Man-Induced Vibrations

Jönsson, Jeppe; Hansen, Lars Pilegaard

Published in:
Proceedings of "Dynamics of Structures"

Publication date:
1994

Document Version
Accepteret manuscript, peer-review version

Man-Induced Vibrations

J. Jönsson and L. Pilegaard Hansen
Department of Building Technology and Structural Engineering,
Aalborg University, Sohngaardsholmsvej 57, 9000 Aalborg, Denmark

Introduction

Human motion can cause various types of periodic or transient dynamic loads. The periodic loads are mainly due to jumping, running, dancing, walking and body rocking. Transient loads primarily result from single impulse loads, such as jumping and falling from elevated positions. The response to these loads are of primary interest for the structural engineer, whereas the exact load as a function of time generally is of minor importance. This is true when the loading time (contact duration) t_p is small compared to the largest natural periods $T_n = 2\pi/\omega_n$ of the structure. The present study is mainly concerned with spectator-induced vertical vibrations on grandstands. The idea is to use impulse response analysis and base the load description on the load impulse. If the method is feasable, it could be used in connection with the formulation of requirements in building codes.

During the last two decades work has been done on the measurement of the exact load functions and related reponse analysis. A recent work using a spectral description has been performed by Per-Erik Erikson [9] and includes a good literature survey. Bachmann and Ammann [1] give a good overview of vibrations caused by human activity. Other relevante references have been included in the reference list.

Periodic motion

The forces acting on a human body performing periodic motion can be decomposed in several ways. In this section the vertical motion is considered. A body shown in figure 1 (left) with mass m is acted upon by a gravitation force $F_g = mg$, a constant reaction force $F_c = \gamma mg$ and a dynamic force F_d. The constant reaction force F_c exists, if the body is in continous contact with a structure and it is the

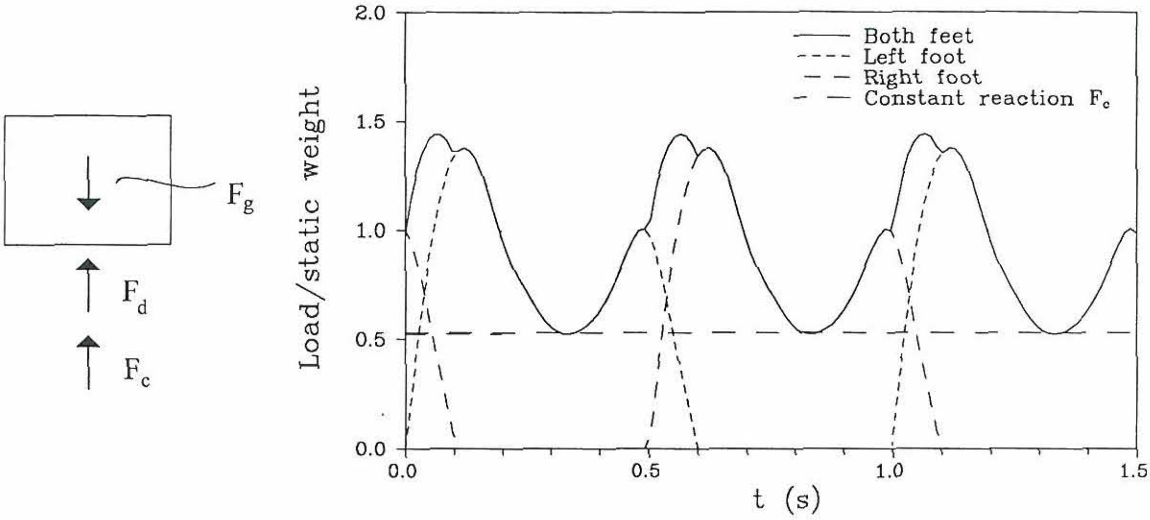

Figure 1: Forces on body and load-time function for brisk walk.

minimum value of the total reaction force ($R = F_c + F_d$). The remaining force is the dynamic force $F_d \geq 0$. The motion of the body is determined by

$$m\ddot{x} = F_d + F_c - F_g \tag{1}$$

The momentum of the periodic motion is also periodic. Conservation of momentum over one time period T_p is found as

$$\int_0^{T_p} (F_d + F_c - F_g)\, dt = 0 \tag{2}$$

Upon inserting the constant forces F_g and F_c the equation (2) yields the periodic impulse I of the dynamic force:

$$I = \int_0^{T_p} F_d\, dt = (1-\gamma)mgT_p \tag{3}$$

Simple human motions can often be modelled by a few periodic impulses. The load-time function of walking, shown in figure 1 (right) could be modelled by a constant reaction force F_c and one periodic load function F_d (impulse). In a simple model F_d would consist of periodic Dirac impulses corresponding to impacts on the structure. Between impacts the body moves in a conservative force field. The simple model then corresponds to bouncing of a ball. Anticipating that the center of mass of the body moves a distance h in the vertical direction, the maximum change in potential energy is $(1-\gamma)mgh$. Setting the maximum potential energy equal to the kinetic energy before impact $\frac{1}{2}mv^2$ yields the impact velocity:

$$v = \sqrt{2(1-\gamma)gh} \tag{4}$$

The change in momentum ΔP due to impact is determined by the mass and the change in velocity $2v$:

$$\Delta P = 2mv = 2m\sqrt{2(1-\gamma)gh} \tag{5}$$

Setting the momentum change equal to the impulse of the dynamic force $I = \Delta P$ yields

$$\gamma = 1 - \frac{8h}{gT_p^2} \tag{6}$$

For discontinous contact such as jumping ($\gamma = 0$) equation (6) gives a direct mechanical link between the motion height and the time period, eg. $h = \frac{1}{8}gT_p^2$. For continous contact it can be used for estimation of the static reaction force. Using a load time function from brisk walk from Baumann & Bachmann [2] with $T_p = 0.5s$ and $\gamma = 0.53$, shown in figure 1 (right), the vertical movement of the center of mass becomes $h = 0.14m$.

In the case of human motion we can estimate the movement of the center of mass, whereby it is possible using equation and (3) and (5) to find the impulse needed for the periodic motion. If the human motion is known as a function of time, the time derivative of the momentum gives the total force on the body $F = \frac{d}{dt}(mv)$. This would enable determination of the load function.

Impulse response

The structural response to the impulsive loads from for example human motion is considered in the next two sections, først for a single impulse load and secondly for one periodic impulse load.

For a single degree of freedom system with (structural) mass M, undamped eigenfrequency ω_n and damping ratio ξ the displacement response to a Dirac impulse I is given by

$$\delta = \frac{I}{M\omega_d} e^{-\xi\omega_n t} \sin \omega_d t \tag{7}$$

where the damped eigenfrequency is $\omega_d = \omega_n\sqrt{1-\xi^2}$. For impulses of finite time duration t_p, the shape of the force time function has to be taken into account. For different impulse shapes figure 2 (left) shows the dynamic magnification factor κ corresponding to the ratio between the maximum dynamic and static response. The magnification factor has been calculated using a damping ratio of $\xi = 0.05$, but could conservatively be calculated for zero damping.

An impulse correction factor α can be found by normalizing the maximum dynamic response with the Dirac impulse response. Figure 2 (right) shows the impulse correction factor for different impulse shapes. An approximation of the impulse response can thus be obtained by using the Dirac impulse response (7) multiplied by the correction factor α.

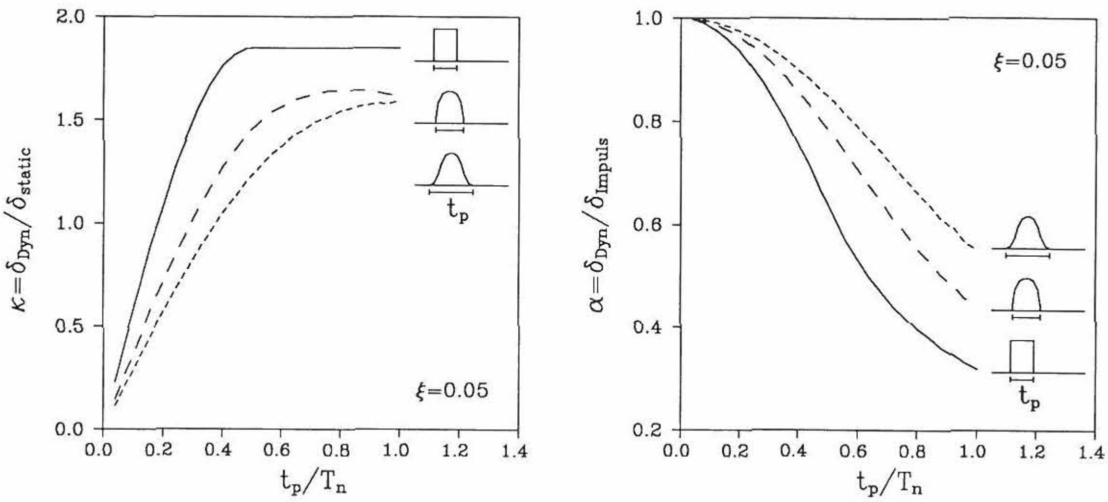

Figure 2: Dynamic magnification factor κ and impulse shape correction factor α.

Periodic impulse response

For a Dirac impulse acting periodically with the period T_p on the damped single degree of freedom system, the response has be found analytically as

$$\delta = \frac{I}{M\omega_d} e^{-\xi\omega_n t} \left(\frac{A}{C} \sin\omega_d t + \frac{B}{C} \cos\omega_d t \right) \tag{8}$$

where the constants are determined as

$$\begin{aligned} A &= 1 - e^{-\xi\omega_n T_p} \cos\omega_d T_p \\ B &= e^{-\xi\omega_n T_p} \sin\omega_d T_p \\ C &= 1 - 2e^{-\xi\omega_n T_p} \cos\omega_d T_p + e^{-2\xi\omega_n T_p} \end{aligned}$$

The maximum displacement response is found at the time

$$t_{ext} = \frac{1}{\omega_d} \arctan\left(\frac{\xi\omega_n B - \omega_d A}{\xi\omega_n A + \omega_d B} \right) + \frac{n\pi}{\omega_d} \tag{9}$$

where n is the lowest integer for which $t_{ext} > 0$. For multiple periodic Dirac impulses superposition can be used and t_{ext} would have to be found for the superimposed responses.

Using a Fourier series solution to find the "correct" response of the periodic half-sine impulse it is possible to compare the maximum response with that of the periodic Dirac impulse response multiplied by the impulse shape correction factor

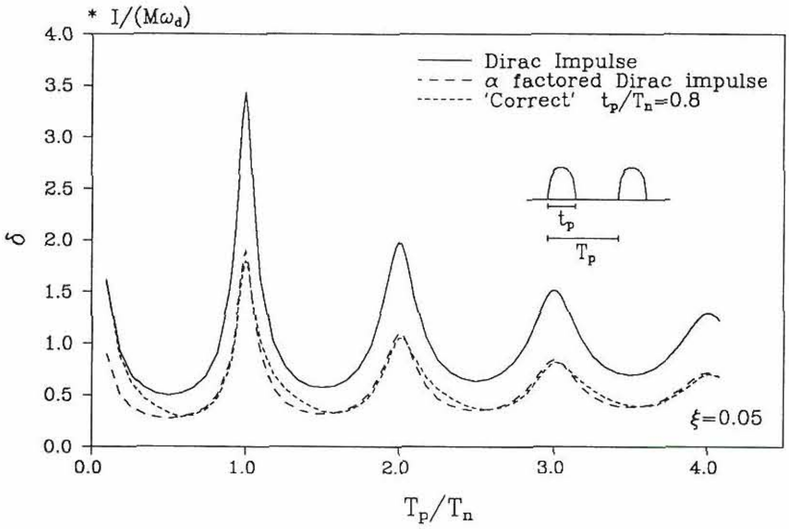

Figure 3: Periodic Dirac impulse response (half-sine impulse).

α. Computing the results for a variety of t_p/T_n ratios and for T_p/T_n ratios in the interval $]0,4]$ shows that the scaled periodic Dirac impulse response is a good approximation. For $t_p/T_n = 0.8$ the results are shown in figure 3. It is seen that the agreement is good even for this large contact duration compared to the natural period. For the case $t_p/T_n = 0.8$ shown in figure 3, it is worth noting that below $T_p/T_n = 0.8$ the impulse time durations overlap, resulting in a static response from the constant reaction part F_d of the load. This has currently not been further investigated.

Experimental ideas

The experimental part of this research project will monitor the movements of the person or persons participating in the experiment, so that it will be possible to estimate the movement of the center of mass. A simple model of a person could consist of 2 parts for each leg and arm, one part for the body and one for the head, thus giving 10 rigid moving parts. The center of mass would have to be confirmed with medical research.

The experiments will be carried out in two main phases, one in the laboratory and another at a grandstand at a rock concert or a football match. In the laboratory there will probably be three stages. In the first stage the body motion and the load as a function of time will be measured on a small platform mounted on a stiff laboratory floor for jumping and the special wave motion ("the wave" seen at football matches). In the second stage the load measuring platform will be mounted on a simple beam structure and the measurements repeated on the beam both on and off the platform. The eigenfrequency of the beam structure may be varied by altering support conditions. In the third stage the effect of multiple persons on the beam will be measured.

At the grandstand measurements will be performed for one person jumping, for multiple persons jumping and for real situations either at concerts or at football matches.

References

[1] H. Bachmann and W. Ammann. *Vibrations in structures - Induced by man and machines*, IABSE, Zürich, 1987.

[2] K. Baumann and H. Bachmann. *Durch Menschen verursachte Lasten und deren Auswirkungen auf Balkentragwerke*, Bericht Nr. 7501-3, Institut für Baustatik und Konstruktion, ETH Zürich, 1988.

[3] A. Ebrahimpour and R. L. Sack. Modeling dynamic occupant loads. *Journal of Structural Engineering*, Vol. 115, No. 6, 1989.

[4] A. Ebrahimpour, R. L. Sack and P. D. Van Kleek. Computing crowd loads using a nonlinear equation of motion, *Computers & Structures*, Vol. 41, No. 6, pp. 1313-1319, 1991.

[5] A. Ebrahimpour and R. L. Sack. Design live loads for coherent crowd harmonic movements,*Journal of Structural Engineering*, Vol. 118, No. 4, 1992.

[6] P-E. Eriksson and S. Ohlsson. Dynamic Footfall loading from groups of walking people. *Proc. of Symposium/Workshop on Serviceability of Buildings*, Vol. 1, NRCC, Ottawa, Canada, pp. 497-511, 1988.

[7] P-E. Eriksson. Modal analysis of pre-cast concrete floor element, *Proc. of the 9th International Modal Analysis Conference*, Firenze, Italy 1991. Published by the Society for Experimental Mechanics, USA, 1991.

[8] P-E. Eriksson. Vibration of low-frequency floors - offices and shopping centers. *Proc. of the First World Conference on Constructional Steel Research*, (Acapulco), Elsevier Science Publishers Ltd., Barking , England, pp. 409-418, 1992.

[9] P-E. Eriksson. *Vibration of low-frequency floors - Dynamic Forces and response Prediction*, Doctoral thesis, Publication D 94:3. Unit for Dynamics in Design, Chalmers University of Technology, Göteborg, Sweden, 1994.

[10] F. C. Harper. The mechanics of walking, Research applied in industry, Vol. 15, pp. 23-28, 1962

[11] L. Nilsson. *Impact loads produced by human motion. Part 1: Background and experimental investigation*, document D13:1976, Swedish Council for Building Research, 1976.

[12] L. Nilsson. *Impact loads produced by human motion. Part 2: Requirements for Structures and Methods of test*, document D20:1980, Swedish Council for Building Research, 1980.

[13] S. V. Ohlsson. *Floor vibrations and human discomfort*, Department of Structural Engineering, Chalmers University of Technology, Göteborg, Sweden, 1982

[14] S. V. Ohlsson and P-E. Eriksson. Structural serviceability of commercial steel buildings - General aspects and vibrations, *Proc. of the Nordic Steel Colloquium*, Danish Steel Institute, pp. 79-88, 1991.

[15] S. V. Ohlsson. Serviceability criteria - especially floor vibration criteria, Proceedings of the *1991 International Timber Engineering Conference, London*, Vol. 1, pp, 1.58-1.65. Published by TRADA, High Wycombe, U.K. 1991.

[16] S. Ohlsson and M. Perstorper. Elastic wood properties from dynamic tests and computer modeling, *Journal of Structural Engineering*, Vol. 118, No. 10, 1992.

[17] G. Pernica. Dynamic live loads at a rock concert, *Can. J. Civ. Eng.*, Vol. 10, 1983.

[18] J. H. Rainer and G. Pernica. Vertical dynamic forces from footsteps, *Canadian Acoustics*, Vol 14, no 2, pp 12-21, 1986.

[19] C. Rebelo and R. J. Scherer. A stochastic model for human induced rhythmic loads, *Structural Safety & Reliability*, Schuëller, Shinozuka & Yao (eds), Balkema, Rotterdam, 1994.