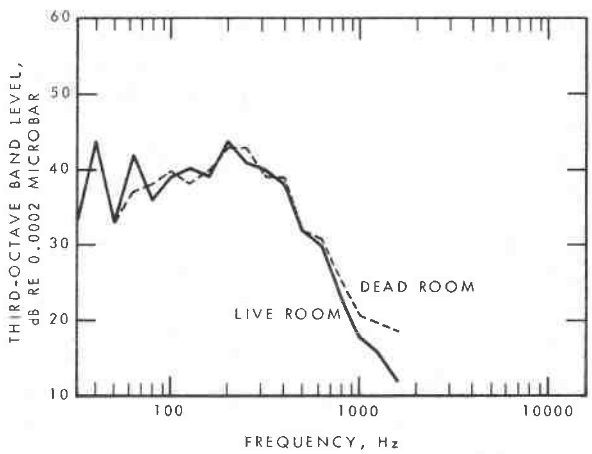


FIGURE 30

WALKER NO. 5 (MALE) ON BARE CONCRETE FLOOR.
PEAK RMS LEVELS

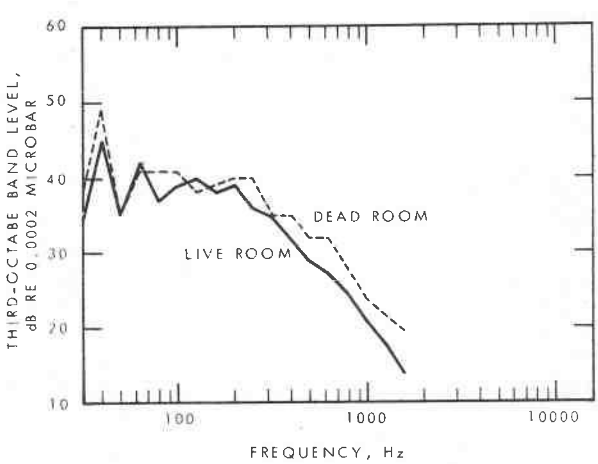


FIGURE 31

WALKER NO. 6 (MALE) ON BARE CONCRETE FLOOR.
PEAK RMS LEVELS

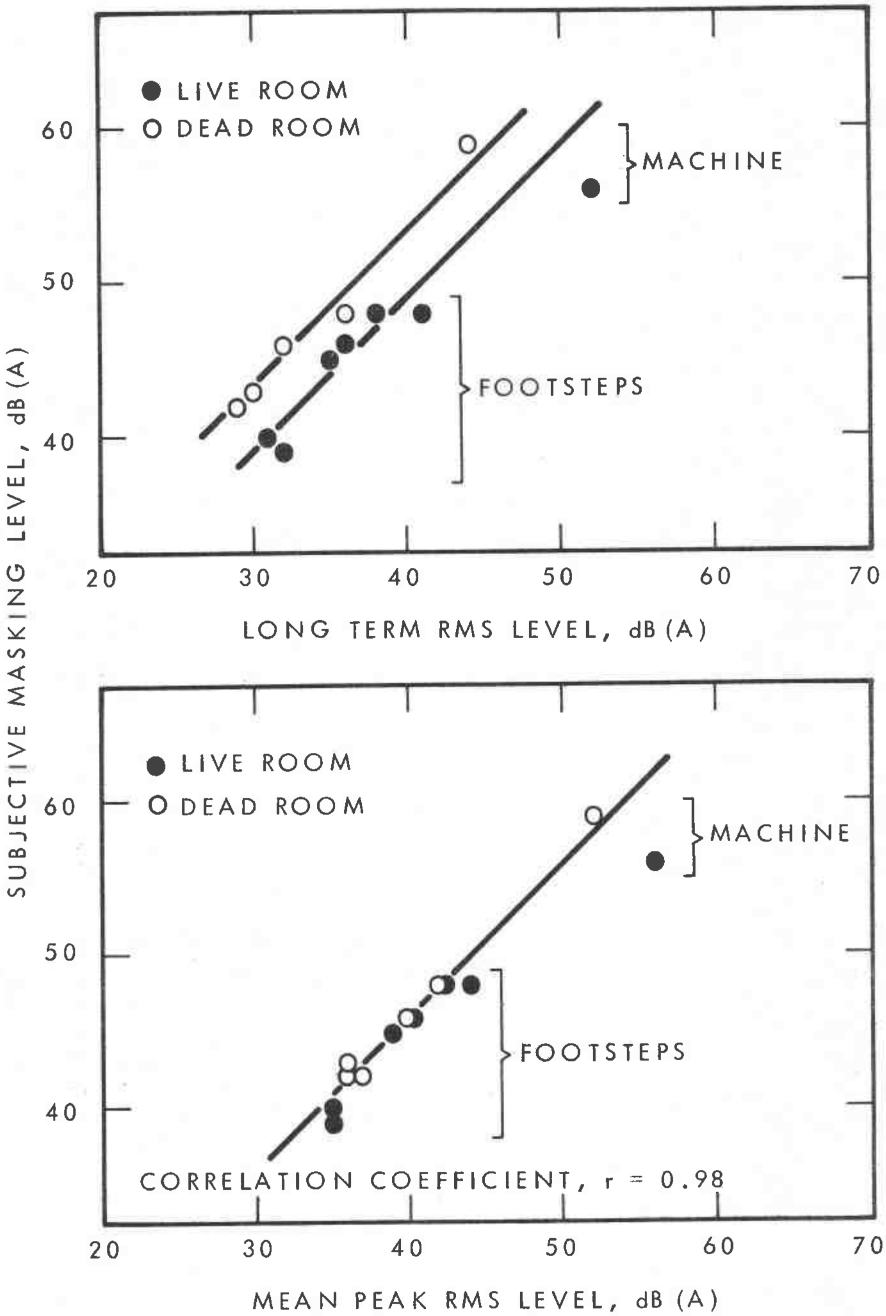


FIGURE 32

CORRELATION BETWEEN SUBJECTIVE EVALUATION AND OBJECTIVE LEVELS IN dB (A)

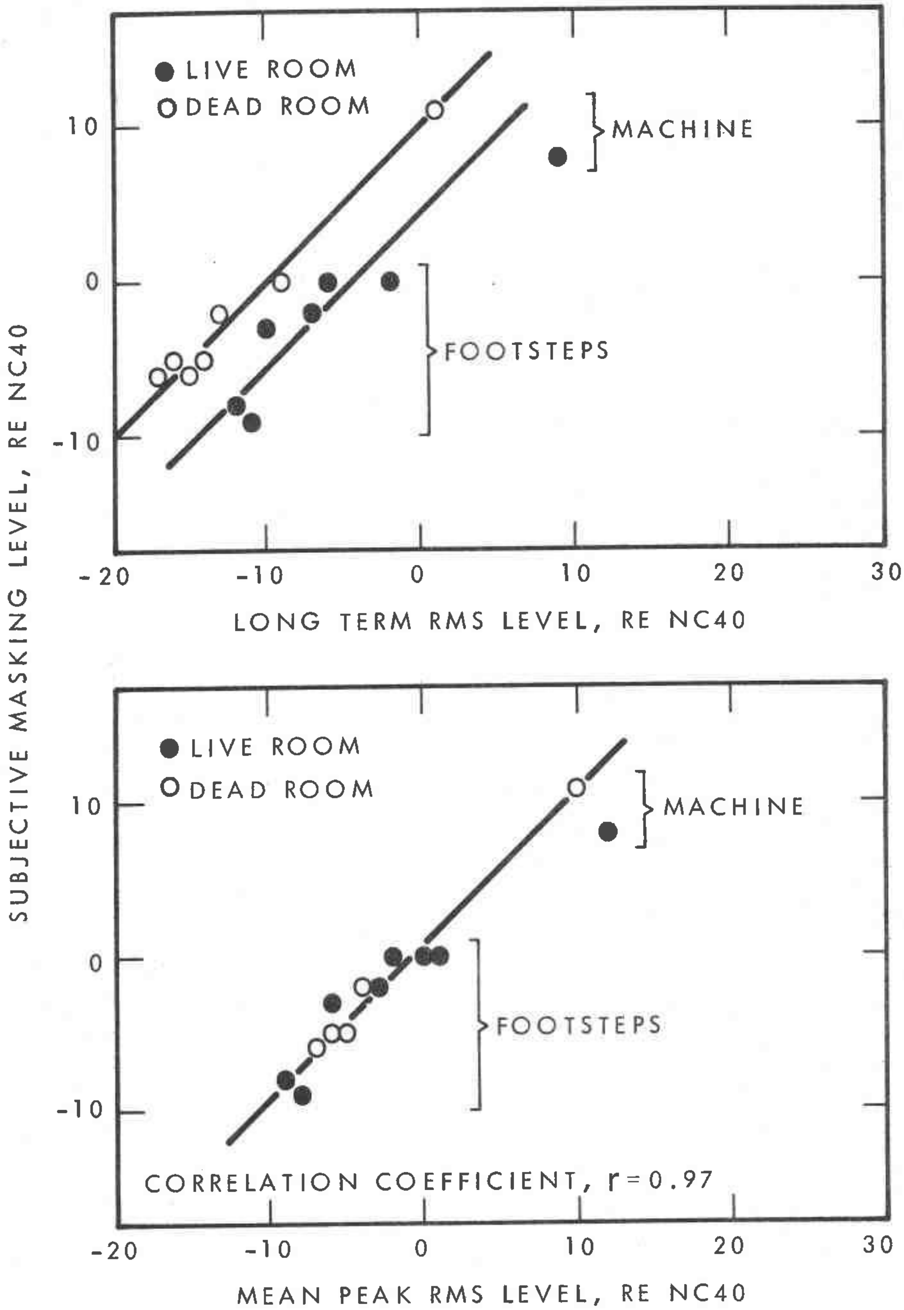


FIGURE 33

CORRELATION BETWEEN SUBJECTIVE EVALUATION AND OBJECTIVE LEVELS RE NC40