COMPDYN 2015
5th ECCOMAS Thematic Conference on
Computational Methods in Structural Dynamics and Earthquake Engineering
M. Papadrakakis, V. Papadopoulos, V. Plevris (eds.)
Crete Island, Greece, 25–27 May 2015

A NEW APPROACH ON THE CALCULATION OF DYNAMIC LOAD FACTORS OF HUMAN INDUNCED LOAD

Lu Dai, Na Yang

School of Civil Engineering, Beijing Jiaotong University, Beijing 100044, China

E-mail: 12115272@bjtu.edu.cn, nyang@bjtu.edu.cn

Keywords: dynamic load factor, human induced load, single foot force model, numerical calculation.

Abstract: *An appreciation of the nature of the force induced by walking is essential in order to predict the structural response from pedestrians. The typical walking model applied on structures is the Fourier series force model, the most important parameter in the model is the dynamic load factor (DLF) which is the basis for this most common model of perfectly periodic human-induced force. Based on Fourier decomposition, many researchers have tried to quantify DLFs, but the existing factors are not suitable for low or high walking frequency, as the more and more load need to be considered in the structural calculation nowadays, the application range of DLFs need to be extended. Based on the single foot force model, this study recalculated the dynamic load factors and expanded the applied frequency range to both low and high frequencies using numerical simulation method, compared the human induced load force model of different walking frequencies. The calculated DLFs in low and high frequency obtained from this study are useful for the following analysis of structural response under more kinds of pedestrian load.*

1 INTRODUCTION

In recent decades, the human induced load by walking person has become an extremely popular topic in structural engineering area, especially for the light and slender footbridges of low modal frequencies. The walking load induced structural vibration not only is a serviceability problem, but also affects the structural safety.

The excessive footbridge vibration due to the pedestrian passage is a major consideration in the footbridge design. To understand the complicated mechanical mechanism of pedestrian-footbridge vibration, a number of numerical and experimental investigations have been performed over the past decades. Li et al [1] investigates vibration characteristics of footbridge induced by crowd random walking, developed a single foot force model for the vertical component of walking-induced force avoiding the phase angle inaccessibility of the continuous walking force. S. Zˇivanovic´ et al. [2] gave a literature review on vibration serviceability of footbridges under human-induced excitation, identified humans as the most important source of vibration for footbridges. M.J. Hudson et al [3] provided a comprehensive state-of-the-art review of AVC for human-induced vibrations in floor structures, discussed a range of active control laws are also discussed and the suitability of these for the mitigation of human-induced vibrations in floors, providing the basis for future research in this area so that the benefits of AVC may be fully realized. V. Racic et al [4] reviewed the experimental identification and analytical models of human walking forces, the review is therefore an interdisciplinary article that bridges the gaps between biomechanics of human gait and civil engineering dynamics. S.C. Kerr [5] investigated the differences between human induced loading on a floor with that generated whilst ascending or descending a staircase, the data obtained from numerous force plate experiments have been compared to existing experimental data and conclusions have been drawn as to what differences between the two should warrant concern by the staircase designers. Luca Bruno [6] based on the mathematical and numerical decomposition of the coupled multiphysical nonlinear system into two interacting subsystems, proposed a mathematical and computational model used to simulate crowd–structure interaction in lively footbridges. Tianjian Ji et al [7] investigated the action of an individual bouncing on a structure, and conducted an individual bouncing test and its responses to bouncing was recorded, then proposed a load model based on the measurements and the concept that dynamic responses induced by the sum of harmonic functions are at discrete loading frequencies. Aikaterini Pachi [8] based on a field test in shopping mall and footbridges, summarized people’s walking frequency and walking velocity, compared the difference of different walking purpose.

This paper focus on the human load induced by walking pedestrian, based on the Fourier series model and the simplified single foot force model, adopting numerical simulation methods, recalculated the dynamic load factors (DLFs), which is essential for the walking model. The DLFs calculation results show a relatively larger frequency range compared to the traditional DLFs, so that the high and low frequency pedestrian can be considered in the following calculation and simulation, providing a more accurate analysis results by taking more kinds of load into consideration.

2 THE LOAD MODEL FOR WALKING PEDESTRIAN

To analyze the structural response under walking load, the reasonable simulation model for pedestrian induced force is necessary. There are many kinds of force model of walking person, among which, the most common used is the Fourier series model, and it is also the simplest model. The studies in the following parts of this paper are all based on the Fourier series force model.

2.1 The traditional walking model

Accurate evaluation of vertical force induced by one walking pedestrian is crucial to estimate the vibration of footbridge. The typical Fourier series time-domain model for walking is based on the assumption that both human feet produce exactly the same force and that the force is periodic. It is well known that the continuous walking force can be considered as a sum of a statistic and a dynamic component, and it can be represented by a Fourier series (eq.1):

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

Where G: the weight of walking person, α_i: the Fourier's coefficient of the ith order, f_p: the walking frequency (Hz), ϕ_i: the phase angle of the ith order, i: the order number, n: the total number of the harmonic order.

Based on the above Fourier series model, the walking pattern is shown as the following figure.

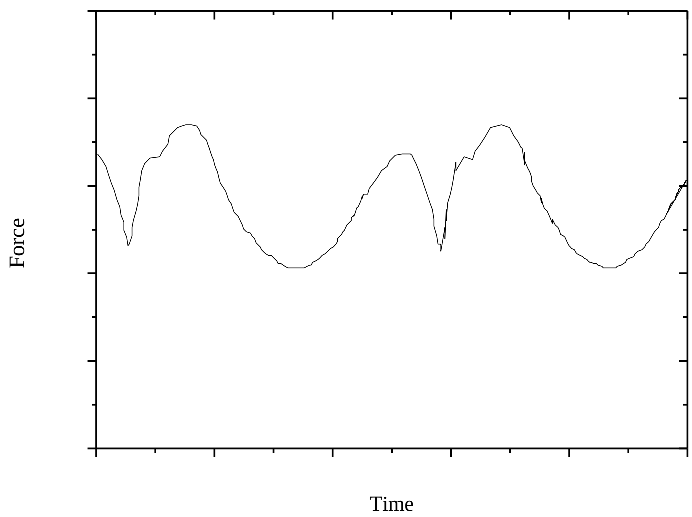


Figure 1: The traditional Fourier series walking load model

2.2 The single foot force model

In the traditional walking force model, the phase angle is an important factor, while it is also the most difficult parameter to obtain, and in the previous study, there still not clear instructions for the phase angle. So based on the Fourier series model, Li (2010) [1] proposed a single foot force model to describe the dynamic loading of pedestrian walking, not only avoiding the inaccessibility of phase angle and also accounting for subsequent random vibration modeling of footbridge. Generally, the common single foot load–time force curve, illustrated in figure 2, is characterized with two peaks, and the first one is higher than the second one.

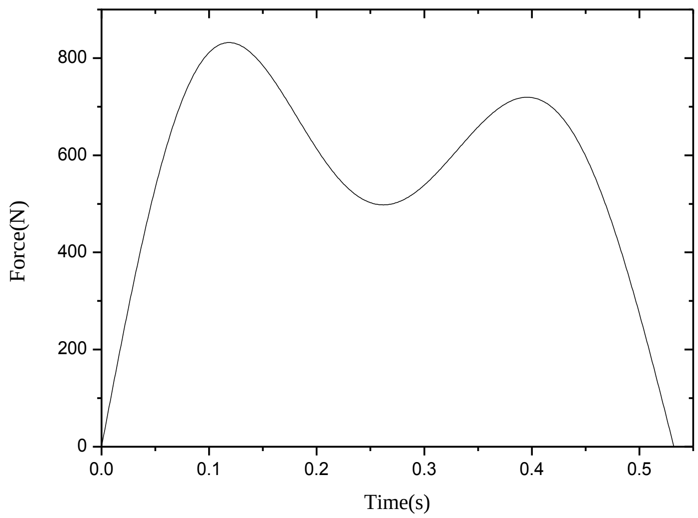


Figure 2: The single foot force model

The single foot force is assumed to be formulated also by Fourier series as:

$$F_e(t) = G\sum_{n=1}^{+\infty} A_n \sin\left(\frac{\pi n}{T_e} t\right), 0 \le t \le T_e \tag{2}$$

Where A_n and T_e is the Fourier coefficient and constant cycle.

3 THE CALCULATION FOR DYNAMIC LOAD FACTORS

It can be seen from the above analysis that the dynamic load factors (DLFs) is the essential parameter in the walking load simulation, and in the previous study there are many calculation and test results for such DLFs values.

3.1 The existing DLFs

Based on Fourier decomposition, many researchers have tried to quantify DLFs which are the basis for this most common model of perfectly periodic human-induced force. S.

Zˇivanovic´ [2] summarized the DLFs calculation results in the previous study, shown in table 1.

Author	DLFs	Frequency Range
Blanchard	α_1=0.257	4-5Hz
Bachmann and Ammann	α_1=0.4-0.5, $\alpha_2=\alpha_3$=0.1	2.0-2.4Hz
Schulze	α_1=0.37, α_2=0.10, α_3=0.12, α_4=0.04, α_5=0.08	2.0Hz
Bachmann	α_1=0.4/0.5, α_2=α_3=0.1/-	2.0/2.4Hz
	α_1=α_3=0.1	2.0Hz
Kerr	α_1=1.6, α_2=0.7, α_3=0.2	2.0-3.0Hz
Young	$\alpha_1=0.37\left(f-0.95\right)\leq 0.5$, $\alpha_2=0.054+0.0044f$, $\alpha_3=0.026+0.005f$, $\alpha_4=0.01+0.0051f$.	1-2.8Hz
Yao	α_1=0.1, α_2=0.25	2.0Hz(bouncing)

Table 1: The DLFs results from the previous study

Despite the DLFs results from traditional Fourier series model, Li's single foot force model also has its own dynamic load factors, shown in equation 3.

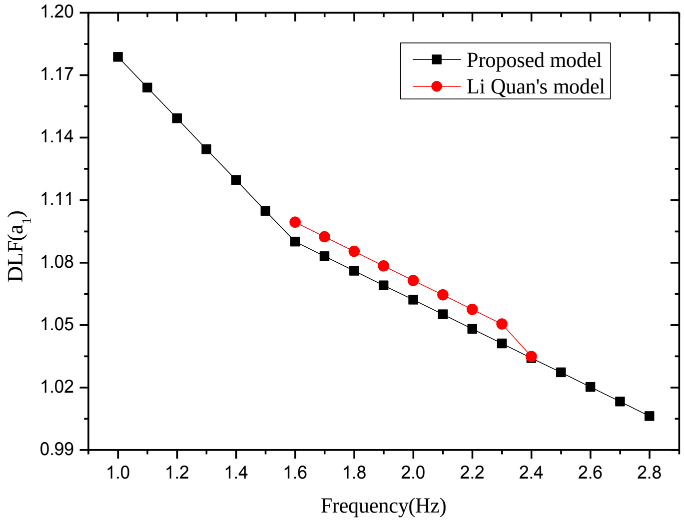
$$
\begin{aligned}
A_1 &= \begin{cases} -0.0698 f_s + 1.211, 1.6Hz \leq f_s \leq 2.32Hz \\ -0.1784 f_s + 1.463, 2.32Hz < f_s \leq 2.4Hz \end{cases} \\
A_2 &= \begin{cases} 0.1052 f_s - 0.1284, 1.6Hz \leq f_s \leq 2.32Hz \\ -0.4716 f_s + 1.210, 2.32Hz < f_s \leq 2.4Hz \end{cases} \\
A_3 &= \begin{cases} 0.3002 f_s - 0.1534, 1.6Hz \leq f_s \leq 2.32Hz \\ -0.0118 f_s + 0.5703, 2.32Hz < f_s \leq 2.4Hz \end{cases} \\
A_4 &= \begin{cases} 0.0416 f_s - 0.0288, 1.6Hz \leq f_s \leq 2.32Hz \\ -0.2600 f_s + 0.6711, 2.32Hz < f_s \leq 2.4Hz \end{cases} \\
A_5 &= \begin{cases} -0.0275 f_s + 0.0608, 1.6Hz \leq f_s \leq 2.32Hz \\ 0.0906 f_s - 0.2132, 2.32Hz < f_s \leq 2.4Hz \end{cases}
\end{aligned} \tag{3}
$$

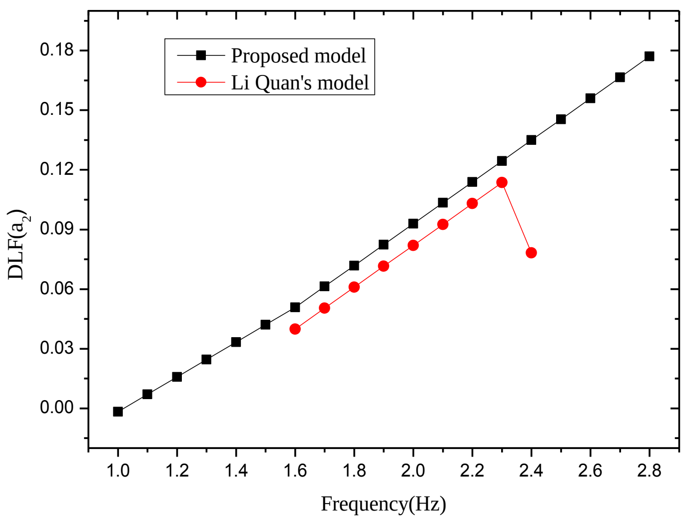
From the above analysis, it can be seen that although there are a variety of dynamic load factors calculation results, the frequency range for applied computation is still narrow. For the single foot force model, the frequency range is 1.6-2.4Hz, which could not cover the load forms, so it is necessary to enlarge the DLFs frequency range for following applying analysis.

3.2 The DLFs for enlarged walking frequency

It is known that the single foot force model is more convenient without the phase angle value, so adopt the model to conduct the following study. The basis DLFs values come from Young's model, because the frequency range is relatively large in his model.

According to the equal relationship of the corresponding coefficients in the above mentioned two models, recalculate the dynamic load factors in the single foot force model. In order to have a more efficient calculation, only adopt the first three dynamic harmonic orders. Compared to the original DLFs proposed by Li, the results are shown in figure 3.





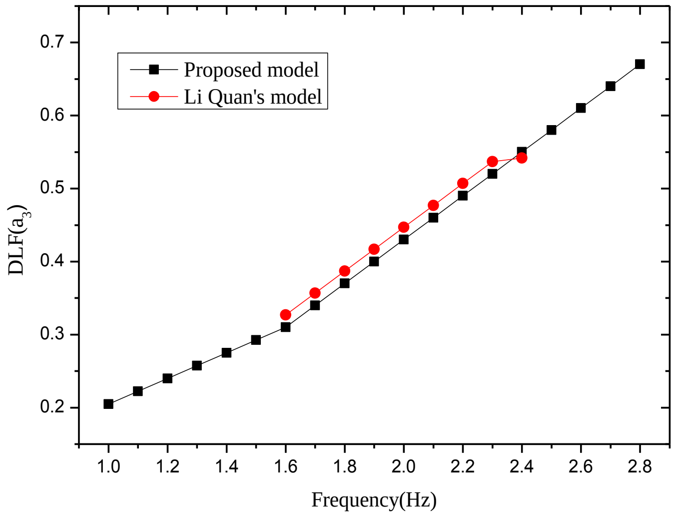


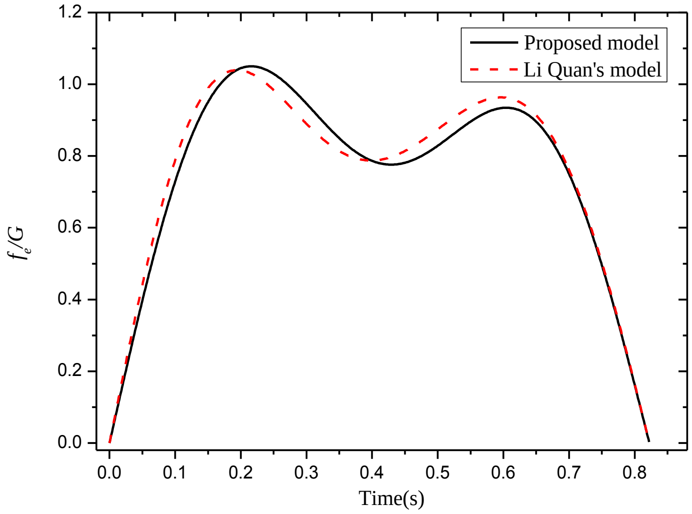
Figure 3: The DLFs calculation results for enlarged frequency

It can be seen by recalculation the coefficients, the DLFs range enlarged from 1.6-2.41Hz to 1.0-2.8Hz, and the numerical values for these factors can be calculated by equation 4.

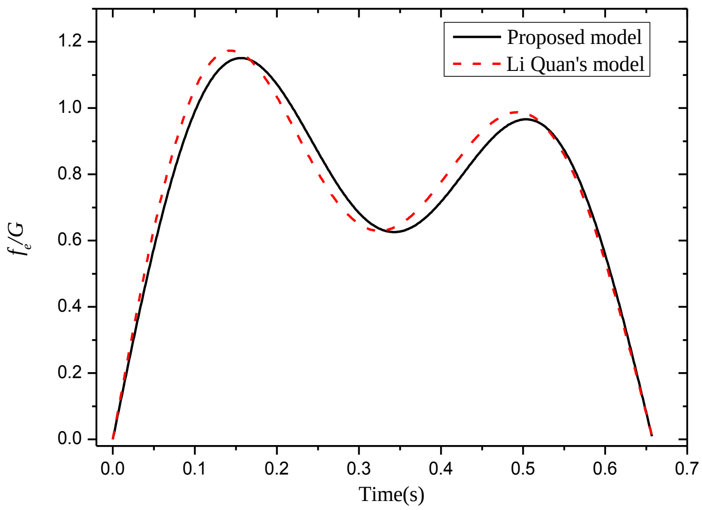
$$A_1=\begin{cases}-0.1480f_s+1.3268,1Hz\le f_s\le 1.6Hz\\ -0.0698f_s+1.2017,1.6Hz< f_s\le 2.8Hz\end{cases}$$
$$A_2=\begin{cases}0.0875f_s-0.0892,1Hz\le f_s\le 1.6Hz\\ 0.1052f_s-0.1175,1.6Hz< f_s\le 2.8Hz\end{cases} \quad (4)$$
$$A_3=\begin{cases}0.1752f_s+0.0297,1Hz\le f_s\le 1.6Hz\\ 0.3002f_s-0.1703,1.6Hz< f_s\le 2.8Hz\end{cases}$$

4 THE APPLICATION OF CALCULATED DLFS

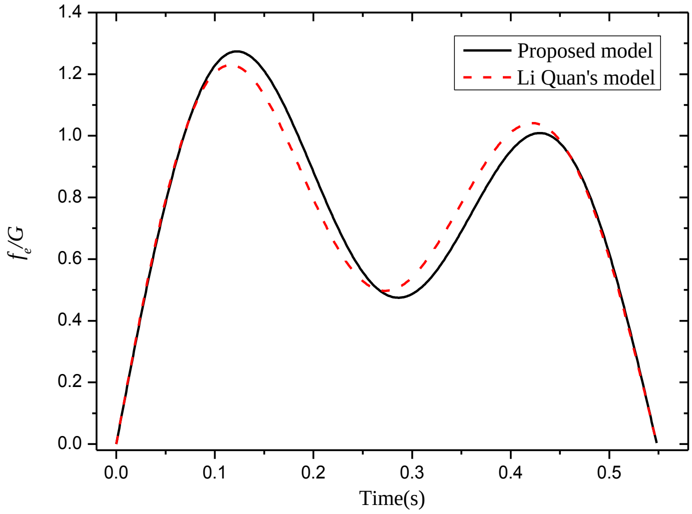
Based on the DLFs calculation results, the pattern of single foot walking force can be obtained, the pedestrian induced load is shown in figure 4 compared to Li's model.



(a) Walking frequency: 1.6Hz



(b) Walking frequency: 2.0Hz



(c) Walking frequency: 2.4Hz

Figure 4: The walking pattern of adopting the recalculated DLFs

It should be noted that by recalculating, the DLFs frequency range has been enlarged, figure 5 shows the human induced load of different walking frequencies using the recalculated DLFs.

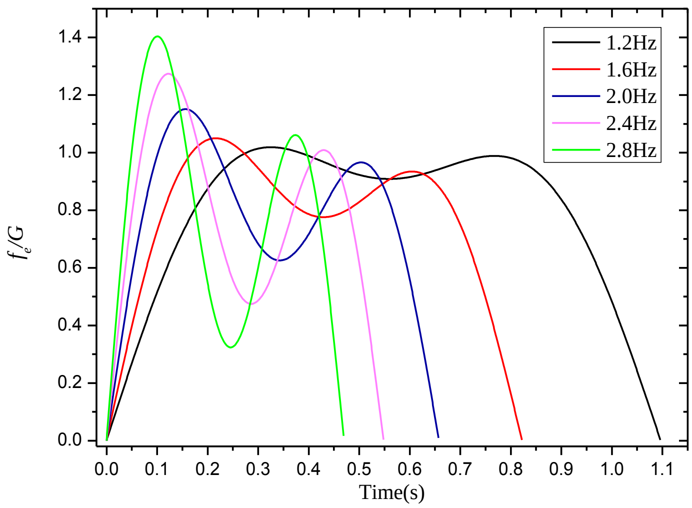


Figure 5: The pedestrian induced load under different walking frequencies

From the above analysis, it can be seen that single foot force model can be applied in a larger frequency range due to the calculation of DLFs.

5 CONCLUSIONS

Based on the study on pedestrian induced load model, this paper summarized the previous study on dynamic load factors and enlarged the DLFs frequency range based on the single foot force model. The main conclusions are as follows:

- The dynamic load factors for the Fourier series walking load model in previous study are summarized.
- Based on the single foot force model, recalculated the DLFs to enlarge the application frequency range for walking load model.
- By adopting the recalculated DLFs, it is feasible that the pedestrian induced single foot force model can be applied in larger frequency range. The more complex load forms can be considered in the structural response analysis.

Acknowledgements

The work described in this paper was supported by National Natural Science Foundation of China (NSFC: 51178028), the National Natural Science Foundation of China for Excellent Young Scholars (NSFC: 51422801), National Natural Science Foundation of China (Key Program) (NSFC: 51338001) and Program for New Century Excellent Talents in University (NCET-11-0571).

REFERENCES

[1] Quan Li, Jiansheng Fan, Jianguo Nie, Quanwang Li, Yu Chen, Crowd-induced random vibration of footbridge and vibration control using multiple tuned mass dampers. *Journal of Sound and Vibration,* **329**, 4068–4092, 2010.

[2] S. Zˇivanovic ́, A. Pavic, P. Reynolds, Vibration serviceability of footbridges under human-induced excitation: a literature review. *Journal of Sound and Vibration,* **279**, 1–74, 2005.

[3] M.J. Hudson, P. Reynolds, Implementation considerations for active vibration control in the design of floor structures. *Engineering Structures,* **44,** 334–358, 2012.

[4] V. Racic, A. Pavic, J.M.W. Experimental identification and analytical modelling of human walking forces : Literature review. *Journal of Sound and Vibration,* **326,** 1–49, 2006.

[5] S.C. Kerr, N.W.M. Bishop. Human induced loading on flexible staircases. *Engineering Structures,* **23,** 37–45, 2001.

[6] Luca Bruno, Fiammetta Venuti. Crowd–structure interaction in footbridges: Modelling, application to a real case-study and sensitivity analyses. *Journal of Sound and Vibration,* **323,** 475–493, 2009.

[7] Ernesto Duarte, Tianjian Ji. Action of Individual Bouncing on Structures. *Journal of Structural Engineering,* **135:7,** 818-827, 2009.

[8] Aikaterini Pachi, Tianjian Ji. Frequency and velocity of people walking. *The Structural Engineer*, **2:1,** 36-40, 2005.