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Dynamic Loading and Response of Footbridges

by J.H. Rainer, G. Pernica and D.E. Allen

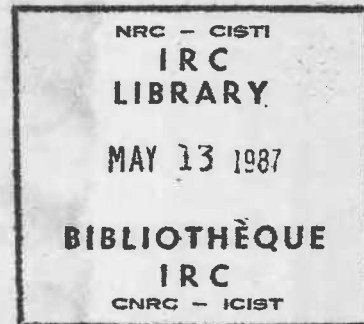
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RÉSUMÉ

On a mesuré, à l'aide d'une plate-forme instrumentée, les forces dynamiques qui s'exercent lors de la marche, de la course et du saut. Les résultats sont exprimés sous forme d'amplitudes des forces sinusoïdales normalisées par le poids du sujet et rapportées à la fréquence. On a constaté que les charges dynamiques maximales au pas de marche étaient près de deux fois plus grandes que celles recommandées dans le Ontario Highway Bridge Design Code de 1983 ou la norme britannique BS5400, et celles au pas de course ou en saut plus de six fois plus grandes.

Les réponses des passerelles sont calculées au moyen d'une formule simple basée sur la charge dynamique due à une personne, la réponse d'une travée simple en résonance, et la durée limitée de l'excitation. On a obtenu une bonne concordance avec la réponse mesurée de deux travées expérimentales de 17 m soumises à une excitation humaine, à la fois pour la première et pour la deuxième harmonique de la fréquence du pas. Les vibrations de résonance des travées peuvent être réduites considérablement par l'emploi d'amortisseurs.

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DYNAMIC LOADING AND RESPONSE OF FOOTBRIDGES

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SUMMARY

Dynamic forces were measured during walking, running and jumping, using an instrumented platform. The results are expressed as sinusoidal force amplitudes normalized by the subject's weight and plotted versus frequency. The maximum dynamic loads for walking were found to be nearly twice as large as those recommended in the 1983 Ontario Highway Bridge Design Code or the British Standard BS5400, and those for running or jumping, more than six times as large.

Responses of footbridges are calculated using a simple formula based on the dynamic loading due to one person, the response of a simple span at resonance, and limited duration of excitation. Good agreement was obtained with the measured response of two 17 m experimental spans subjected to human excitation, for both the first and second harmonics of the step rate. The resonant vibrations of the spans can be substantially reduced by resonant dampers.

1. INTRODUCTION

Since the primary purpose of footbridges is the conveyance of pedestrians, such bridges need to be safe and to exhibit acceptable behaviour for users. Walking, running, and jumping produce dynamic forces and, as a consequence, a vibrational response which can annoy or alarm people. Serviceability will therefore be a major design consideration.

A number of studies have dealt with the problem of vibrating footbridges [1-4]. Design requirements and guidelines have been established, such as the British Standard BS5400 [5], the 1983 Ontario Highway Bridge Design Code (OHBDC) [6] and those used in Australia [3]. The OHBDC bases its design requirements and recommendations largely on BS5400, but has an additional condition that the lowest natural frequency (f_0) shall not be less than 4 Hz. Both codes specify a dynamic design load of $180 \sin(2\pi ft)$ newtons. The resulting vibrations shall not exceed $0.5\sqrt{f_0}$ m/s² in BS5400 and half of that in OHBDC. Wheeler [3] presented a study of footbridge vibrations in Australia, in which the pedestrian model was a sequence of measured single-step force pulses. The acceptance level was based on the "unpleasant" boundary contour by Kobori and Kajikawa [7].

This paper presents the results of force measurements from persons walking, running and jumping, and a comparison between calculated and measured responses of two test structures. Comparisons are made with available design procedures for acceptability of vibrations on footbridges.

2. FORCES INDUCED BY PEDESTRIAN MOTION

A number of previous studies of forces induced by human activity can be found in References 8 to 11. These employed the forces produced by one step and then formed a simulated walking sequence by adding single step results with appropriate time delays. The present investigation measures directly the continuous dynamic forces produced by one or more persons walking, running or jumping.

2.1 Test Procedure and Analysis

The effects of walking and running were determined for a platform 17 m long by installing load cells at a centre support. A plan view and elevation of the platform are shown in Fig. 1. Further details of the construction and measurement techniques are presented in Reference 12.

The tests were conducted by playing pre-recorded pulses at the desired walking or running rate through loudspeakers, and requesting the subject to walk or run along the span at the pulse rate using a stride of his own choosing. The lowest natural frequency of the instrumented floor strip was 12 Hz. Useful results were limited to frequencies below about 10 Hz, since beyond that frequency the dynamic amplification becomes large and rather sensitive to damping.

2.2 Results of Force Measurements

2.2.1 Walking: A typical record of the force induced at the centre support due to a single person walking is shown in Fig. 2a. The record contains only the dynamic portion of the induced forces, since the static component has been eliminated by a 0.2 Hz high pass filter. These forces are bounded by a

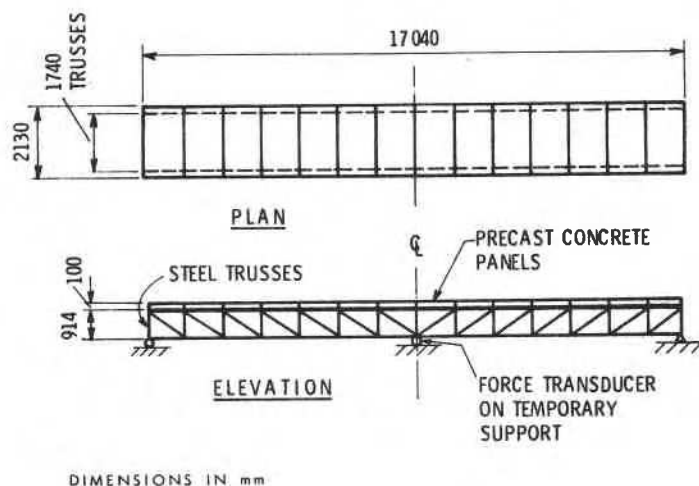


Figure 1. Instrumented platform (Span 1)

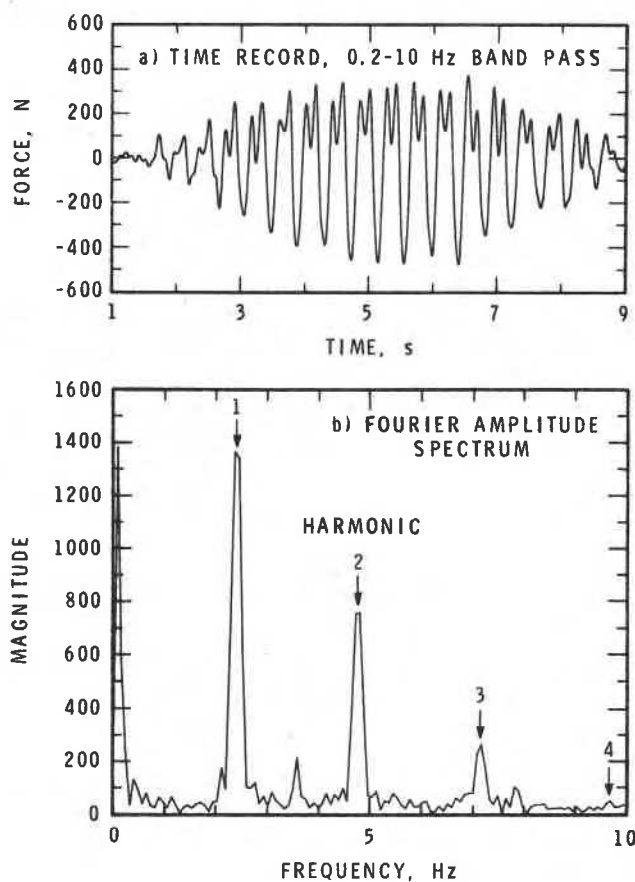


Figure 2. Forces from walking at 2.4 steps per second, Subject A

parabolically shaped envelope that corresponds to the static influence line for the mid-span support of the test platform. The Fourier amplitude spectrum of this force record is shown in Fig. 2b. The spectrum shows that the force produced by one person walking consists of distinct frequency components at integer multiples (harmonics) of the footstep rate, with amplitudes that

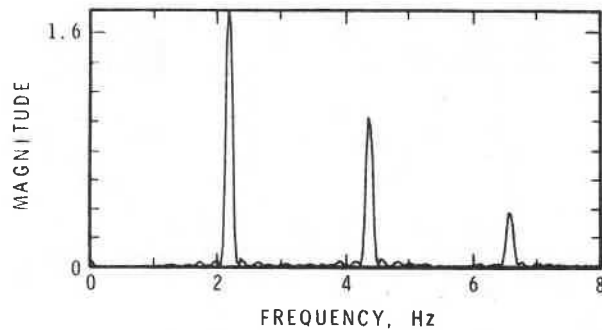


Figure 3. Fourier amplitude spectrum of forces due to jumping at 2.2 jumps per second

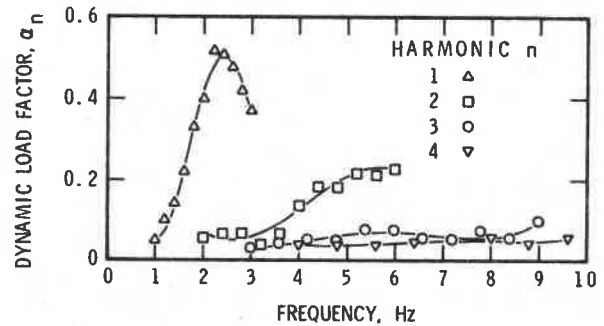


Figure 4. Averaged dynamic load factors for walking, Subjects A, B and C

decrease with increasing frequency. The first three or four harmonics comprise the main dynamic components of walking forces. As the time record in Fig. 2a shows, the forces are periodic functions of the footstep rate.

2.2.2 Running: The forces from one person running are similar to those for walking, except that they are truncated below zero during the time the runner is airborne. The Fourier spectrum of the force record again contains discrete frequency components at harmonics of the footstep rate.

2.2.3 Jumping: The jumping forces consist of a sequence of isolated pulses separated by a section of zero force [13]. The Fourier spectrum of the force record (Fig. 3) again consists of harmonic components similar to that for walking.

2.3 Mathematical Representation of Forces

The above analysis of force records indicates that the forces ($F(t)$) from walking, running, and jumping can be represented by:

$$F(t) = P \left(1 + \sum_{n=1}^N \alpha_n \sin(n2\pi ft + \phi_n) \right) \quad (1)$$

where P = static weight of person;
 α = Fourier amplitude or coefficient;
 n = order of harmonic of the footstep rate, $n = 1, 2, 3, \dots$
 f = footstep rate in steps per second;
 t = time;
 ϕ = relative phase angle;
 N = total number of harmonics.

The dynamic component of the activity force in Eq. (1) is represented by the summation term, which is a Fourier series with Fourier coefficients α_n at the discrete frequencies nf . These correspond to the centre amplitudes of the various harmonics of the force record as in Fig. 2a, normalized by the person's weight (P).

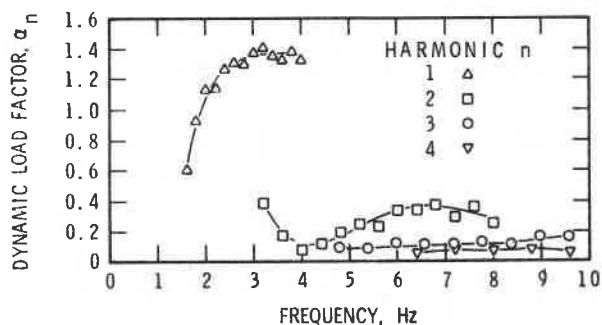


Figure 5. Averaged dynamic load factors for running, Subjects A, B and C

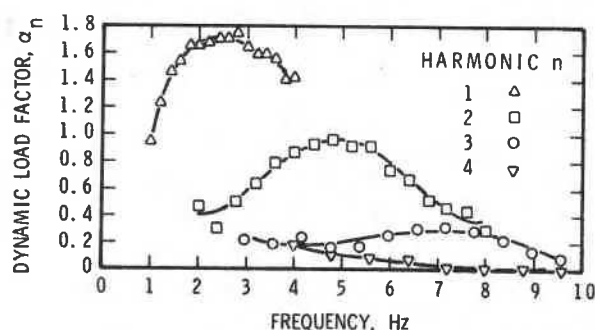


Figure 6. Averaged dynamic load factors for jumping, Subjects A, B, C and D

2.4 Variation of Dynamic Forces With Step Frequency

The key parameters in Eq. (1) that describe the dynamic force are the Fourier coefficients (α_n) and the footstep frequency (f). In a manner similar to that used to describe rhythmic forces [13,14], the Fourier coefficients (α_n) are called "dynamic load factors", which are defined as the ratio of the force amplitude of each harmonic to the weight of the person. The variation of α_n with step frequency was studied for walking rates from 1.0 to 3.0 Hz, running rates between 1.6 and 4.0 Hz, and jumping rates from 1.0 to 4.0 Hz. The results of each activity for the test subjects were averaged and are shown in Figs. 4, 5 and 6. Results for individual test subjects are similar to the averaged ones and are presented in Reference 13 for walking and running. Figure 4 shows that for walking, the dynamic load factor of the first harmonic (α_1) is the largest, at 2.4 Hz, and reaches an averaged maximum of 0.52. For running, Fig. 5 shows a maximum averaged value for α_1 of about 1.4 between 2.8 and 4.0 Hz, whereas for jumping, Fig. 6 shows the maximum averaged α_1 to be about 1.75 between 2 and 3 Hz.

Not all of these rates are equally likely to occur in practice, however. Walking rates are generally within 1.7 to 2.3 steps per second, with a mean rate of 2.0 [4], whereas running or jogging rates range from 2 to 3 steps per second.

2.4.1 Multiple Persons Jumping: For groups of two or four people jumping to a common timing signal, the peak value for α_1 was little different than that for a single person jumping, although the peaks for the second harmonic are about 15% lower. For eight persons jumping, however, the dynamic load factor for the first harmonic was about 15% lower, and that of the second harmonic (α_2), 50% lower than for a single male. The third harmonic (α_3) was reduced even more relative to that for one person.

3. RESPONSE OF TEST SPANS TO PEDESTRIAN MOVEMENT

Two simply-supported test spans were located side by side for dynamic testing. Span 1, the trussed span shown in Fig. 1, but with the centre support removed, had a fundamental natural frequency (f) of 4.17 Hz. Span 2, a structure of equal length and decking but using two wide-flange beams as the main

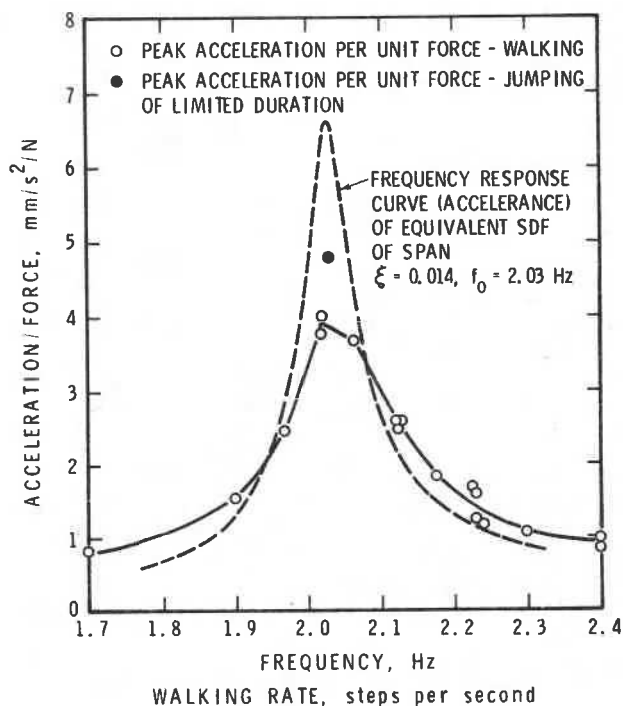


Figure 7. Peak acceleration per unit force and frequency response curve for Span 1

structural members, had a fundamental natural frequency (f) of 2.05 Hz. A single test subject weighing 735 N was used to excite the spans at selected step frequencies as given by an audible pulse. The response of each span was measured by two vertical accelerometers at midspan; their signals were added, recorded and analyzed. The dynamic load factors for walking and running for the test subject were reported in Reference 12 under "Subject A".

3.1 Span 2, $f = 2.05$ Hz

The peak acceleration response of Span 2 to different walking rates is shown in Fig. 7. This plot has been normalized by the force input; i.e., by the weight of the test subject times the dynamic load factor applicable to each walking rate. The peak response occurs when the walking rate coincides with the fundamental frequency of the span. These results were compared with the steady-state frequency response curve of the span in the form of "accelerance" (acceleration/force input) at midspan, shown in Fig. 7 by the dashed line. At resonance, the normalized response from walking is considerably lower than for steady state, whereas below and above resonance, the peak response for walking is slightly larger. The difference at resonance is caused by the limited duration and changing amplitude of the effective walking force (Fig. 2a). Away from resonance, the larger walking responses can be attributed to beating between the forced response at the walking frequency and the simultaneously excited vibration at the resonance frequency of the span. It is the response at resonance that is maximum, however, and only this will be addressed here.

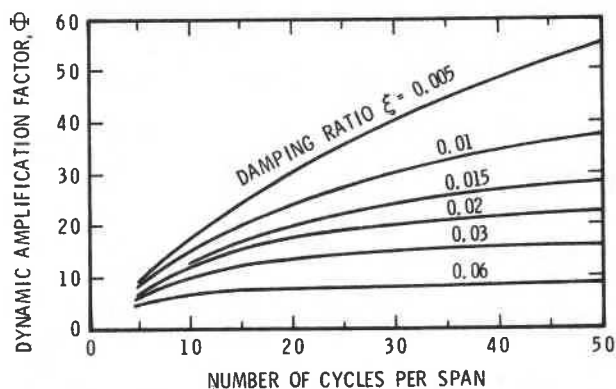


Figure 8. Dynamic amplification factor for resonant response due to sinusoidal load moving across simple span

3.2 Calculation of Resonant Response

3.2.1 Walking: To calculate the peak dynamic response at midspan, the span is modelled as an equivalent single-degree-of-freedom (SDF) oscillator. The amplitude of the sinusoidal excitation at the walking frequency is $F = \alpha P$. As the pedestrian crosses the span, the effective force variation across the span is enveloped by a curve corresponding to the fundamental mode shape with maximum αP occurring at midspan. When such a force variation is applied to the SDF vibration model of the span, the maximum response is given by a dynamic amplification factor (Φ), similar to but smaller than the dynamic amplification factor for steady state excitation. The factor Φ for simply supported spans as a function of the number of cycles applied and various damping ratios has been calculated and is presented in Fig. 8. This amplification factor decreases with an increase in the damping ratio and increases monotonically towards the steady state solution with increasing number of cycles of excitation, i.e. with the number of steps it takes the person to traverse the span. Thus the peak acceleration response (a) at the fundamental frequency is given by:

$$a = (2\pi f)^2 \frac{\alpha P}{k} \Phi . \quad (2)$$

$\alpha P/k$ is the static displacement at midspan due to the dynamic force amplitude, and multiplication by $(2\pi f)^2$ converts the displacement to acceleration.

An alternate expression for Eq. (2) is obtained by substituting $(2\pi f)^2 = k/m$:

$$a = \frac{\alpha P}{m} \Phi , \quad (2b)$$

where m = mass of equivalent SDF oscillator. For a uniform simply supported beam, $m = 17/35$ times the total mass (M) of the span, which is often approximated as $m = 0.5 M$. Thus,

$$a = \frac{2\alpha P}{M} \Phi . \quad (3)$$

Eq. (3) indicates that the acceleration response of a span when excited at its natural frequency is directly proportional to the dynamic load (αP) and the

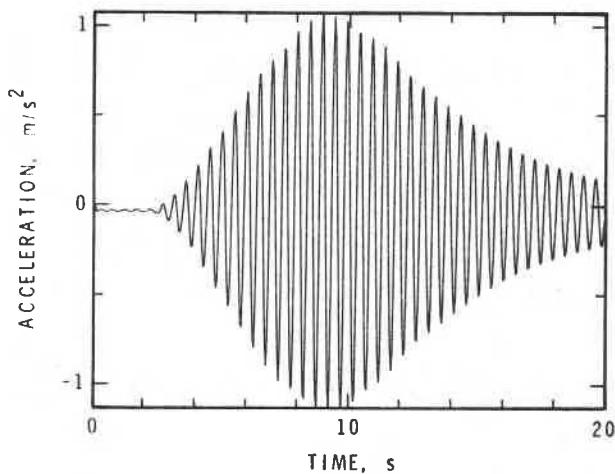


Figure 9. Response of Span 2 to walking at 2.06 steps per second

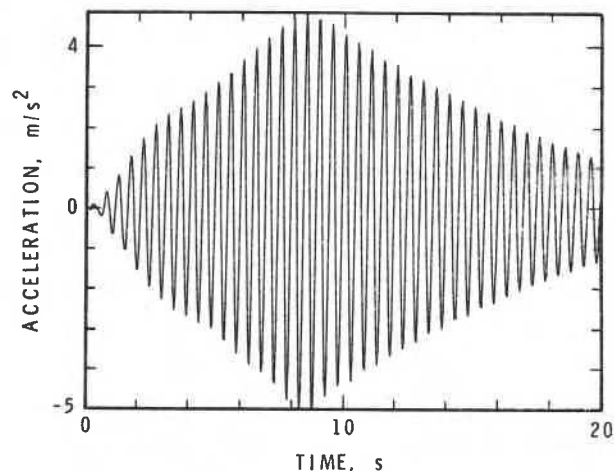


Figure 10. Response of Span 2 due to jumping at resonance frequency

amplification factor (Φ), and inversely proportional to the total mass of the span.

For calculating the response of Span 2 to walking, the following data were used:

- $\alpha = 0.41$ (Subject A [12]);
- $P = 735$ N;
- $\Phi = 20$ for damping ratio of 1.43% and 19 steps (Fig. 8);
- $k =$ measured stiffness of span at centre, 897000 N/m;
- $f =$ resonance frequency of span, 2.05 Hz.

Substitution in Eq. (2) gives a peak acceleration of 1.06 m/s^2 , or 11% of gravity. This compares well with the maximum measured response at resonance of 1.14 m/s^2 . Figure 9 shows the response of Span 2 to the test subject walking at a rate that coincides with the natural frequency of the span.

3.2.2 Running: As for walking, the response of Span 2 to running is also given by Eq. (2) or (3). With a dynamic load factor $\alpha = 1.1$ at 2.05 Hz (subject A [12]), the calculated peak acceleration is 3.14 m/s^2 . The measured acceleration for the test subject running at 2.05 steps per second is 3.3 m/s^2 . When the running rate does not coincide with the resonance frequency of the span, the response is significantly reduced; at 3.0 steps per second, a peak acceleration of 0.4 m/s^2 was measured.

3.2.3 Jumping: Span 2 was excited at the resonance frequency by the test subject jumping at centre span, and the response is shown in Fig. 10. Since this represents a steady state excitation, much greater response can be expected than from walking or running. At the peak acceleration of 5 m/s^2 (and up to 6 m/s^2 for other tests) the excitation was stopped, but this was evidently not the limit to which the span could have been excited. Using $\alpha = 1.7$ at 2.05 Hz (subject A [12]), this response of 6.0 m/s^2 corresponds to an acceleration-to-force ratio of $4.8 \text{ mm/s}^2/\text{N}$ and is shown in Fig. 7 by the solid circle. An upper bound response, corresponding to the peak of the

frequency response curve in Fig. 7, can be calculated from the relation applicable to steady state excitation:

$$a = (2\pi f)^2 \frac{\alpha P}{k} \frac{1}{2\xi}, \quad (4)$$

or, with the substitution as for Eq. (3),

$$a = \frac{\alpha P}{M\xi}, \quad (5)$$

where ξ = critical damping ratio.

For Span 2 this gives a peak acceleration of 8.0 m/s^2 or a peak dynamic displacement of 49 mm. The possibility that the damping ratio changes at these large amplitudes needs to be considered. It seems plausible, however, that a response close to this full resonance response can be reached. Such a response level, often referred to as "vandal" excitation, should thus be considered in the design procedure and a check on stresses carried out.

3.3 Span 1: $f = 4.17 \text{ Hz}$

The results from the force measurements presented in Figs. 4, 5 and 6 indicate substantial components also at twice and, to a lesser degree, at 3 or 4 times the walking, running or jumping rate [12]. Thus a resonant condition could also be produced at these higher harmonics. This was investigated on Span 1. Walking rates were chosen so that the second harmonic of the forces falls near the natural frequency of the span. The measured peak accelerations are shown in Fig. 11. A peak acceleration of nearly 0.8 m/s^2 occurred at a walking rate of 2.08 steps per second, which corresponds to an excitation frequency of 4.16 Hz that is provided by the second harmonic of the walking forces.

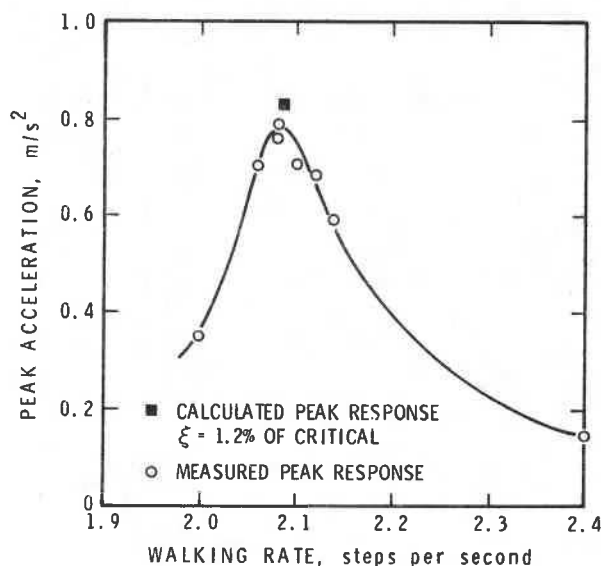


Figure 11. Peak responses of Span 1 to walking

The response to walking of Span 1, having a natural frequency of 4.17 Hz, will now be determined by the proposed procedure, Eq. (2) or (3). For the test subject walking, the dynamic load factor α_2 of the second harmonic at 4.17 Hz is 0.20; for 36 cycles, double the number of steps, the amplification factor

$\Phi = 31$ from Fig. 8 for the applicable damping ratio $\beta = 1.2\%$. Substitution in Eq. (2) gives:

$$a = 4\pi^2(4.17)^2 \frac{(0.20)(735)}{3720 \times 10^3} (31) = 0.84 \text{ m/s}^2 .$$

This compares with a measured peak response of 0.80 m/s^2 for walking by the test subject.

4. COMPARISONS WITH BS5400 AND ONTARIO HIGHWAY BRIDGE DESIGN CODE (OHBDC)

The procedure used here and the methods outlined in BS5400 [5] and OHBDC [6] need to be compared using a consistent set of assumptions. Although the stated forcing function in BS5400 and OHBDC is $F = 180(\sin 2\pi ft)$ newtons to represent forces from walking, this is not used explicitly. Instead, the acceleration is calculated from an equivalent static deflection (w_g) due to a person weighing 700 N:

$$a = 4\pi^2 f^2 w_g K \psi \quad (6)$$

where f = natural frequency of span;
 K = configuration factor;
 ψ = dynamic response factor.

The stiffness k at the centre of Span 2 was measured as 897 N/mm, so the deflection due to a 700 N person is $w_g = 0.780$ mm, $K = 1.0$ for a simple span, and $\psi = 7.5$ from the graphs in References 6 and 7. Thus the calculated acceleration (a) is 0.97 m/s^2 .

The response calculation given by Eqs. (2) or (3) results in a peak acceleration (a) of 1.06 m/s^2 , using $f = 2.03$ Hz, $\alpha = 0.41$, $P = 735$ N, and $\Phi = 19$ for 18 steps at 1.4% damping. This compares favourably with the measured peak response for the fundamental mode of 1.05 m/s^2 .

Although the final answers from BS5400 and OHBDC and the method proposed here are in good agreement, the values for the parameters used are quite different (Table 1).

Table 1: Response Calculations and Measured Values for Span 2

Method	α	P (N)	Dynamic Factor	Peak Acceleration (m/s^2)
Proposed method	0.41	735 700	$\Phi = 19$ (Fig. 8)	1.06 1.01
BS5400, OHBDC	180/700 = 0.257	700	$\psi = 7.5$ [5,6]	0.97
Measured		735		1.05

The differences in α and the dynamic factors Φ and ψ largely compensate one another in the two calculation methods. The proposed method, however, has a wider application in that it would permit a designer or investigator to substitute different parameters that are applicable to other specific loading cases. For example, Eqs. (2) and (3) apply to walking and running for one or

more people in step, and Eqs. (4) and (5) apply to jumping. These formulas can also be used with other than the first harmonic of the forcing function, as for example when the natural frequency of the span coincides with the second harmonic of the excitation.

The criterion given by BS5400 is that the peak response should not exceed $0.5\sqrt{F}$ m/s². For Span 1, $0.5\sqrt{2.05} = 0.72$ m/s², while for Span 2, $0.5\sqrt{4.17} = 1.02$ m/s². The permissible values in the OHBDC are half these, i.e., 0.36 and 0.51 m/s², for Span 1 and Span 2, respectively. Thus the observed accelerations for walking on Span 1 exceed the criteria under BS5400, and the accelerations on both spans exceed the criteria under OHBDC. A subjective assessment of the investigators would support the OHBDC result, although this perception would not necessarily be applicable to in-service behaviour.

5. RESPONSE REDUCTION BY RESONANT DAMPERS

Resonant dampers were constructed with natural frequencies of 2.06 and 2.14 Hz, applied at midspan of Span 2. A series of walking tests was performed and the resulting peak accelerations for various damper properties plotted in Fig. 12. Comparison with results without the damper shows major reductions in peak accelerations, well below the criteria quoted above. A similar observation was made when a resonant damper was applied to Span 1. Thus the objectionable vibrations at the resonant frequencies of the spans can be drastically reduced by an appropriately sized resonant damper. This confirms what other investigators [1,3,4] have reported. Footbridges could therefore be designed with a resonant damper, or provision can be made for using one as a retrofit measure, should objectionable vibrations occur. The latter strategy may be a cost-effective solution, particularly in view of uncertainties in estimating damping and calculating the natural frequency of the structure.

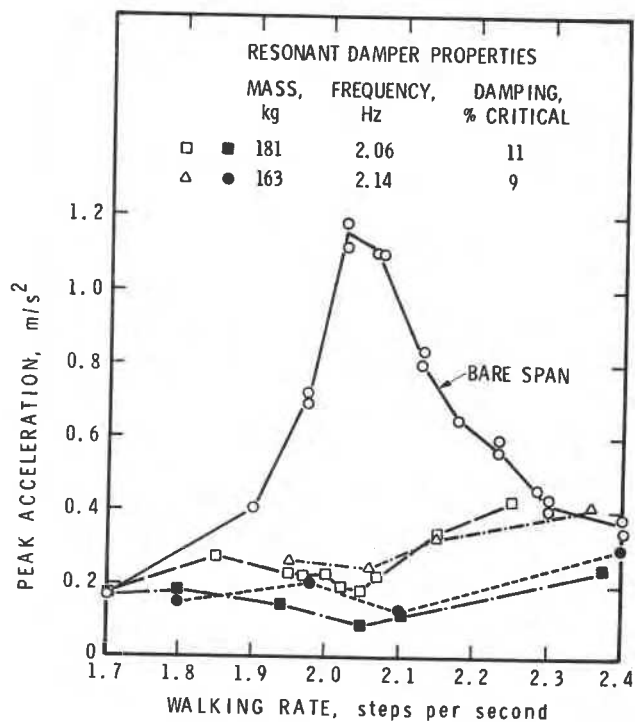


Figure 12. Response reduction due to resonant damper

6. CONCLUSIONS

Dynamic forces for walking, running and jumping have been presented for the range of step frequencies usually associated with these activities. The loading function primarily consists of up to four harmonic components with frequencies of integer multiples of the footstep rate and decreasing amplitudes for the higher frequencies.

A procedure is described for evaluating the response of simple spans to walking, running and jumping excitations at the resonance frequencies. The peak acceleration response at the frequency resonance of two test spans is computed. This is similar to the method in BS5400 and OHBDC, except that the latter two do not fully reflect the actual loading functions. The new procedure permits the designer to employ other loading functions that may be applicable to footbridges, as, for example, where excitation arises from the second harmonic component of pedestrian movement. The predicted peak accelerations are verified by tests on two laboratory footbridges. It is suggested that the response to jumping also be considered in design.

7. ACKNOWLEDGEMENTS

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