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DYNAMIC LOAD FACTORS FOR PEDESTRIAN MOVEMENTS AND RHYTHMIC EXERCISES

G. Pernica
Institute for Research in Construction
National Research Council of Canada
Ottawa, Canada, K1A OR6

ABSTRACT

A force platform at the Institute for Research in Construction, National Research Council of Canada, was used to obtain the dynamic load factors for five rhythmic activities for footstep rates below 4 Hz. Two pedestrian movements, walking and jogging, and three rhythmic exercises, jumping, stride jumps and running-on-the-spot, were studied. Load factors for the first four harmonics of the footstep rate were obtained for groups of one, two and four people. For jumping, load factors for eight people were also measured.

The variation of the dynamic load factors with footstep rate and group size is discussed. Load factors suitable for design are suggested for floors subjected to these types of rhythmic activities.

SOMMAIRE

Une plate-forme de charge a été utilisée à l'Institut de recherche en construction, Conseil national de recherches du Canada, pour déterminer les facteurs de forces dynamiques de cinq activités rythmiques à des fréquences de pas en dessous de 4 Hz. On a étudié deux mouvements pédestres, soit la marche et la course, et trois exercices rythmiques, soit le saut, le saut en longueur et la course sur place. Les facteurs de forces pour les quatre premières harmoniques de la fréquence du pas ont été obtenus pour des groupes de un, deux et quatre personnes. On a mesuré les facteurs de forces du saut pour huit personnes.

Ce document examine la variation des facteurs de forces dynamiques en fonction de la fréquence du pas et de la taille des groupes. On y suggère des facteurs de forces adéquats pour la conception de planchers soumis à ce type d'activités rythmiques.

1.0 INTRODUCTION

The National Building Code of Canada 1985 (NBCC) now requires that the dynamic behaviour of a structural system supporting an assembly occupancy be investigated by means of a dynamic analysis when the fundamental frequency of the system is less than 6 Hz (Sentence 4.1.10.4(1)). This is to ensure that overloading of the structural system does not occur as a result of the dynamic response of the system to periodic forces produced by rhythmic activities. The Code also requires that all floor systems be designed so that no significant adverse effects on the intended occupancy of the building result from floor vibrations (Sentence 4.1.1.6.(1)). For assembly occupancies, this serviceability requirement is designed to eliminate floor vibrations induced by rhythmic activities likely to annoy participants or other occupants in the building and thus cause portions of the building to be unacceptable for its intended use. Guidance on performing the dynamic analysis or the serviceability investigation is given in the Supplement to the NBCC 1985, Commentary A, Serviceability Criteria for Deflections and Vibrations (2).

The procedure outlined in Commentary A for assessing the safety or in-use acceptability of a floor system requires knowledge of the dynamic load factors of rhythmic activities that might be performed on the floor system. Dynamic load factors for several rhythmic activities are given in Commentary A. They are taken from a paper by Allen, Rainer and Pernica (3) in which dynamic load factors for several activities were calculated from field tests and direct load measurements. For two activities, jumping and jogging, load factors were ascertained from forces measured on a force platform at the Institute for Research in Construction, National Research Council of Canada (IRC/NRCC). However, only a few of the load factors that were measured on the force platform are presented either in that paper and in others by Rainer and Pernica (4), and by Rainer, Pernica and Allen (5). Load factors for groups of two or more people and for other types of rhythmic exercises are still unreported.

The present paper describes and discusses: the force platform at IRC/NRCC that was used to measure floor forces of rhythmic activities; the experimental procedure followed in making these dynamic force measurements; the dynamic load factors obtained for two pedestrian movements (walking and jogging) and three rhythmic exercises (jumping, stride jumps and running-on-the-spot); and the variation of these load factors with both footstep rate and group size. Load factors suitable for design are suggested for floors subjected to pedestrian movements and rhythmic exercises.

2.0 DESCRIPTION OF FORCE PLATFORM

2.1 Physical Properties

The force platform at IRC/NRCC was constructed from a simply supported floor strip 17.04 m long and 2.13 m wide (Fig. 1) consisting of two open-web steel trusses 914 mm deep and 1.74 m apart, topped by 14 non-composite, precast concrete panels. The panels were 1.19 m long, 2.13 m wide and 100 mm thick, positioned on the trusses with about a 25-mm gap between adjacent panel members. A 150 x 50 mm wood plank was placed across the top of the panels directly above the top chord of the trusses. The panels were clamped to the trusses by bolting the wood planks to the top chord of the trusses at every panel gap.

At mid-span of the floor strip a piezoelectric force transducer was placed between the bottom chord of each truss and an adjustable ground support. The force transducers had a sensitivity of 0.23 mV/N, an unloaded resonant frequency of 70 kHz, and a dynamic load range in compression from about 1 N to 22 kN. By adjusting the camber in the trusses each force transducer was pre-loaded to about 4 kN.

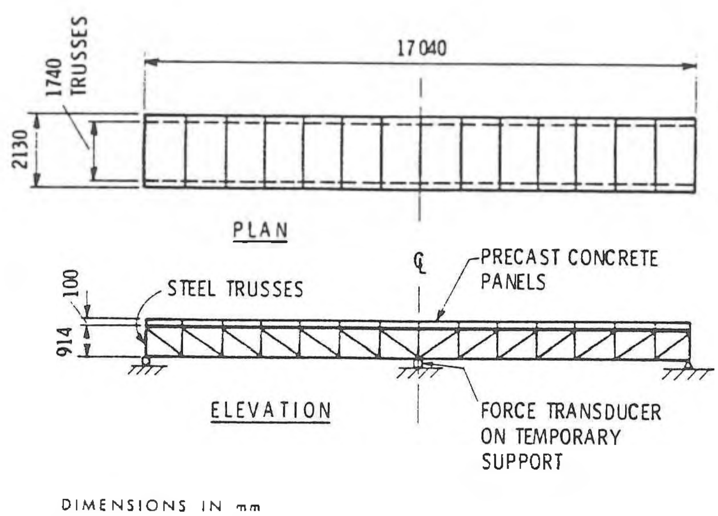

Figure 1. Force Platform

2.2 *Mechanical Properties*

The dynamic properties of the fundamental mode of vibration of the force platform (floor strip with mid-span support) were determined from heel impacts and from forced vibration tests using an electro-magnetic shaker. The force platform had a fundamental frequency of about 13 Hz, a damping ratio of about 2% of critical, and a nearly sine-wave mode shape with nodes at the mid-span and end supports.

2.3 *Correction Coefficients*

For excitation frequencies close to the fundamental frequency of the force platform the dynamic forces measured by the force transducers were too large because of the near-resonant response of the platform. The magnitude of this response was dependent on the proximity of the excitation frequency to the fundamental frequency of the platform and on the fundamental damping ratio. Damping ratio, however, varied with number and location of participants on the platform (6) so that the near-resonant response of the platform changed with each group of participants. To ensure that variations in modal damping would have little effect on response, the dynamic range of the platform was restricted to frequencies below 10 Hz.

To correct for the dynamic behaviour of the platform, response coefficients for the force transducers were determined for excitation frequencies from 2 to 10 Hz using the electro-magnetic shaker. Influence line coefficients for the force transducers were also determined to correct forces for activities in which groups of participants moved horizontally on the platform relative to the mid-span support.

3.0 PARTICIPANTS

3.1 *Composition*

Twenty-two people, 18 men and four women, participated in the experimental program to determine dynamic load factors for two pedestrian movements and three rhythmic exercises. Ages ranged from 20 to 60 for the men and 20 to 30 for the women and weights ranged from 580 to 930 N for men and from 510 to 640 N for women. Each of the five activities was performed by several group sizes (Table 1): with one and two people, activities were performed by at least two different sets of participants; for groups of four and eight people, activities were performed by only one set of participants, except that rhythmic jumping by four people was performed by three sets.

TABLE 1 Group size and range of activity rates for pedestrian movements and rhythmic exercices

Activity	Group Size	Range of Activity Rate, Hz (Footsteps/s)	
	No. of people	Normal Range	Measured Range
Pedestrian Movements			
Walking	1, 2 and 4	1.6 - 2.2	1.0 - 3.0
Jogging	1, 2 and 4	2.2 - 3.2	1.6 - 4.0
Rhythmic Exercises			
Jumping	1, 4 and 8	2.0 - 3.0	1.4 - 4.0
Stride jumps	1 and 4	2.0 - 2.6	1.6 - 3.4
Running-on-the-spot	1 and 4	2.2 - 3.2	1.4 - 4.0

Note: Normal ranges for the five activities were determined from the literature and from personal observation of pedestrian movements within buildings and rhythmic exercises in aerobic classes

Participants were initially chosen from the staff at IRC if they appeared to be physically fit. They were re-selected for additional performances only if

1) they displayed reasonable coordination skills in performing physical activities to an audible beat, and

2) they were able to perform an entire program of activity rates without quitting or showing signs of physical distress.

Load factors for some of the activities therefore contain the effects of individuals who had difficulty maintaining the beat or footfall unison with a group.

3.2 *Effective Weight of Group*

Participants who performed the rhythmic exercises were assigned fixed locations on the platform. A single participant performing alone was positioned at the mid-span of the platform so that the participant's effective weight on the force platform (i.e., the weight of the participant as measured by the force transducers) was comparable to the static or scale weight of that participant. Members of groups of two or more were placed symmetrically and as close as possible to the mid-span of the force platform. They were also positioned on the platform so as to minimize differences in their individual effective weights. The total effective weight of a group with members in their assigned positions was determined at the beginning and at the end of each program of activity rates.

For pedestrian movements, the effective weight of a single participant performing alone was also determined at mid-span. For larger groups, effective weight was determined with members at their assigned starting positions on the platform. Members were also positioned so that variation in effective weight while performing the movement was minimized.

4.0 MEASUREMENT PROCEDURE

4.1 Group Activities

Rhythmic exercises were performed with group members remaining at their assigned positions on the platform throughout the prescribed program of activity rates.

For pedestrian movements, single participants began at one end of the platform and moved to the other end at the required activity or footstep rate using a stride length of their own choosing. Groups of two or more pedestrians were handled differently because of space limitations on the platform. Group members were assigned starting positions (mid-span or 1/6-points) on the platform and were asked to move in unison at the required footstep rate in a counter clockwise circle about the centre of the platform. Groups were made up of members having similar height and weight characteristics so that the initial spacing could be maintained throughout the program of activity rates.

4.2 Program of Activity Rates

Activities were performed to pre-recorded pulses played through loudspeakers. A frequency (footstep rate) increment of 0.2 Hz (footsteps/s) was used, resulting in a measurement program of 11 footstep rates for walking, 14 for jogging, 16 for jumping and running-on-the-spot and 10 for stride jumps. The measured range of footstep rates for each of the five activities together with the range normally encountered in practice is shown in Table 1. Normal ranges for the five activities were determined from the literature (7) and from observations of pedestrian movements within buildings and rhythmic exercises in aerobic classes.

Each footstep rate for the rhythmic exercises was performed in unison for 30 seconds. For pedestrian movements, a participant performing alone traversed the length of the platform twice for each footstep rate; groups of two or more completed three circuits of the circular course laid out on the force platform.

4.3 Instrumentation

Signals from the two force transducers were low-pass filtered at 25 Hz, amplified and recorded on an FM tape recorder.

5.0 DEFINITION OF DYNAMIC LOAD FACTOR

Forces produced by rhythmic activities can be represented by the following expression (3);

$$P(t) = W_P \left\{ 1+\sum_{n=1}^{N_T} \alpha_n \sin(2\pi f t + \varphi_n) \right\} \qquad [1]$$

where

$P(t)$ = forcing function of the activity
W_p = static weight of the group
α_n = dynamic load factor of the nth harmonic
(normalized Fourier Coefficient)
n = order of harmonic of activity rate
f = activity rate in Hz (footsteps/s)
ϕ = phase angle of nth harmonic
N_T = total number of harmonics
t = independent variable, time.

The summation term is the dynamic component of the forces produced by the rhythmic activity. The dynamic load factors, α_n, are the Fourier coefficients of the Fourier series representation of the rhythmic forcing function normalized by the static weight of the group performing the activity.

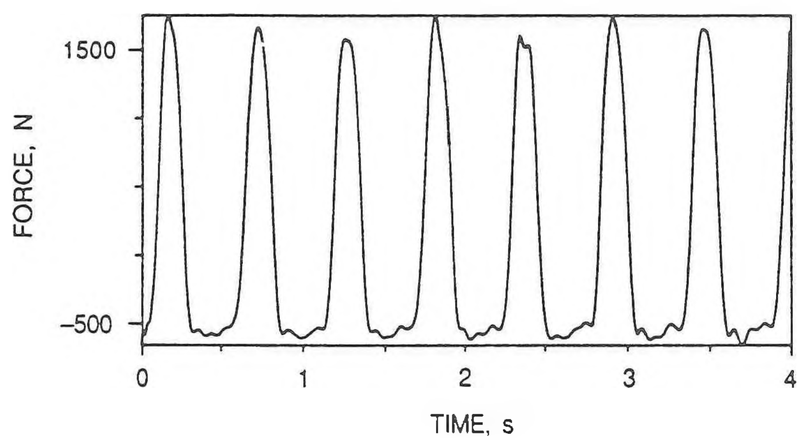

Figure 2. Time Record of Forces Produced by One Person Stride Jumping at 1.8 steps/s (Low-Pass Filtered at 9.0 Hz)

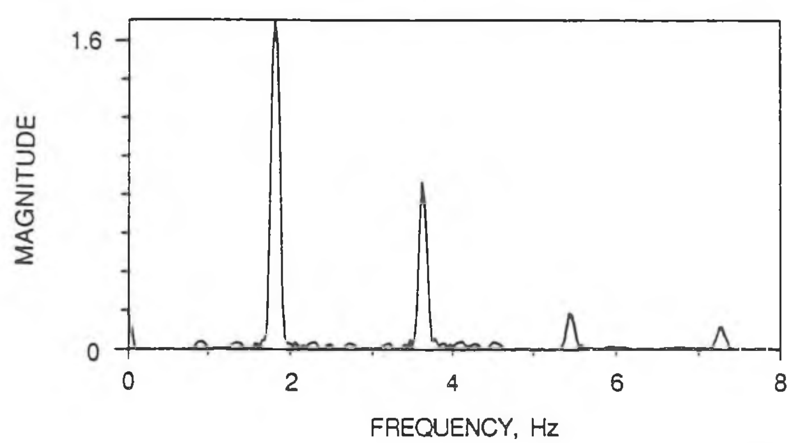

Figure 3. Fourier Spectrum of Forces Produced by One Person Stride Jumping at 1.8 steps/s

6.0 ANALYSIS PROCEDURE

6.1 Fourier Analysis

Dynamic load factors for the five activities were determined from Fourier spectra of force transducer signals. Recorded time signals from the two force transducers were added (Fig. 2) and Fourier spectra of the combined signal obtained using a narrow-band (FFT) analyser (Fig. 3). Fourier amplitudes at harmonics of the activity rate were converted to Fourier coefficients, which in turn were divided by the effective weight of the group to obtain dynamic load factors.

6.2 Fourier Amplitude Corrections

No influence line corrections of the Fourier amplitudes were required for the three rhythmic exercises since group members did not move on the platform relative to the force transducers. Neither were they needed for pedestrian movement by one person, since only the portion of the force record centred in time over the mid-span support was analysed. Influence line corrections were, however, applied to the spectral amplitudes for pedestrian movements performed by groups of two or more. The corrections accounted for the circular movement of group members on the force platform about the mid-span support.

Dynamic load factors for footstep harmonics above 9.6 Hz were not determined because the dynamic amplifications of these force components were too sensitive to the number, positioning, and physical conditioning of group members. Load factors for harmonics below 9.6 Hz were corrected to take into account the dynamic properties of the force platform.

7.0 DYNAMIC LOAD FACTORS FOR RHYTHMIC ACTIVITIES

Dynamic load factors for the five rhythmic activities are presented in Figs. 4 to 8. Curves for the first and second harmonics of footstep rate are drawn over the measured range of activity rates and for the third and fourth harmonics for harmonic frequencies to 9.6 Hz. Load factors for the first and second harmonics are not plotted for footstep rates of 3.8 and 4.0 Hz in Fig. 5(c) because it was not possible for the four participants to jog on the force platform at the two highest rates with any semblance of unison.

Average load factors are plotted in the figures for group sizes for which there were more than one set of participants. The number of sets (N) from which the averages were obtained is also noted. For the first harmonic, the largest and smallest load factors at each footstep rate are shown with the average curve. Bounds for the second, third and fourth harmonics were omitted because of space limitations within the figures.

Maximum dynamic load factors for each activity and each group size are given in Table 2. The table also shows the footstep rate at which maximum load factors for the first three harmonics were obtained. Footstep frequencies separated by a slash indicate that the harmonic maximum was attained at more than one footstep rate. Those for the maximum of the fourth harmonic were omitted because load factors for the fourth harmonic were fairly constant over the measured footstep range.

Table 2 Maximum Dynamic Load Factors for Pedestrian Movements and Rhythmic Exercises

Group size	Maximum load factor				Activity rate at which maximum occurred Hz (Footsteps/s)		
	Harmonic No.				Harmonic No.		
	1	2	3	4	1	2	3
Pedestrian Movements							
Walking							
1	0.56	0.28	0.16	0.09	2.4	2.6/3.0	3.0
2	0.46	0.19	0.11	0.10	2.4	3.0	2.4
4	0.36	0.07	0.07	0.03	2.4/2.8	1.4	2.6
Jogging							
1	1.50	0.55	0.17	0.09	3.4	3.4	3.0/3.2
2	1.65	0.47	0.16	0.10	2.4	2.4	1.6
4	1.05	0.14	0.11	0.08	2.2	1.6	1.6
Rhythmic Exercises							
Jumping							
1	1.80	1.10	0.47	0.18	2.8	2.6	2.4
4	1.75	0.96	0.28	0.12	2.6	2.4	2.4
8	1.55	0.52	0.11	0.04	2.6	2.2/2.4	1.4
Stride Jumps							
1	1.75	1.10	0.42	0.11	2.6	2.2	2.2
4	1.80	1.00	0.32	0.09	2.2	2.2	2.2
Running-on-the-spot							
1	1.57	0.58	0.26	0.15	2.8	2.8/3.0	1.6
4	1.44	0.38	0.28	0.10	2.4	2.6	1.4

7.1 *Walking*

Maximum load factors for the first three harmonics were primarily associated with footstep rates between 2.4 and 3.0 Hz (Table 2). These rates, which were in the upper half of the measured footstep range, were above the range of normal walking rates (1.6-2.2 Hz). Within the normal range the first harmonic (α_1) increased with footstep rate for all group sizes from about 0.2 at 1.6 Hz to about 0.4 at 2.2 Hz (Fig. 4). Over the measured range, however, α_1 maxima decreased with group size, falling from 0.56 for one person to 0.46 for two and to 0.36 for four people.

The variation of the second harmonic over the normal range reversed as the size of the group increased. Load factors for α_2 went from rapidly increasing with footstep rate for one person to slightly decreasing with footstep rate for four people. The footstep rate of the harmonic maximum also changed location with increasing group size, moving from a suggested location above 3.0 Hz for one and two people to below 3.0 Hz for four people.

Dynamic load factors for the third and fourth harmonics were relatively constant over the measured frequency range irrespective of group size, but overall amplitudes of the two harmonics dropped slightly as group size increased. The third harmonic fell from about 0.07 for one and two people to 0.04 for four people, and the fourth harmonic from 0.05 for one and two people to 0.02 for four people.

The drop in dynamic load factors with rise in group size was not surprising. As people were added to the group, overall group coordination in performing the activity on the platform was reduced as participants found it more difficult to maintain the walking rate and the distance between themselves and other group members. Although this reduction in group coordina-

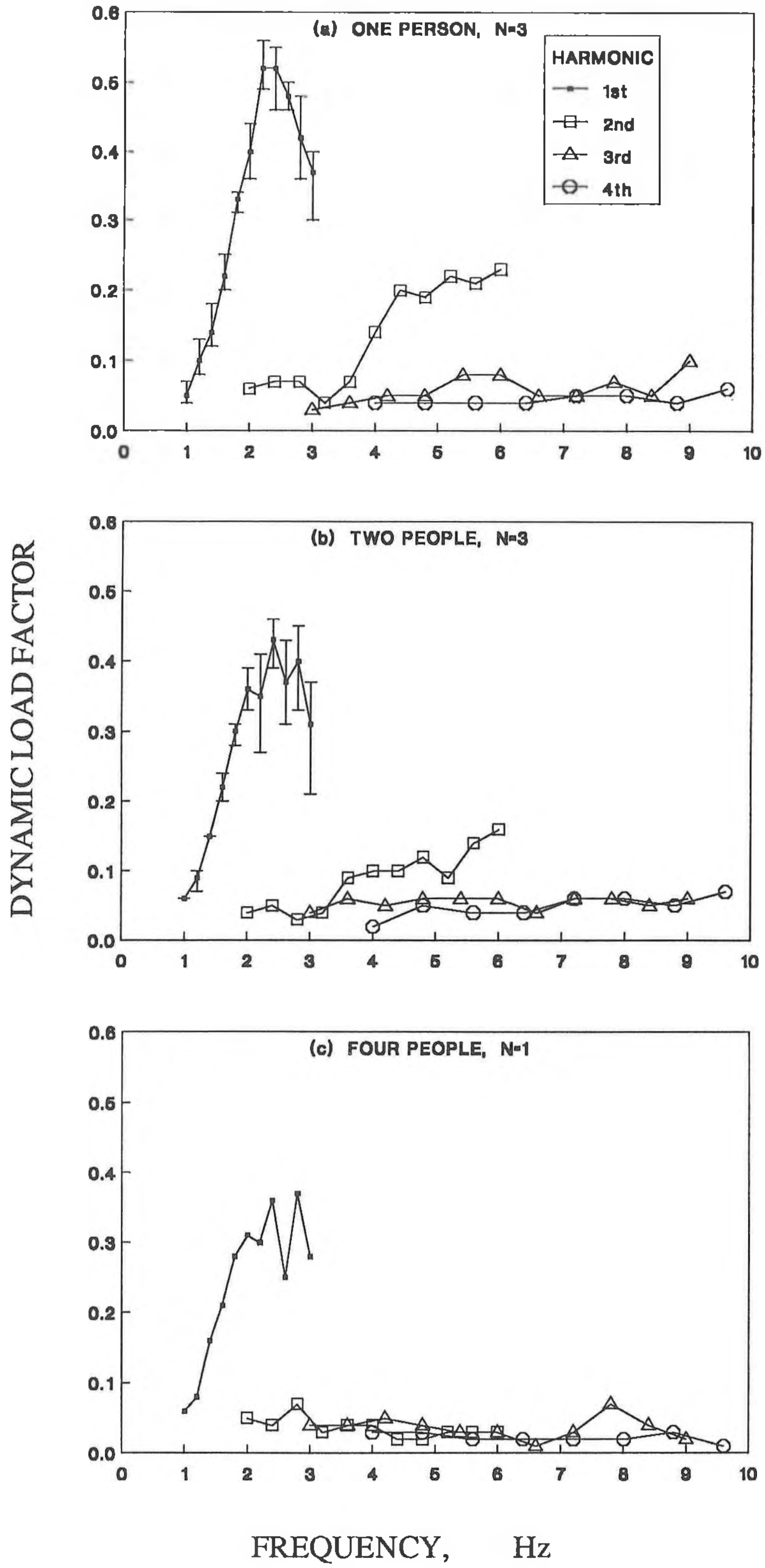

Figure 4. Dynamic Load Factors for Walking

tion appears to be a quirk of the experimental procedure, the same difficulties are apparent for group members under regular walking conditions. Members are forced to adjust their walking characteristics if they wish to walk in unison with and be part of a large group of walkers.

7.2 *Jogging*

Maximum amplitudes for the first harmonic of jogging did not follow the emerging pattern associated with group size; the maximum for two people exceeded that for one person by about 10% (Table 2). The maximum for four people was just as notable, since jogging registered the greatest drop in α_1 maxima of the five activities, falling from 1.5 for one person to 1.05 for four people. Footstep frequencies for these maxima, however, followed the group size pattern closely, sequentially decreasing from 3.4 Hz for one person to 2.2 Hz for four.

Average load factors for the first harmonic also followed a group size pattern in spite of differences in N. First harmonic curves became increasingly flattened and lower over the normal range of footstep rates as group size increased (Fig. 5). The variation in load factors over the normal range dropped from about 20% for one person to 15% for two and 6% for four. The flattening of the α_1 curves and the fall in both the maximum and the footstep frequency of the maximum reinforce what seems intuitively evident that both the level of group unison and the range of footstep rates easiest for joggers to perform fall with increasing group size. These effects of group size may again be partly the result of the experimental procedure used on the platform. As was noted for walking, however, the same difficulties are experienced by individuals trying to jog in unison within a group.

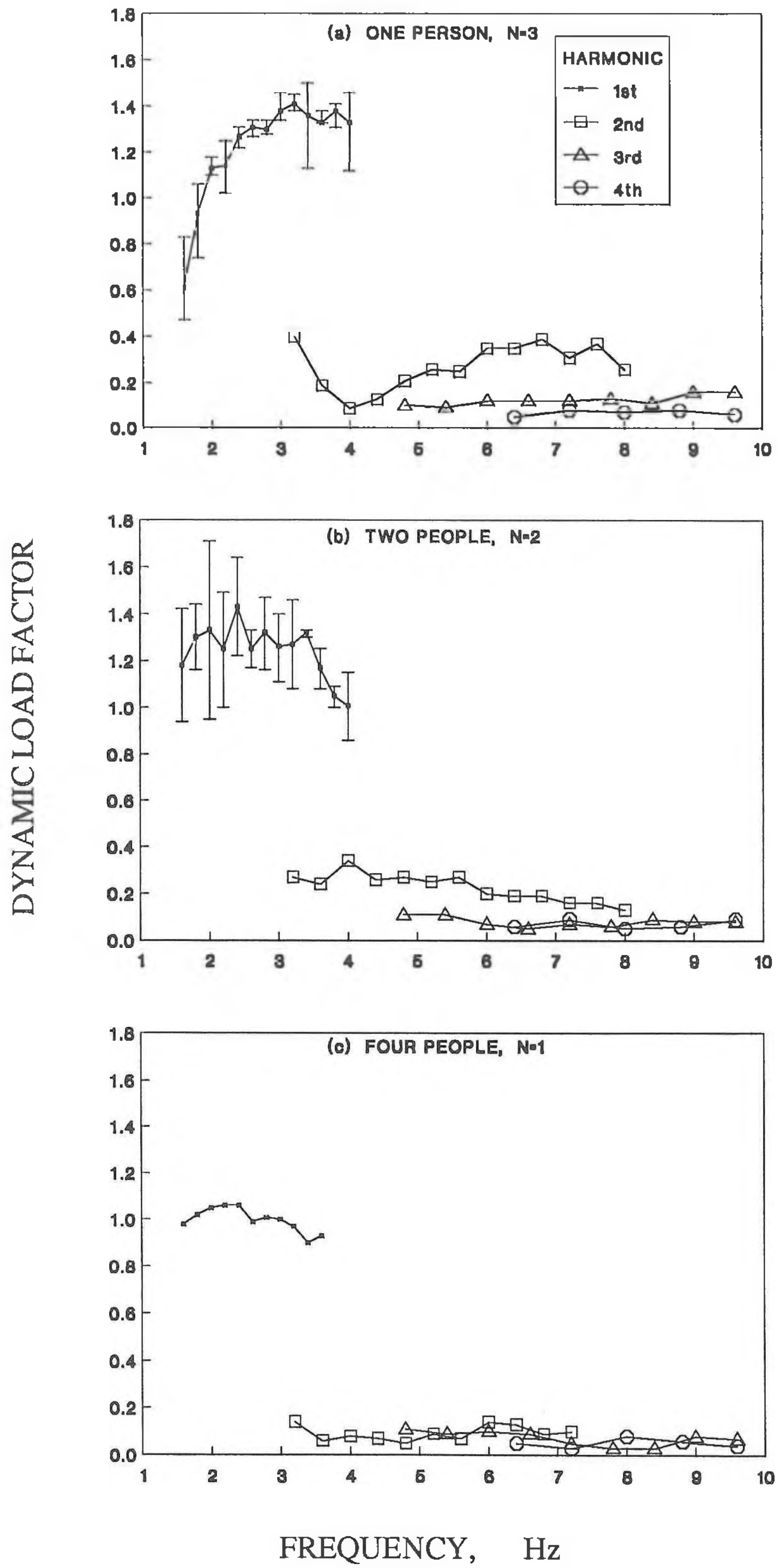

Figure 5. Dynamic Load Factors for Jogging

The decrease in the level of group unison with group size was also apparent in the dynamic load factors of the second harmonic. Maximum load factors for α_2 decreased from 0.55 for one person to 0.14 for four people and footstep frequencies for the maxima from 3.4 Hz for one person to 1.6 Hz for four people. The second harmonic also exhibited (as had the first) decreasing variability with increasing group size over the normal range of footstep rates. The range in α_2 amplitudes in Fig. 5 dropped from 0.13 to 0.35 for one person to 0.07 to 0.13 for four people.

Dynamic load factors for the third and fourth harmonics remained fairly constant for each group size over the measured range of jogging rates. The effect of group size was again evident as the average amplitudes of the two harmonics over the measured range fell, α_3 from about 0.12 for one person to 0.07 for four people and α_4 from about 0.07 for one person to about 0.05 for four people.

7.3 *Jumping*

Dynamic load factors for four people were strikingly similar in shape to those for one person (Fig. 6a,b). Curves for the first three harmonics were convex, with the largest amplitudes located at the centre of the normal range of footstep rates (2.0-3.0 Hz) and the smallest at the lower and upper ends. Within the normal range, average load factors for the first two harmonics were not only fairly constant but those for the first were within 5% of their maximum (Table 2) and those for the second were within 30% of their maxima for groups of one and four people.

Dynamic load factor curves for eight people (Fig. 6c) were more jagged than those for the smaller groups; the curves for eight people were obtained with only one set of participants and those for one and four people were averages of the results for several sets of participants. Load factors for eight people were also

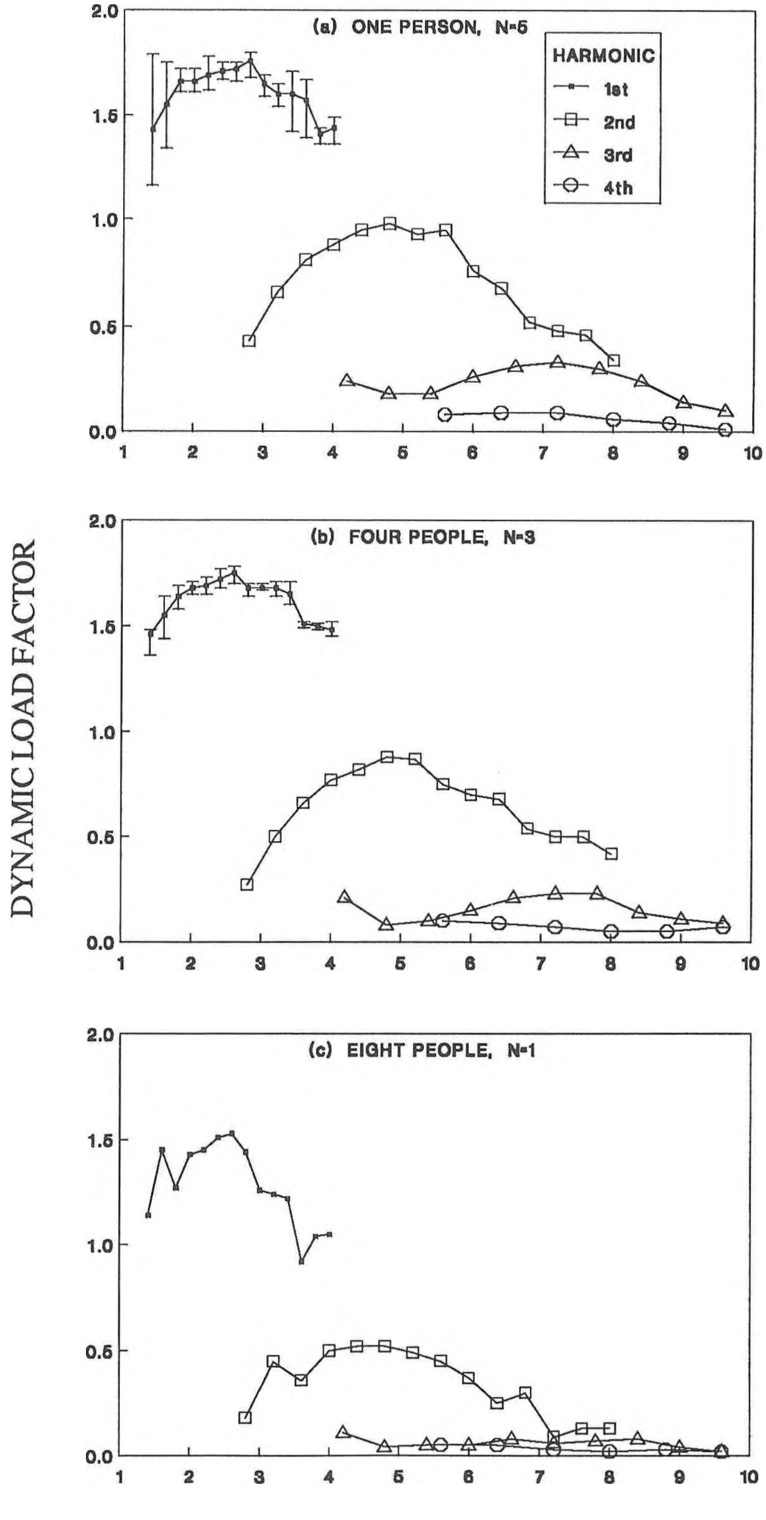

Figure 6. Dynamic Load Factors for Jumping

noticeably smaller than the averages for smaller groups. One reason for the large reduction was the difficulty experienced by one of the participants in the group of eight in maintaining group unison.

Maximum load factors for the four harmonics consistently decreased with increasing group size (Table 2). The size of the decrease also increased with harmonic number, so that forces associated with the first harmonic of the footstep rate became more dominant as group size increased. Ratios of the harmonic maxima of eight people to one person were 0.85 for the first, 0.47 for the second, 0.23 for the third and 0.22 for the fourth. Footstep rates for the maxima also decreased consistently with group size, but remained within the normal range (2.0-3.0 Hz) for the first three harmonics.

7.4 *Stride Jumps (Jumping Jacks)*

Dynamic load factors for stride jumps (also called jumping jacks) were comparable in amplitude and similar in shape to those obtained for jumping (Figs. 6 and 7). This resemblance between the two sets of load factors exists because stride jumps are a type of jumping (although slightly more complex) in which the arms move up with the outward movement of the legs and down with their inward movement within each complete stride jump cycle.

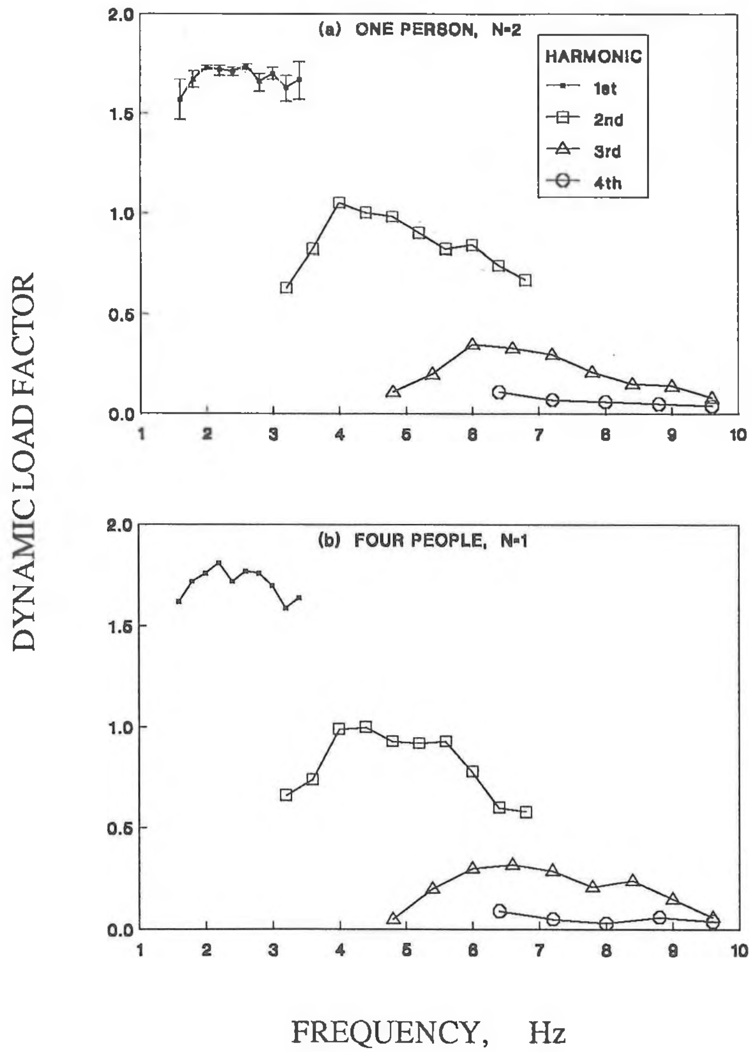

Figure 7. Dynamic Load Factor for Stride Jumps

Dynamic load factors for one and four people were similar in shape and amplitude, suggesting that four people jumped to the broadcast beat with the same degree of harmony as one person. A trend to smaller load factors with increasing group size was suggested by α_2, α_3 and α_4, whose maxima for four people were about 10% smaller than those for one person. However, α_1 countered the trend by registering a slightly larger maximum for four people (Table 2). Footstep rates for harmonic maxima stayed within the normal range (2.0-2.6 Hz) for both group sizes. For α_2 and α_3 the rate remained at 2.2 Hz, while for α_1 the rate fell from 2.6 Hz for one person to 2.2 Hz for four.

7.5 *Running-on-the-Spot*

The shape and distribution of the dynamic load factors were similar to those obtained for jogging (Figs. 5 and 8). This similarity was not surprising since running-on-the-spot is jogging with no horizontal movement. Like jogging, ratios of the second and third harmonics to the first over the normal range of footstep rates (2.2-3.2 Hz) were only about 25% for the second and 10% for the third for both one and four people. This indicated that running-on-the-spot is also a rhythmic activity in which the components of the footstep forces are dominated by the first harmonic of the footstep rate.

Dynamic load factors for running-on-the-spot contained some of the effects of group size already noted for the two pedestrian activities. Curves for the first two harmonics were flatter, although not lower over the measured footstep range (1.4-3.4 Hz); maximum load factors for three of the four harmonics decreased (Table 2); and footstep frequencies of the maxima of the first three harmonics moved downward. These changes with group size, however, were less pronounced than they had been for jogging, suggesting that it was easier for groups of participants to run on-the-spot at a given level of unison than to jog across the platform (with the same level of unison). The difference in group performance for the two activities was probably related to a dual requirement for unison for those who jogged. Participants who jogged were instructed to keep both the beat and the spacing between themselves and other group members on the platform, whereas for running-on-the-spot participants were required only to step to the beat.

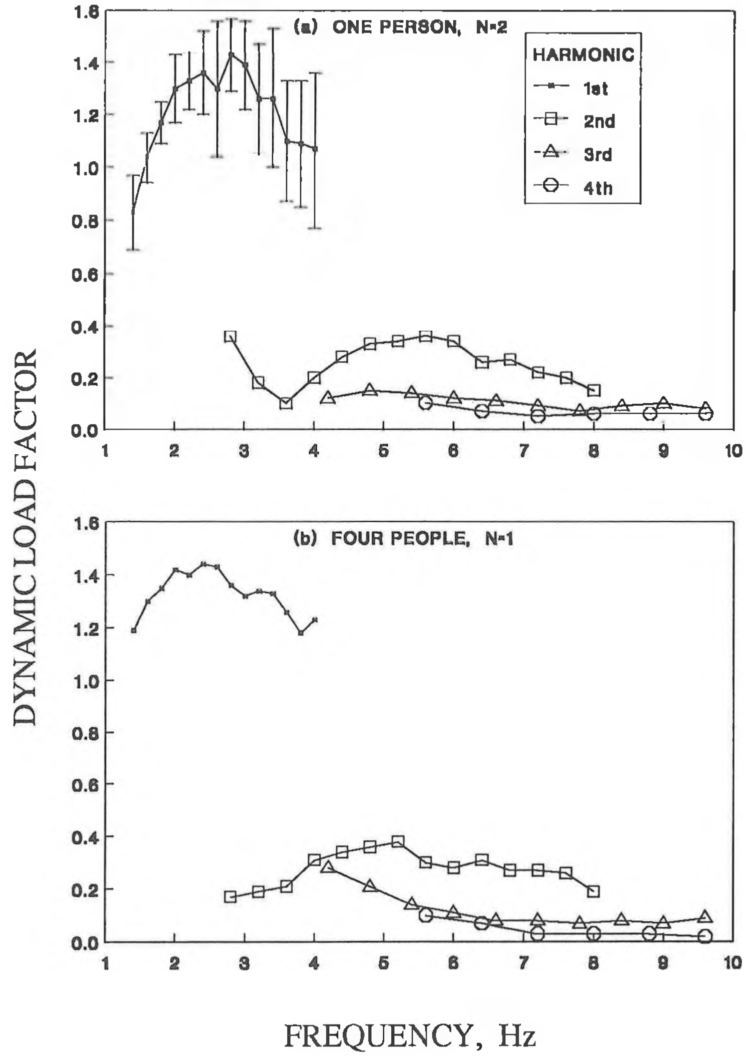

Figure 8. Dynamic Load Factors for Running-on-the-Spot

8.0 DISCUSSION AND SUMMARY

8.1 Force Platform

A force platform at the IRC/NRCC was used to obtain the dynamic load factors for five rhythmic activities for footstep rates below 10 Hz. Two pedestrian movements, walking and jogging, and three rhythmic exercises were studied. The 10 Hz upper bound for the platform was not a serious problem since footstep rates for the five activities did not exceed 4 Hz. Footstep rates above 4 Hz were unrealistic for these types of human endeavour.

The 10 Hz frequency bound did, however, limit the number of harmonics for which load factors were obtained to three for footstep rates above 2.4 Hz and to two for footstep rates above 3.2 Hz. This restriction was not a major drawback. Load factors for the third and fourth harmonics were considerably smaller than those for the first and second. In absolute terms, the third and fourth harmonics were also fairly constant over the measured portion of their frequency range. As a result, load factors for the third and fourth harmonics for frequencies above 9.6 Hz could be reasonably interpolated from the existing data without giving rise to substantial error.

8.2 *Group Size*

Maximum dynamic load factors for the five rhythmic activities decreased with increasing group size. Some amplitude reversals did occur in three of the four harmonics (except the second one) and in four of the activities (except jumping), but the trend to smaller maxima with increasing group size was present in all activities. Footstep rates for the maxima also fell. For the three rhythmic exercises, the rates remained within the normal ranges for the first and second harmonics, but followed no pattern with respect to the normal range for the third one. There was no overall trend for the two pedestrian movements. Rates for the three harmonics of walking remained generally above the normal range, while rates for jogging varied differently with respect to the normal range with harmonic number.

Group size also reduced the variation with frequency in the dynamic load factors of the first and second harmonics of pedestrian movements. The two activities required group members to move across the platform at a specified footstep rate and with about the same stride length. Although group members were of approximately equal height and weight, they did not necessarily have similar walking or jogging gaits. As a result, group members were forced to take smaller (or larger) than normal strides in trying to maintain group unison for each activity rate. The smoothing of the load factors for the first two harmonics may indicate the uncharacteristic movements required of some participants in trying to maintain group unison while traversing the platform. This dual requirement did not arise in the rhythmic exercises since participants did not change position on the platform while performing.

8.3 *Harmonic Number*

Dynamic load factors for the five rhythmic activities decreased with increasing harmonic number. The rate at which the decrease occurred varied with activity and group size. At one end of the variability spectrum, jumping by one person, the decrease was monotonic. Each of the load factors for a given harmonic of jumping was larger than the set of load factors for each higher harmonic and smaller than the set of load factors for each lower harmonic (Fig. 6). At the other end of the spectrum, walking by one or more people, dynamic load factors for the three higher harmonics overlapped in the frequency domain (Fig. 4), so that the decrease was only visible when harmonic maxima were compared (Table 2).

8.4 *Pedestrian Movements*

Of the five activities studied, walking had the smallest maximum load factors for the first three harmonics. This was not surprising, considering that walking was the only activity in which one foot was always in contact with the platform. Because of this continuous contact, walking produced smaller footfall impacts than the other four activities in which body contact with the floor was lost during a portion of each footstep cycle. Ratios of harmonic maxima of jogging to walking were about three for the first harmonic, two for the second and 1.5 for the third. Maxima for the fourth harmonic were comparable for one and two people, but with four people that for jogging was significantly larger.

8.5 *Rhythmic Exercises*

Dynamic load factors for jumping and stride jumps had similar harmonic shapes and comparable amplitudes for identical group sizes (stride jumps are generically jumps with additional leg and arm movements within each jump cycle). The two jumping exercises produced the largest harmonic maxima of the five activities, 1.8 for the first, 1.1 for the second, and 0.47 for the third. Footstep rates for the harmonic maxima of the jumping exercises occurred within their normal ranges of activity rate as these were the easiest to perform.

Running-on-the-spot is a version of jogging in which the position of the participants relative to the floor stays fixed. For one person, dynamic load factors for the two activities were comparable in amplitude and similar in shape. For groups, load factors for running-on-the-spot were much larger than those for jogging because group members did not have to adjust their stride length to maintain unison during the measurement program. For four people, maximum load factors for running-on-the-spot were about 1.5 times as large for the first harmonic and 2.5 times as large for the second and third harmonics.

9.0 SUGGESTED LOAD FACTORS

Suggested load factors for pedestrian movements and rhythmic exercises are contained in Table 3. They are considered suitable for the design of floors in active or assembly occupancies and are based on the maxima obtained for groups of four and eight participants within the measurement program.

Table 3. Suggested Load Factors for Pedestrian Movements and Rhythmic Exercises for Large Groups of People

Activity	Suggested Load Factors Harmonic No.			
	1	2	3	4
Pedestrian Movements	1.10	0.20	0.10	0.05
Rhythmic Exercises	1.60	0.60	0.20	0.10

9.1 *Pedestrian Movements*

Load factors for pedestrian movements are based on those for jogging since load factors for walking were significantly smaller. Those shown in Table 3 are for groups in which some discord in performing the pedestrian movement will tend to be present. For small or well-coordinated groups of pedestrians the suggested load factors for the four harmonics could be increased by as much as 50% so that the amplitudes reflect the maxima obtained for running-on-the-spot.

9.2 *Rhythmic Exercises*

Suggested load factors are primarily the maximum for jumping by eight people. Load factors up to 50% larger than those given in Table 3 should be considered for the second and third harmonics for small or well-coordinated groups.

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11 REFERENCES

[1] National Building Code of Canada, 1985. Associate Committee on the National Building Code, National Research Council of Canada, Ottawa, Canada, NRCC 23174, 600 p.

[2] Supplement to the National Building Code of Canada, 1985. Commentary A, Serviceability Criteria for Deflections and Vibrations. Associate Committee on the National Building Code, National Research Council of Canada, Ottawa, Canada, NRCC 23178, p. 146-152.

[3] Allen, D.E., Rainer, J.H., and Pernica, G. (1985), "Vibration Criteria for Assembly Occupancies". Canadian Journal of Civil Engineering, 12(3), p. 617-623

[4] Rainer, J.H. and Pernica, G. (1986), "Vertical Dynamic Forces From Footsteps". Canadian Acoustics, 14(2), p. 12-21.

[5] Rainer, J.H., Pernica, G. and Allen, D.E. (1988), "Dynamic Loading and Response of Footbridges". Canadian Journal of Civil Engineering, 15(1), p. 66-71.

[6] Rainer, J.H. and Pernica, G., (1985), "Vibration Characteristics of a Floor Sample", National Research Council of Canada, Division of Building Research, NRCC 24298, 27 p.

[7] Matsumoto, Y., Nishioka, T., Shiojiri, H. and Matsuzake, K. (1978) "Dynamic Design of Footbridges". International Association for Bridges and Structural Engineering, Proceedings P-17/18. p.1-15

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