Interdependence between Structural Engineering and Construction Management
Edited by Ozevin, D., Ataei, H., Modares, M., Gurgun, A., Yazdani, S., and Singh, A.

ISBN: 978-0-9960437-6-2

A STUDY OF HUMAN GAIT FOR VIBRATION SERVICEABILITY EVALUATION

MEHDI SETAREH and MATT TILLER

Virginia Tech, Blacksburg, USA

The vibration serviceability problem of structures such as building floors, footbridges, large balconies, and monumental stairs due to human movements has become an important issue, which requires careful attention of designers and engineers. Design engineers often create Finite Elements models of structures to predict their dynamic properties and their responses due to human movements. Therefore, one important aspect of the dynamic analysis of structures is the identification and quantification of excitation forces due to human movements. As part of this research study, measurements of ground reaction forces (GRF) from a number of individuals were conducted at the Virginia Tech Vibration Testing Laboratory using an instrumented force platform. The subjects walked at various speeds synchronized using a metronome. The same tests were subsequently repeated while the subjects ascended and descended over an instrumented mock stair. Considering the periodicity of human excitation force, the Fourier Series parameters (Fourier Coefficients and corresponding phase angles) of the measured forcing functions were computed. Correlations between the measured GRF's on a flat surface and an inclined surface (stair) were established. The results of the analysis were compared to the available information in the literature in an attempt to check their accuracy.

Keywords: Ground reaction force, Fourier coefficients, Dynamic load factors, Stair forcing function, Flat-surface forcing function.

1 INTRODUCTION

To predict the dynamic response of a structure subjected to human activities, the designer needs to define the excitation force accurately. In general, the human induced ground reaction force (GRF) on floors or inclined surfaces such as stairs, can be defined using Fourier Series as shown in Eq. (1):

$$F(t) = G\left[1 + \sum_{i=1}^{n} \alpha_i \, sin\left(2\pi i f_p t + \phi_i\right)\right] \tag{1}$$

where $F(t)$ is the applied force, G is the weight of person, α_i is the dynamic load factor (DLF) or Fourier coefficient for the *i-th* harmonic, f_p is the step frequency, t is the time variable, and ϕ_i is the phase angle associated with the *i-th* harmonic.

A number of studies with the aim of computing the DLF for flat surfaces have been conducted and different values and equations have been recommended (Blanchard *et al.* 1977, Bachmann and Ammann 1987, Rainer *et al.* 1988, Bachmann *et al.* 1995, Young 2001, Yao *et al.* 2006). However, few studies have focused on defining DLFs for stair vibration serviceability evaluation purposes. The following is a brief summary of attempts to define the GRF and the DLF values for stairs:

Bishop *et al.* (1993, 1995) found that, in general, ascent has larger first harmonic dynamic load factor (α_1) than descent; however, the opposite is true for the higher harmonics. Kerr and Bishop (1997, 2001) noted much larger second harmonic DLF for descents in particular for higher footfall rates. Also, the first harmonic DLF of fast descents (4.3 Hz) was significantly larger than for normal descents (1.85 Hz). They found no major differences between the DLFs of higher harmonics for descents and ascents. They measured forces up to 3 times the body weight for fast descents and about twice the body weight for slow descents. For fast ascents the measured forces were up to 2.5 times the subjects' body weight.

Kerr (1998) conducted experimental studies to measure forcing function of individuals on stairs. He found that the most important factor affecting the DLFs of various harmonics was the step frequency. Twenty-five individuals participated in the tests, ascending and descending the test stair. He found that the DLF for the first harmonic of ascent was larger than for descent. However, the second harmonic DLF for very fast descent (greater than 4 Hz) was about three times greater than for ascent. Comparing to the applied forces on flat floors, the magnitude of forces on stairs was found to be larger and higher footfall rates were also possible.

Kasperski and Czwikla (2012) studied the differences between the right versus left foot loading in terms of DLF of different harmonics, and step frequency when one ascends or descends a stair. Using a force plate, the researchers measured the applied forces from eight people walking on floor and over four small wooden steps. They found that the first harmonic of descents to be larger than ascents at the same step frequency, which is not consistent with the findings of Bishop *et al.* (1993, 1995) and Kerr (1998).

This paper presents an experimental study of GRF by measuring the exerted footfall forces by a number of subjects using an instrumented force platform/plate. The measurements were conducted on a flat surface and on a stair with a typical slope. The DLF's for various harmonics for each measured force were then computed. Relationships between the values for the sloped surface (stair) and flat surface were then established. In addition, comparison between the values obtained from the tests and the information available in the literature on the GRF for stairs were made.

2 DESCRIPTION OF THE TESTS

The GRF measurement tests were conducted at the Virginia Tech Vibration Testing Laboratory. A Bertec force platform was used to measure the applied footfall forces on a flat surface. A total of 84 human subjects participated in these tests. A mock stair was used for the stair GRF measurements. A force plate, made of strain gages, was placed within one of the stair treads to enable the force measurements. First, each subject stood still on the force platform/plate to measure his/her weight. Then, using a metronome to synchronize their movements, the subject walked over the force platform/plate measuring the right and left feet GRF separately. The following step frequencies were used: 100, 110, 120, 129, 135, 140, 155, 160, 163, 178, 190, 210 steps/min. These were selected to range from a slow walk to a fast run. The same tests were repeated to measure the GRF for the stair. The mock stair had a very high natural frequency to ensure the accuracy of the force measurements. Figures 1 and 2 show the weight and force measurements on the flat surface and on the stair, respectively.

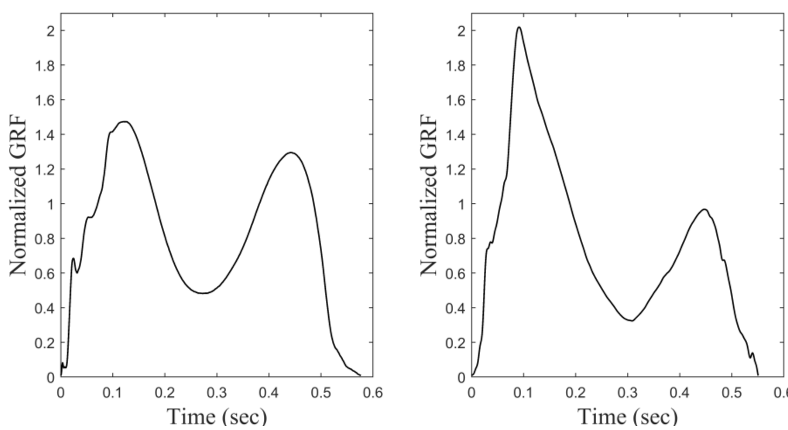
(a) (b)

Figure 1. GRF measurement on a flat surface: (a) Weight measurement, (b) Gait measurement.

(a) (b)

Figure 2. GRF measurements on the instrumented mock stair: (a) Weight measurement, (b) Gait measurement.

Once the GRF measurements were completed, they were normalized by the individual's weight (G). Figure 3 shows a typical measured GRF on the flat surface and stair.



(a) (b)

Figure 3. Typical measured GRF: (a) Flat surface (2 steps/sec), (b) Stair (descending 2 steps/sec).

3 MEASURED DLF AND THE CORRELATION BETWEEN THE FLAT SURFACE AND STAIR

The DLF values were computed by combining the right and left feet forcing functions and conducting a Fourier Series analysis. The effects of half-harmonics were neglected in this study. The above were repeated for both the flat surface and stair. The computed DLF values on the stair were divided by their counterparts for the flat surface for each test subject to compute the DLF ratios. These values were then averaged and plotted versus the step frequency, f_p. Figure 4 shows these plots for the first harmonics of the forcing function.

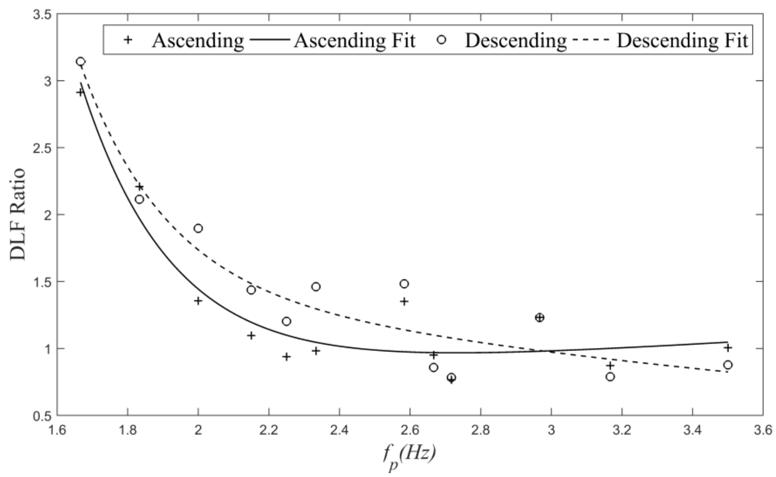


Figure 4. Variation of the first harmonic DLF ratio.

Curve-fitting of the graph showed a consistent trend of the DLF ratios with step frequency. This is represented by approximate exponential distributions shown below:

$$Ascent\ DLF\ Ratio = 1{,}323e^{-3.84f_p} + 0.62e^{0.15f_p} \tag{2}$$

$$Descent\ DLF\ Ratio = 1{,}758e^{-4.19f_p} + 2.51e^{-0.32f_p} \tag{3}$$

The R^2 goodness-of-fit for ascending and descending DLF ratios were 0.91 and 0.92, respectively. DLF ratios for ascending and descending were greater than 1 for majority of tested step frequencies. Descending stair DLF ratios were larger than ascending DLF ratios for most step frequencies less than 2.7 Hz. There were multiple instances where DLF ratios dropped below 1. The lowest DLF ratios for ascending and descending occurred at 2.7 Hz, where DLF ratios were 0.77 and 0.78, respectively.

Ascending DLF ratios for the first harmonic were largest at the lowest tested step frequencies with a maximum value of 2.9 at 1.7 Hz. Descending DLF ratios showed a similar trend to the ascending ratios. They were highest at the lowest step frequencies and had a maximum value of 3.1 at 1.7 Hz. DLF ratios for descent at 2 and 3 Hz were measured to be 1.9 and 1.2 respectively. These values are approximately 25 to 50 percent lower than an average ratio of 2.5 reported by Kerr and Bishop (1997).

Between 2.3 and 3 Hz there is a slight discrepancy in the trend of the overall data. It is possible that in this range subjects switched from a walk to a run. This resulted in a larger coefficient of variation at 2.6 Hz than that of the surrounding step frequencies, and thus potentially less accurate data.

Descending DLF values for the first harmonic were larger than ascending values for all step frequencies below 2.7 Hz with the exception of the 1.8 Hz case. At step frequencies greater than 3 Hz, ascending DLF values were larger than descending. These trends are consistent with the results from Kasperski and Czwikla (2012) at frequencies below 2.7 Hz, and with that of Bishop *et al.* (1993, 1995) and Kerr (1998) at above 3 Hz.

Figure 5 shows second harmonic DLF ratios plotted versus step frequency.

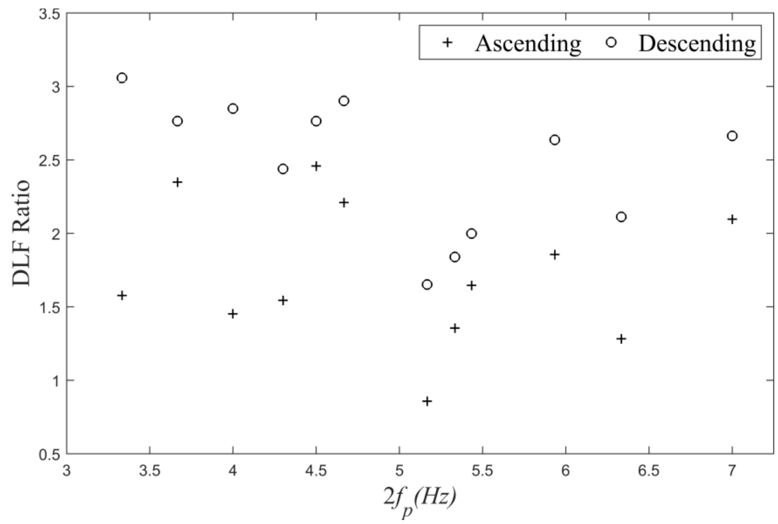


Figure 5. Variation of the second harmonic DLF ratio.

DLF ratios for the second harmonic did not show a trend with step frequencies. Descending ratios remained consistently larger than ascending ratios throughout the range of step frequencies used in this study, which is consistent with the observations of Kerr and Bishop (1997). The average descending second harmonic DLF ratio was 2.5 across the range of tested step frequencies.

4 CONCLUSION

A comparative study of human gait on a flat and inclined surface (stair) was conducted. Dynamic load factors were computed from the measured footfall forces of a number of individuals. It was found that the DLF values for ascending and descending forces were, for majority of cases, larger than that of walking on a flat surface. First harmonic DLF ratios for ascending and descending forces showed a decreasing exponential trend relative to increasing step frequency. First harmonic DLF ratios for descending forces were larger than those of ascending forces for the large majority of step frequencies below 2.7 Hz. Second harmonic DLF ratios for ascending and descending forces showed no trend relative to step frequency. Second harmonic descending DLF ratios were larger across all frequencies tested; ranging from 1 to 2 times larger than ascending DLF ratios.

Acknowledgments

The research presented here was supported by the National Science Foundation under grant number CMMI-1335004. This support is gratefully acknowledged. Any opinions, findings, and conclusions expressed in this paper are those of the writers and do not necessarily reflect the views of the National Science Foundation.

References

Bachmann, H., and Ammann, W., *Vibrations in Structures Induced by Man and Machines,* International Association of Bridge and Structural Engineering, Zurich, Switzerland, 1987.

Bachmann, H., Ammann, W. J., Deischl F., Eisenmann, J., Floegl, I., Hirsch, G. H., Klein, G. K., Lande, G. J., .Mahrenholtz, O, Natke, H. G., Nussbaumer, H., Pretlove, A. J., Rainer, J. H., Saemann, E. U., and Steinbeisser, L., *Vibration Problems in Structures: Practical Guidelines*, Birkhauser Verlag, Basel, Boston, Berlin, 1995.

Bishop, N. W. M., Willford, M., and Pumphrey, R., Multi-Person Excitation of Modern Slender Staircases, *Engineering for Crowd Safety*, Elsevier Science Publishers, Amsterdam, 399-408, 1993.

Bishop, N. W. M., Willford, M., and Pumphrey, R., Human Induced Loading of Flexible Staircases, *Safety Science*, 18, 261-276, 1995.

Blanchard, J., Davies, B. L., and Smith, J. W., *Design Criteria and Analysis for Dynamic Loading of Footbridges*, Proceedings of the DOE and DOT TRRL Symposium on Dynamic Behaviour of Bridges, Crowthorne, UK, 1977.

Kasperski, M., and Czwikla, B., A Refined Model for Human Induced Loads on Stairs, *Topics on the Dynamics of Civil Structures*, *Vol. 1*, Proceedings of the Society for Experimental Mechanics Conference, 26, 27-39, 2012.

Kerr, S. C., and Bishop, N. W. M., Human Induced Loading of Flexible Staircases, *Innovation in Civil and Structural Engineering*, Topping, B. H. V., and Leeming, M. B., (Eds.), Civil-Comp Press, Edinburgh, Scotland, 311-317, 1997.

Kerr, S.C., *Human Induced Loading on Staircases*, PhD. Thesis, Mechanical Engineering Department, University of London, London, UK., 1998.

Kerr, S.C., and Bishop, N. W. M., Human Induced Loading on Flexible Staircases, *Engineering Structures*, 23, 37-45, 2001.

Rainer, J. H., Pernica, G., and Allen, D. E., Dynamic Loading and Response of Footbridges, *Canadian Journal of Civil Engineering*, 15, 66–71, 1988.

Yao, S., Wright, J. R., Pavic, A., and Reynolds, P., Experimental Study of Human-Induced Dynamic Forces Due to Jumping on a Perceptibly Moving Structure, *Journal of Sound and Vibration*, 296, 150–165, 2006.

Young, P., *Improved Floor Vibration Prediction Methodologies*, Proceedings of Arup Vibration Seminar on Engineering for Structural Vibration - Current Developments in Research and Practice, London, UK, 2001.