Low-Frequency Forces Caused by People: Design Force Models

Charges de basse fréquence produites par les piétons: modèle de charges

Durch Menschen induzierte Lasten mit niedrigen Frequenzen: Lastmodelle

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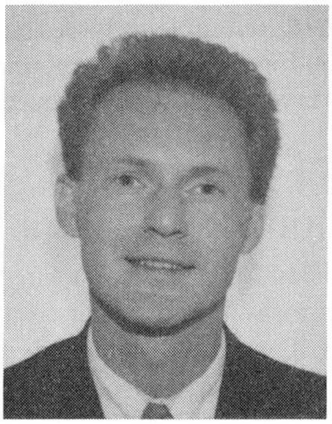

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SUMMARY

The dynamic forces from walking, running and jumping can be divided into two parts: an impulsive part of higher frequencies from the initial contact between the foot and the floor and a continuous excitation of lower frequencies from the successive footsteps. In this paper, models of the latter, low-frequency excitation based on laboratory measurements are presented. One of the options for frequency domain force models is to treat the forces as a sum of harmonic components. Another, better suited for a loading case of less coordinated pedestrian motion is a broad-band model of the force. Both these options are presented and discussed here.

RESUME

Les forces dynamiques résultant de marche, course et saut, peuvent être classées en deux groupes: un cas avec de hautes fréquences, au moment du contact initial du pied avec le plancher, et une excitation continue de fréquences basses pour les pas suivants. Des modèles pour le second groupe, à basses fréquences, ont été élaborés sur la base de mesures en laboratoire. Une des options pour les modèles de charge est de considérer les charges comme somme d'éléments harmoniques. Une autre option, mieux adaptée au cas de charges non coordonnées des piétons est un modèle à large bande. Les deux options sont présentées et discutées.

ZUSAMMENFASSUNG

Die dynamischen Kräfte, die von gehenden, laufenden oder springenden Menschen verursacht sind, können in zwei Teile aufgeteilt werden: Einen Impulsteil, von höheren Frequenzen, der vom initialen Kontakt, zwischen Fuss und Fussboden herrührt, und eine kontinuierliche Erregung niedrigerer Frequenzen von den aufeinanderfolgenden Fussschritten. In diesem Beitrag werden Modelle für die zweite Erregung, mit niedrigeren Frequenzen vorgeschlagen. Diese Modelle basieren auf Labormessungen. Eine von den Möglichkeiten für Kraftmodelle im Frequenzbereich bedeutet, dass man die Kräfte als eine Summe harmonischer Komponenten behandelt. Eine andere, die für einen Lastfall mit weniger koordinierten Fussgängerbewegungen besser geeignet ist, ist ein Breitbandmodell der Kraft. Diese beiden Möglichkeiten werden hier erläutert und diskutiert.

1. INTRODUCTION

Forces from footsteps and jumping have been studied for various reasons ranging from ergonomic considerations to prediction of floor and footbridge vibrations. Only relatively recently have the results, however, been presented in the frequency domain, which is the form most suitable for design purposes. Measurements and a model of the impulsive, high-frequency part of the forces from footsteps were presented in [1]. For low-frequency floors, where the response is dominated by resonances below 8 Hz, the steady-state forces caused by succesive footsteps are, however, most important. The main frequency components of these steady-state forces are found at the step or jump frequency and at integer multiples thereof. These are called the harmonics of the step frequency. There are few reported measurements of the *continuous* forces from walking and running. Those known by the author are [2] (these results are more extensively reported in [3]) and to some extent [4] and [5]. The latter reference does not, however, present any frequency domain models.

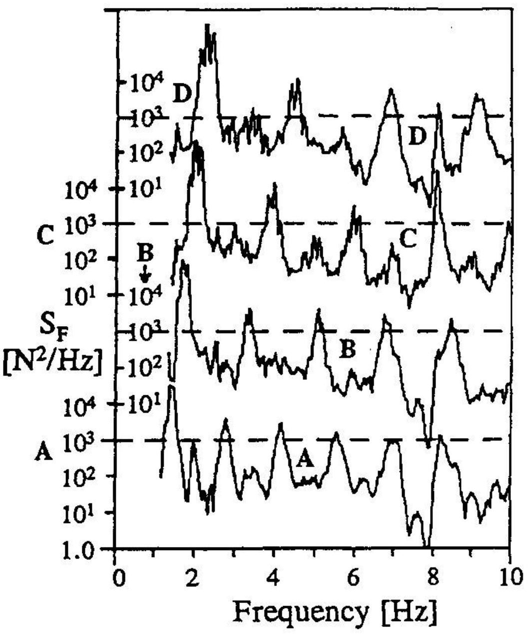
2. EXPERIMENTAL METHOD AND RESULTS

In order to measure the dynamic load from natural walking or running, it is necessary to use a large test floor. The technique used for measuring the force from a single step, i.e. using a "stiff, massless" platform with one (or more) force transducer is apparently not applicable here. The method chosen for this study was to determine the vertical dynamic force *indirectly* from measurements of the response of a floor structure with well-known dynamic properties to excitation from walking, running and jumping. The "semi-static" part of the response, i.e. the frequency range below the first natural frequency of the test floor, was mainly used and the measurement point was selected so that the contributions to the response from all modes except the fundamental mode could be neglected. The measured quantity was the vertical acceleration at midspan.

Measurements were made with different activity frequencies and with a varying number of participants. For the tests with *one subject* the main objective was to study the effect of various footstep frequencies f_s. f_s was kept constant by means of a metronome. All results for a single person, given below, refer to a male person weighing 740 N. Tests with *several walking subjects* were done with the subjects walking in step (1.7 or 2.0 Hz) as well as with each subject using his/her own rate, although all moved with the same speed. The largest group size used was 11 people.

In the test with walking the footstep frequency was varied from 1.3 up to 2.5 Hz in increments of 0.1 Hz. In Fig. 1, the spectral densities of the load from walking at four different step frequencies are given. This figure shows very clearly the peaks at each harmonic of f_s. Also, when comparing the amplitudes of the peaks of the first harmonic, a strong dependence upon the rate of walking is evident. The peaks of the higher harmonics are all of the same order of magnitude but decrease with increasing frequency. Fig. 1 also shows that the peaks at each "harmonic" has a certain width. This means that a description of the force as a sum of harmonic forces at the harmonics of the step frequency is not exactly true. The spread of the force power means that for a lightly damped structure, the fraction of the force input that will actually cause resonant vibration will depend on the damping ratio ζ_n of the structure. This variation with ζ_n may, however, not be as strong as to justify the use of a broad-band force model for the loading case "one person walking". Instead the simpler model consisting of a sum of harmonic components mentioned above may be used.

For groups walking, the test groups consisted of 7 and 11 people respectively and the mean weight of the subjects were 800 and 745 N respectively. Coordinated walking at the step frequencies 1.7 and 2.0 Hz and uncoordinated walking at a leisurely stride as well as at a fast stride was performed. The resulting force spectral density for the group of eleven people at f_s=1.7 Hz as well as at a leisurely stride is shown in Fig. 2. The leisurely stride seems to have corresponded to a mean step frequency of about 1.65 Hz which means that these spectral densities are comparable. As can be seen in Fig. 2 the force spectral density increases strongly with the group size as expected. At uncorrelated walking, the different walking rates within the groups have the effect of smoothing the force spectral density function. This suggests that a broad-band force model is the most appropriate for groups of pedestrians.



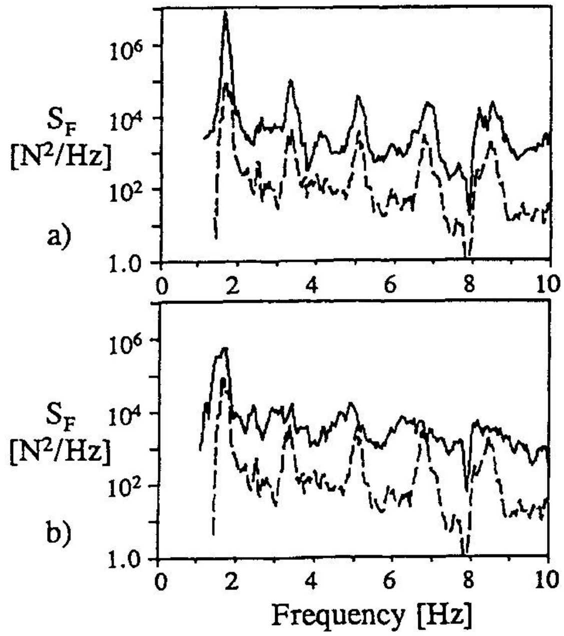


Fig. 1 Spectral densities of the force from one person walking at f_s = : A) 1.4, B) 1.7, C) 2.0 and D) 2.3 Hz respectively.

Fig. 2 The force spectral densities for a group of 11 persons at a) coordinated walking, f_S=1.7 Hz, and b) uncoordinated walking at a leisurely stride. S_F for one person at f_S=1.7 Hz, is shown with a dashed line.

In the test with one person running, the footstep frequency was varied from 2.0 up to 3.0 Hz in increments of 0.2 Hz. The resulting force spectral densities from three different footstep frequencies are shown in Fig. 3a. The shapes of the spectral density functions are very similar to those obtained for walking but their magnitudes are approximately an order higher at the first and second harmonics and somewhat less higher at the third harmonic. The spread of the force power around each harmonic is nearly identical to that for walking (one subject). This means that the same reasoning as previously applied to walking, about what kind of force model to use, will also be valid for the loading case "one person running". No measurements of the forces from groups running have been performed here.

For jumping, the frequency was varied from 1.8 up to 3.2 Hz in increments of 0.2 Hz. The resulting force spectral densities from three different jumping frequencies are shown in Fig. 3b. These are somewhat different in shape as compared to those for walking and running. The main differences are that the peaks at all the harmonics are sharper here and that the second and third harmonic peaks have higher magnitudes relative to that of the first harmonic. Compared to the magnitudes of the the peaks for running, those for jumping are 3-4 times higher at the first, 15-100 times higher at the second and 40-100 times higher at the third harmonic respectively. This means that jumping is a rather severe loading case also in the frequency range above 3 Hz. The sharpness of the peaks means that for jumping the most reasonable force model to use is one based on a sum of harmonic components.

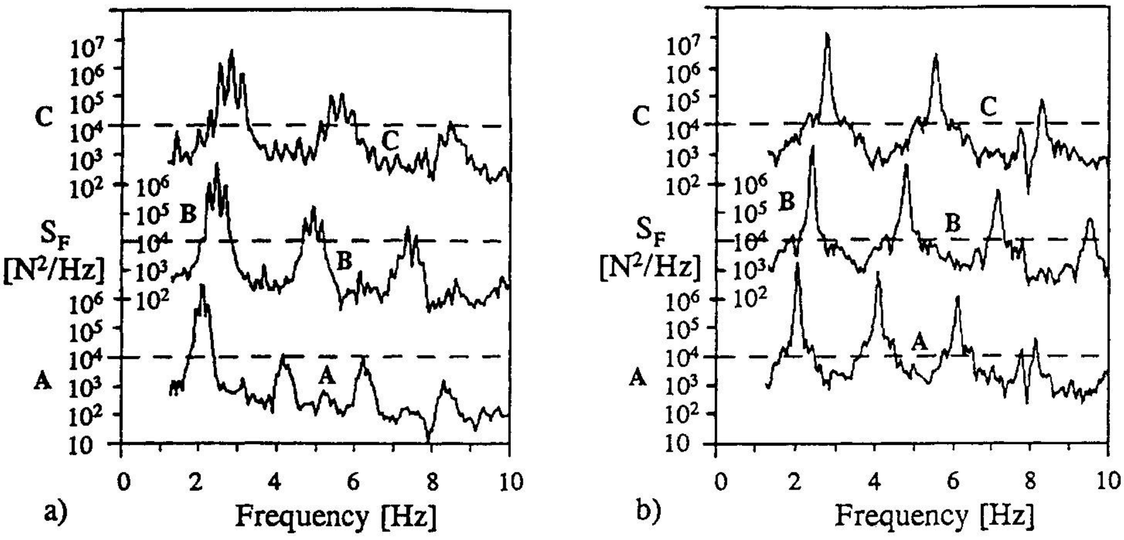


Fig. 3 Spectral densities of the force from one person a) running and b) jumping at f_s = : A) 2.0, B) 2.5 and C) 3.0 Hz respectively.

3. COMPARISON WITH RESULTS FROM THE LITERATURE

Extensive measurement series of the continuous vertical low-frequncy forces from walking, running and jumping have been reported in [3]. The results are given as "dynamic load factors" α_k, i.e. the fourier component at the k:th harmonic of the step frequency, divided by the body weight of the test persons. However, the dependence of the magnitude of the load factors on the frequency band-width they represent is not discussed. The mesurements were performed for different sets of participants, except in some group activities, and the results discussed here are the mean values. The second reference used for comparison is [4], where the forces from individual footsteps at various activity frequencies were measured and the fourier components from artificial "pulse trains" for walking and running were computed. These components were then checked against the resonant vibrations of a beam with variable resonance frequency when subjected to the same loading. The continuous forces from jumping were also measured.

In order to compare the results presented in the previous section with those referred to above, the latter are converted into root-mean-square (rms) values of the force component at each harmonic.The force rms value $F_{rms,k}$ for the k:th harmonic of the step frequency is calculated from the dynamic load factors in [3] as shown by Eq. (1). These values are compared with results from the present study, determined from the measured force spectral densities as in Eq. (2), i.e. each value for $F_{rms,k}$ is calculated over a certain bandwidth Δf around the corresponding harmonic. The bandwidth Δf is selected as an "equivalent width" of the frequency response function resonance peak of a dynamic system with $\zeta_n = 1\%$, which can be taken as $\Delta f = \pi k f_s \zeta_n = 0.0314 k f_s$, according to [6]. The factor $\sqrt{2}$ in Eq. (1) accounts for the difference between the amplitude and the root-mean-square (rms) value of a harmonic process and G is the weight of the test person in the present test (740 N).

$$F_{rms,k} = \frac{\alpha_k G}{\sqrt{2}} \qquad (1)$$

$$F_{rms,k}(\Delta f) = \sqrt{F_k^2(\Delta f)} = \int_{kf_s - (\Delta f/2)}^{kf_s + (\Delta f/2)} S_F(f) df \qquad (2)$$

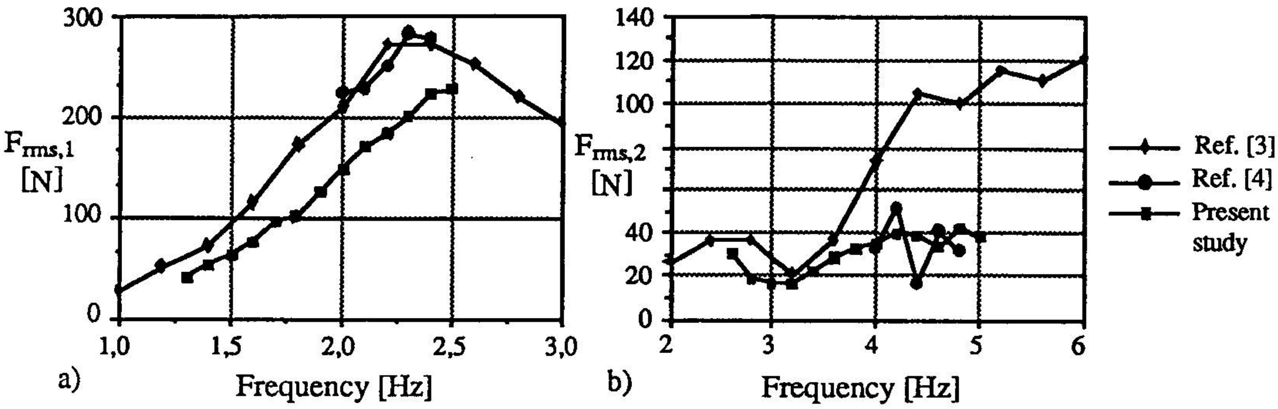


Fig. 4 Comparison of rms force components for a) the first and b) the second harmonic of the forces from walking.

The force components from walking at the first and second harmonics from the two refences above and from the present study are compared in Fig. 4. The results for the second harmonic diverge significantly. Ref. [3] reports forces at 4.4 Hz and above, that are more than twice as high as those from the present study as well as those from [4]. The differences between the three different subjects used in the former test were indeed biggest for the second harmonic but none of them gave second harmonic forces as low as those found in the present study for frequencies above 4 Hz.

The the first and second harmonics of the forces from running obtained in the present study agree very well with Ref. [3] as shown in Fig. 5a. The results from[4], presented in Fig. 5a, are not necessarily directly comparable to the other results as they were not obtained from measurements of *continuous* forces as discussed above. Neither are the forces in [4] given as a function of the step frequency. The results presented here are therefore based on those that are given in the report as the *highest* computed load factors based on the individual measured footsteps. As can be seen in the figure these are somewhat higher than the other results, especially for the second harmonic.

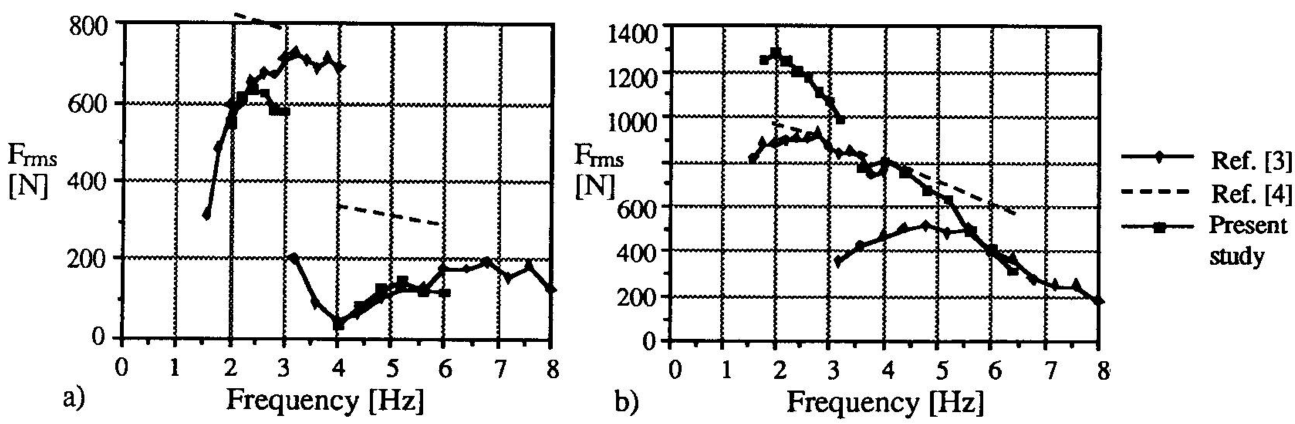


Fig. 5 Comparison of rms force components for the first two harmonics of the forces from a) running and b) jumping.

The forces from jumping measured in the present study are significantly higher than those presented in [3], at least for jumping frequencies below 3 Hz (see Fig. 5b). For the first harmonic they are also higher than those given in [4]. The explanation is partly found in the instructions given to peformers in the test. In Pernica's test [3] the subjects were asked to jump as they normally would whereas in the present study the subject was jumping relatively hard. Baumann & Bachmann [4], however, measured the forces due to different styles of jumping and the force components presented in Fig. 5 are the highest they found and they are still considerably lower than those obtained here.

4. FORCE MODELS

The *broad-band* or *spectral density model* is composed of an "envelope function" E and a "mean function" M. The E function can be regarded as a function connecting the peaks of the spectral density functions for different footstep frequencies and the M function represents the force power around each "harmonic" of the step frequency divided by the bandwidth, i.e. the step frequency. The level of the E function is chosen in such a way that it will yield the correct resonant response of a mode of vibration of the structure having a modal damping ratio $\zeta_n = 1\%$. The E(f) function of the model is therefore a curve-fit of the experimentally obtained levels $E_{exp,k}$ calculated according to Eq. (3) at each harmonic k of each step frequency f_s in the measured range. The mean square force at the k:th harmonic F_k^2 is calculated according to Eq. (2). In the same way the M(f) function of the model is a curve-fit of the experimentally obtained mean force spectral densities $M_{exp,k}$ around each harmonic, see Eq.(4).

$$E_{exp,k} = \frac{\overline{F^2}(\Delta f = 0.0314 k f_s)}{\Delta f} \tag{3}$$

$$M_{exp,k} = \frac{\overline{F^2}(\Delta f = f_s)}{f_s} \tag{4}$$

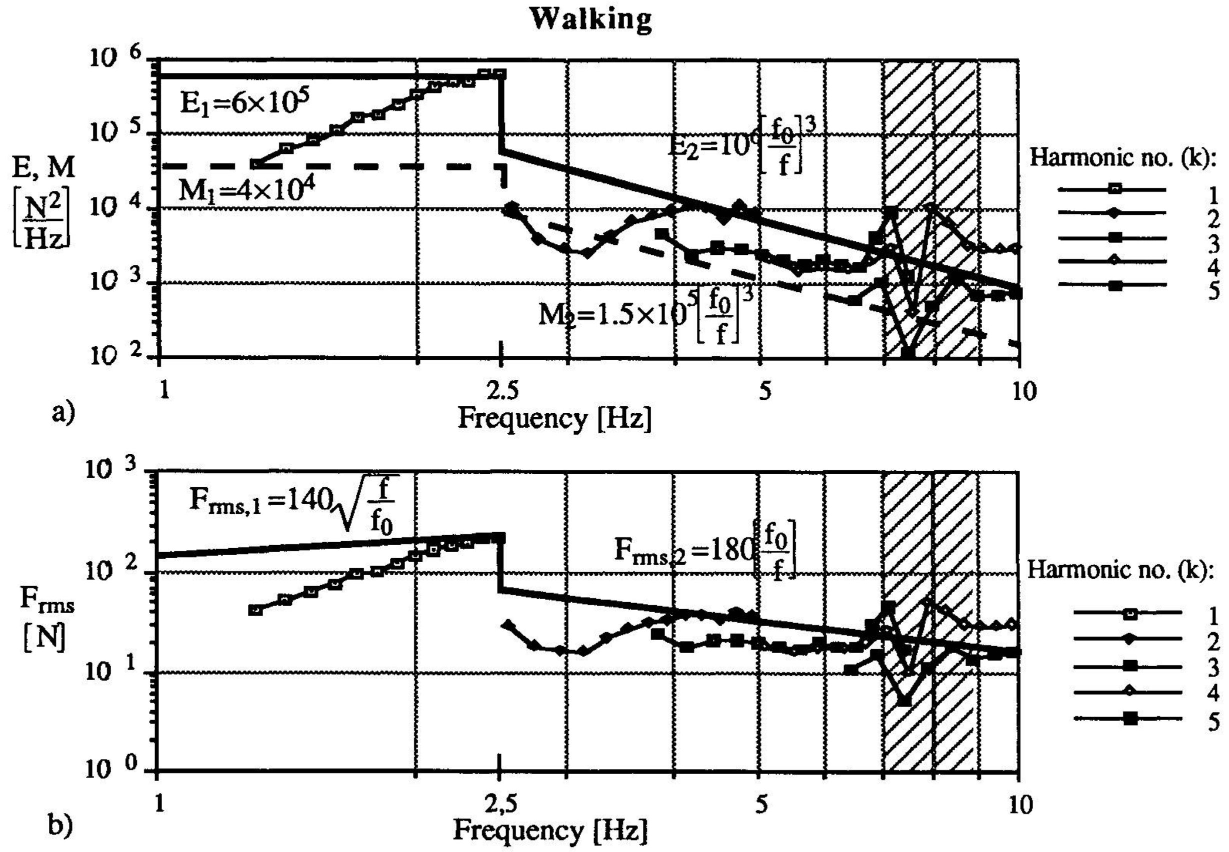


Fig. 6 Models of the forces from one person walking. a) shows the E and the M functions of the broad-band model respectively and b) the narrow-band model. f_0=1 Hz.

The *narrow-band model* of the forces used here is a model of the root-mean-square values of the forces at each harmonic F_{rms}, derived directly from the E function of the broad-band model as

$$F_{rms} = \sqrt{E(f)\times\Delta f} \tag{5}$$

where E(f) is the curve-fitted model function and $\Delta f = 0.0314f$. This means that the calculated resonant rms-response of a certain mode of vibration would be the same using either the E function or the F_{rms} function provided that the modal damping ratio ζ_n is 1%. The corresponding experimental values $F_{rms,exp}$ are obtained from the measured force spectral densities as in Eq. (2) with $\Delta f = 0.0314kf_s$, c.f. Ch. 3.

Each model consists of two different functions to take account of the drastically higher force levels at the first compared to the higher harmonics. The frequency of the shift from the first function to the second is 2.5 Hz for walking (Fig. 6), 3.0 Hz for running (Fig. 7) and 3.5 Hz for jumping (Fig. 8), which are taken as the highest occuring step frequencies. In the frequency range around the first natural frequency of the measurement platform the experimental values obtained are not reliable. In Figs. 6-8, the frequency range 7-9 Hz, which was disregarded in the curve-fitting, is therefore indicated. All these models are based on a body weight of the person that causes the vibrations of 740 N, as for the subject used in the tests. This is believed to be a fairly representative value. If another standard body weight is preferred, the F_{rms} models should be multiplied by the ratio of this body weight to 740 N and the E and M models should be multiplied by this ratio squared. For jumping, only an F_{rms} model is presented for reasons stated above. As compared to the forces from jumping measured in this study, the model gives lower forces for frequencies below 3 Hz and beteween 4 and 6 Hz. This adjustment of the model is made with respect to the comparisons made in Ch. 3.

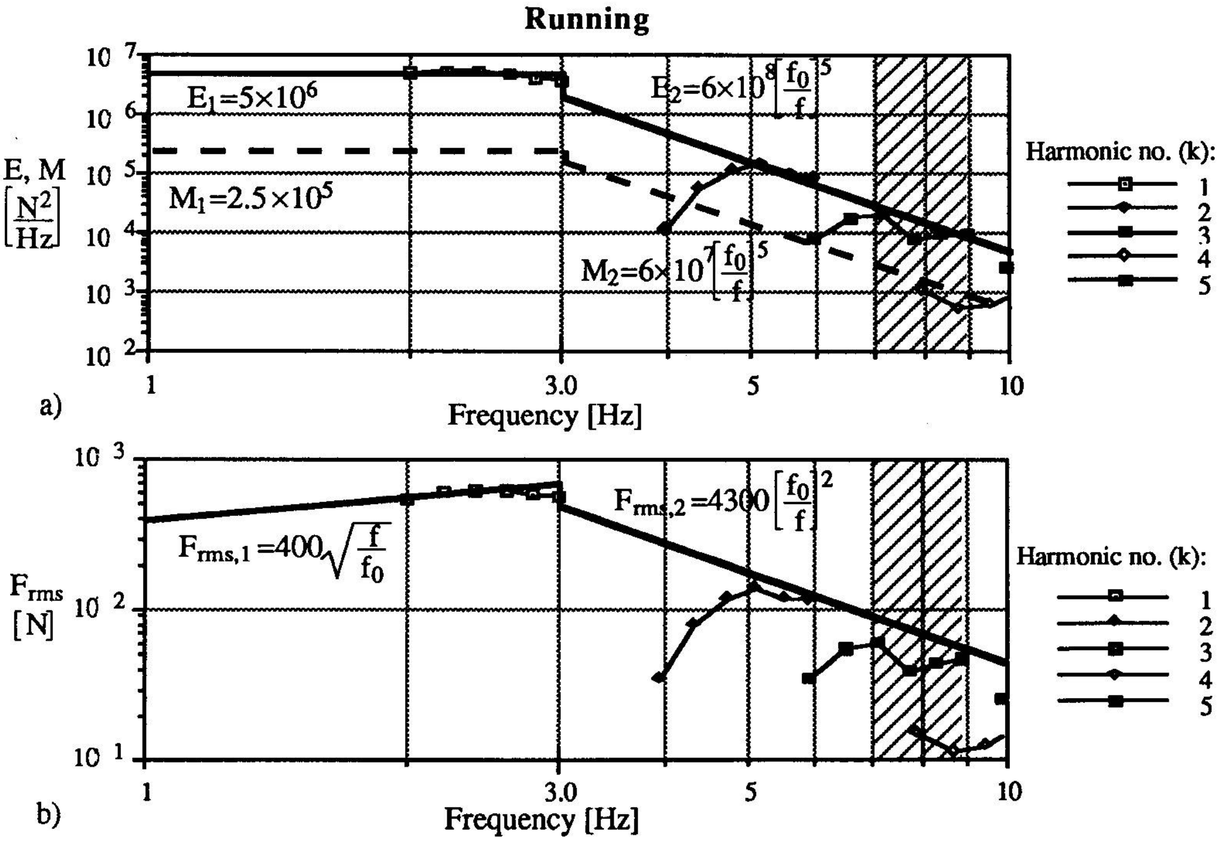


Fig. 7 Models of the forces from one person running. a) shows the E and the M functions of the broad-band model respectively and b) the narrow-band model. f_0=1 Hz.

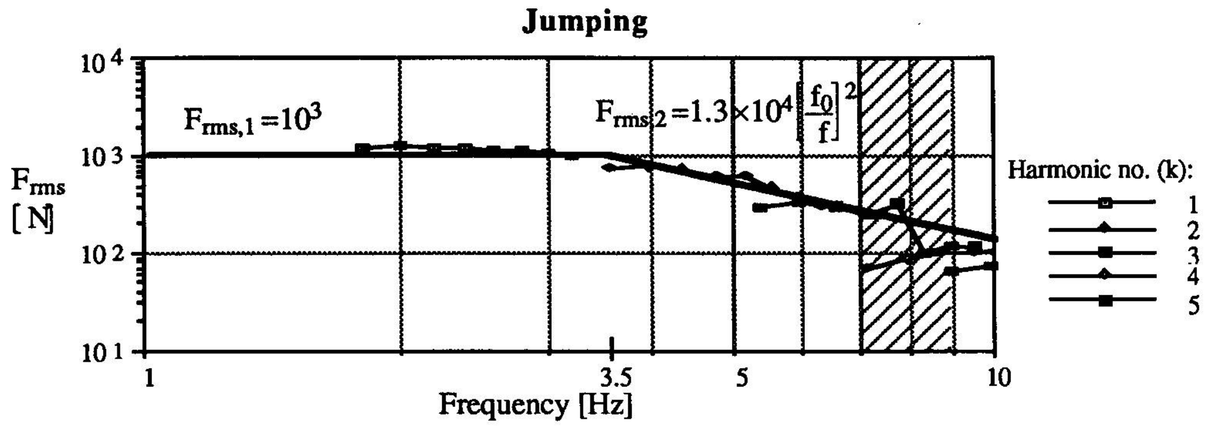


Fig. 8 Narrow-band model of the forces from one person jumping. f_0=1 Hz.

5. CONCLUDING REMARKS

The results from an experimental study of the forces from walking, running and jumping have been presented together with models to be used in the design of low-frequency floors against human-induced vibrations. A method for design calculations, using these force models, is presented in [7].

Furthermore, the experimental results presented above have been compared with results reported by other researchers. These comparisons have provided valuable information on the reliability of the various reported results as there are only a few studies covering the issue and as the measurement series, in all cases, comprise only one or a few individuals. The overall agreement between the results of the present study and those referenced has been found to be fairly good.

6. REFERENCES

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