Comparative study on different walking load models

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ABSTRACT

Since the 1970s, researchers have proposed many human walking load models, and some of them have even been adopted by major design guidelines. Despite their wide applications in structural vibration serviceability problems, the difference between these models in predicting structural responses is not clear. This paper collects thirteen popular walking load models and compares their effects on structure's responses when subjected to human walking load. Model parameters are first compared among all the models including orders of the model, dynamic load factors, phase angles and initial load. The responses of a single-degree-of-freedom system with various natural frequencies and damping ratios to the thirteen load models are then calculated and compared in terms of peak values and root mean square values. It is found that the difference among all the models are significant, indicating that a proper walking load model is crucial for the structure's vibration serviceability assessment.

1. BACKGROUND

Nowadays in China, long-span concrete floors are popular in public buildings like offices, shopping centers and stadiums due to wide application of high-strength light-weight construction materials, advanced design and construction technology to fulfill the increasing demand for multifunction of buildings. Though structure design satisfies the safety and deformation requirements, there exists a problem that even due to occupants' normal activities like walking and jumping, the floor experiences annoying vibration. Provided that the vibration is too severe, occupants will feel uneasy. As a result, the vibration serviceability problem caused by dynamic response of walking load has become the most decisive constraint to the broad application of long-span concrete floor and attracted increasing attentions among researchers and engineers. However, at the design stage, usually a walking load model is merely selected objectively by the designer.

Actual walking load contains several harmonic components, which are affected by step frequency, stri

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de, individual's weight and some other factors, so the walking load model is hard to determine. In 1961, for the first time Harper introduced force plate to the field of civil engineering for walking load tests. Since then, many scholars have dedicated to this and proposed diverse walking load models, some of which have even been adopted by some countries' load codes. For the reason that every model possesses different variables, namely load orders, dynamic load factors, phase angles and initial load, it is necessary to carry on a comparative study on these models.

This paper presents a summary of thirteen representative walking load models available and focuses on a thorough assessment of their influence on structure's responses. This study is instructive and of great significance in selecting walking load models, notably when referring to comfort evaluation.

2. WALKING LOAD MODELS

Human's walking procedure can be treated as a periodic progress and Fourier series model is the most common type to formulate the walking load in engineering design. Different walking load models have been proposed based on Fourier decomposition. Basic equation of the models comprises the individual's weight and a combination of harmonic forces as expressed in Eq. (1).

$$F_p(t) = G + G\sum_{i=1}^{n} a_{vi}\sin(2i\pi f_p t - \phi_{vi}) \quad (1)$$

where G is the individual's weight (N), a_{vi} is the Fourier's coefficient of the i th harmonic dynamic load factor (DLF), f_p is the step frequency (Hz), φ_{vi} is the phase angle of the i th harmonic, i is the order number of the harmonic, n is the total number of contributing harmonics, t is time in seconds.

Blanchard et al. (Blanchard 1977) suggested a simple harmonic walking load model considering the resonance response of bridges with $a_{v1}=$0.257 and $G=$700N, which is suitable for bridges with frequency below 4Hz. As for structures with frequency of 4-5Hz, a_{v1} should be reduced and the second harmonic be taken account. This model was incorporated in British standard BS 5400-2-1978 and then its update version BS 5400-2-2006.

Bachmann and Ammann (Bachmann 1987) reported a vertical walking load model which contains three harmonic components. The DLF value for the first harmonic varies from 0.4 (at step frequency 2.0Hz) to 0.5 (at step frequency 2.4Hz) with linear interpolation. The second and third DLF values are both equal to 0.1. This model was adopted by International Association for Bridge and Structural Engineers (IABSE).

Allen and Murray (Allen 1993) presented a force model for frequency between 1.6Hz and 2.4Hz in which the recommended DLF values of the first four harmonics are 0.5, 0.2, 0.2 and 0.05, respectively. This model is used to evaluate the dynamic response of floor systems under walking excitations by American Guide Series 11: Floor Vibrations Due to Human Activity.

Peterson (Petersen 1996) put forward a model with three harmonics, DLF values of which are listed as follow (Table 1) and taken with linear interpolation. With respect to angle phase, he suggested $\varphi_1 = 0$ and $\varphi_2 = \varphi_3 = \pi / 5$.

Table 1 Suggested Value of Peterson's Model

$f_p(Hz)$	$f_p = 1.5Hz$	$f_p = 2.0Hz$	$f_p = 2.5Hz$
α_1	0.073	0.408	0.518
α_2	0.138	0.079	0.058
α_3	0.018	0.018	0.041

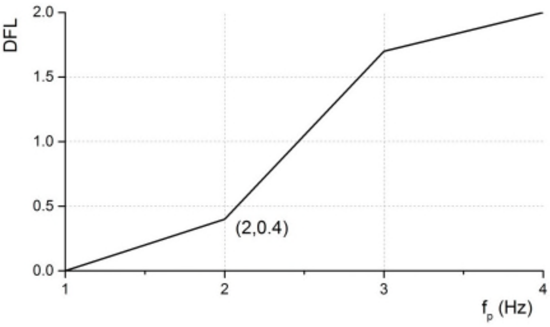

Fig. 1 DFL value of Kajikawa's model

Kerr (Kerr 1998) conducted a large amount of tests and got statistical characteristics of DLF values. He proposed that DLFs were strongly depended on the step frequency and the first harmonic DLF to be a polynomial function of step frequency.

British BS 5400 (Institution BS 1999) adopted a vertical walking load model

$$F_p = 180\sin\left(2\pi f_p t\right) \tag{2}$$

where the unit of 180 is *N*, and the applicable frequency is 1.5-2.5Hz.

Based on Kerr's model (Kerr 1998), Young (Young 2001) suggested all the first four harmonic DLFs to be a function of the step frequency (1-2.8Hz). It was used by Arup Consulting Engineers when modeling walking loads.

Kajikawa put forward a figure of DLFs and step frequency (Fig. 1), Yonda (Yonda 2000) advised a load model

$$F_p\left(t\right) = \alpha G\cos\left(2\pi f_p t\right) \tag{3}$$

Japanese load code (AIJ Recommendations for Loads on Buildings 2004) introduced a model for frequency of 1.7-2.3Hz. DLF values of the first three harmonics are 0.4, 0.2 and 0.06, respectively.

Živanović, S et al. (Živanović 2005) made some improvement on Kerr's model and there are five harmonics in their walking load model.

According to German Bridge Design Guide EN03 (Design of Footbridge 2008), the walking load model is expressed in Eq.(4)

$$F_p\left(t\right) = P\cos\left(2\pi f_p t\right) \times n'\psi \tag{4}$$

This model takes consideration of vertical, lateral loads of two harmonics and longitudinal load of one harmonic. The step frequency is between 1.25Hz and 2.3Hz, same with some frequency of bridge. n' is on behalf of the number of people walking simultaneously on the bridge, equivalent to *n* people walking freely on the bridge, which can be found from EN03 Guide. ψ represents reduction factor shown in Fig. 2. The values of *P* corresponding to vertical, lateral and longitudinal components are 280N, 140N and 35N, separately.

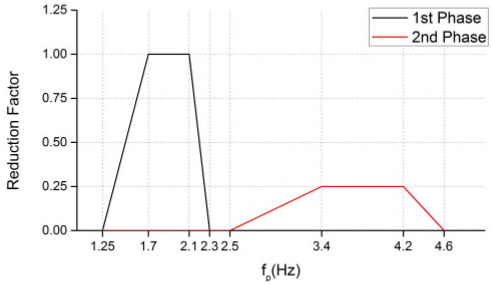

Fig. 2 Value of reduction factor ψ of Eq.(4)

Table 2 DLFs and phase angles for single pedestrian walking load models after different authors

Time	Scholar	DLFs	Phase Angles	Step frequency
1977	Blanchard	$\alpha_{v1}=0.257$	/	/
1987	Bachmann & Ammann	$\alpha_{v1}=0.37$， $\alpha_{v2}=0.10$， $\alpha_{v3}=0.12$， $\alpha_{v4}=0.04$， $\alpha_{v5}=0.08$	/	2Hz
1988	Bachmann el al.	$\alpha_{v1}=0.4\sim0.5$ $\alpha_{v2}=\alpha_{v3}=0.1$	$\varphi_2=\pi/2$ $\varphi_3=\pi/2$	2.0Hz~2.4Hz
1993	Allen & Murray	$\alpha_{v1}=0.5$， $\alpha_{v2}=0.2$， $\alpha_{v3}=0.1$， $\alpha_{v4}=0.05$，	/	1.6Hz~2.2Hz
1996	Petersen	$\alpha_{v1}=0.073$， $\alpha_{v2}=0.138$， $\alpha_{v3}=0.018$ $\alpha_{v1}=0.408$， $\alpha_{v2}=0.079$， $\alpha_{v3}=0.018$ $\alpha_{v1}=0.518$， $\alpha_{v2}=0.058$， $\alpha_{v3}=0.041$	$\varphi_2=\pi/5$ $\varphi_3=\pi/5$	1.5Hz 2Hz 2.5Hz
1999	BS 5400	$F_p=180\sin(2\pi f_p t)$	/	1.5Hz~2.5Hz
1999	Kerr et al.	$\alpha_{v1}=-0.2649f_p^3+1.3206f_p^2-1.7597f_p+0.7613$ $\alpha_{v2}=0.07$ $\alpha_{v3}=0.06$	/	/
2000	Young	$\alpha_{v1}=0.41(f-0.95)\leq0.56$， $\alpha_{v2}=0.069+0.0056f$， $\alpha_{v3}=0.033+0.0064f$， $\alpha_{v4}=0.013+0.0065f$，	/	1Hz~2.8Hz
2002	Yoneda	$F_p(t)=\alpha G\cos(2\pi f_p t)$ $\alpha=0.4$	/	2.0Hz
2004	Japanese Load Code	$\alpha_{v1}=0.4$， $\alpha_{v2}=0.2$， $\alpha_{v3}=0.06$	/	1.7Hz~2.3Hz
2007	Živanović, S et al.	$\alpha_{v1}=-0.2649f_p^3+1.3206f_p^2-1.7597f_p+0.7613$ $\alpha_{v2}=0.07$， $\alpha_{v3}=0.05$， $\alpha_{v4}=0.05$， $\alpha_{v5}=0.03$，	/	/
2008	EN03	$F_p(t)=P\cos(2\pi f_p t)\times n'\psi$	/	1.25Hz~2.3Hz
2012	Chen	$\alpha_{v1}=0.235f_p-0.2010$， $\alpha_{v2}=0.0949$， $\alpha_{v3}=0.0523$ $\alpha_{v4}=0.0461$， $\alpha_{v5}=0.0339$	$\varphi_1=-\pi/4$ $\varphi_4=\pi/4$ $\varphi_5=\pi/2$	/

Chen (Chen 2011, 2012) did a lot of tests by using three-dimensional motion capture technique in conjunction with fixed force plates and established a basic Chinese walking load database. A continuous walking load model featured with comprising sub-harmonics is proposed and all the model parameters are given based on the experimental data.

It should be emphasized that the thirteen previous models are based on test results of different groups of people in different countries. Table 2 is a detailed description of DLFs and phase angles for each of the thirteen load models. Time history curves obtained by previous walking load models at step frequency 2Hz are shown in Fig. 3. Note that there are some differences between these thirteen models in amplitude and frequency component. A general approach is to make a comparison of each model from the perspective of response. In the following work, a detailed comparison of acceleration response for SDOF system is presented.

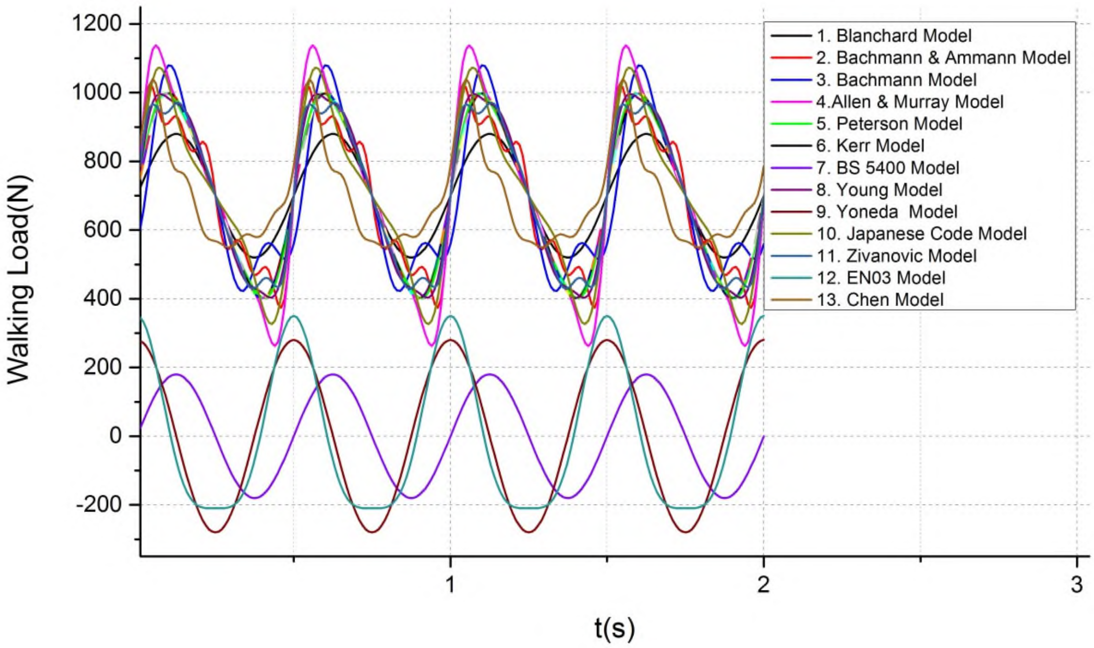

Fig. 3 Simulated walking load time histories of different models at 2.0Hz

3. STRUCTURAL RESPONSE CALCULATION

The main process is, separately, subjecting every load model to a single-degree-of freedom system possessing a mass of unit one, supposed damping ratio and stiffness deduced from both mass and given frequency of the system. From this process, the corresponding response was obtained. Frequency of the system ranges from 0.05Hz to 20Hz with an increment of 0.05Hz, covering the extent of very soft to very stiff structures. If there is no information of phase angle provided, it is taken to be zero uniformly. It is found that for all walking load models, the variation of response (root mean square of acceleration) is fairly remarkable. The gravity of walker is assigned to be 700N, the step frequency 2Hz, damping ratio 0.05 and the load time duration 500 sec. The calculation result is shown in logarithmic scale in Fig. 4, in which x lable is f_n and y lable is root mean square.

As illustrated in Fig. 4, when subjected to every load model, the structure presents a fair large disparity in acceleration response. When the natural frequency is 2Hz, the maximum response (Allen and Murray model) among all the load models reaches 2482.17 $m/s^2/kg$, the minimum (BS 5400 model) is 1273.65 $m/s^2/kg$ and the ratio of these two is 1.95. When the natural frequency is 4Hz, the maximum response (Allen and Murray model) reaches 1001.60 $m/s^2/kg$, the minimum (BS 5400 model) is 42.38 $m/s^2/kg$ and ratio of maximum and minimum is around 50.Thus, the response of each load model has roughly the same tendency, but the corresponding peak acceleration varies a lot in values.

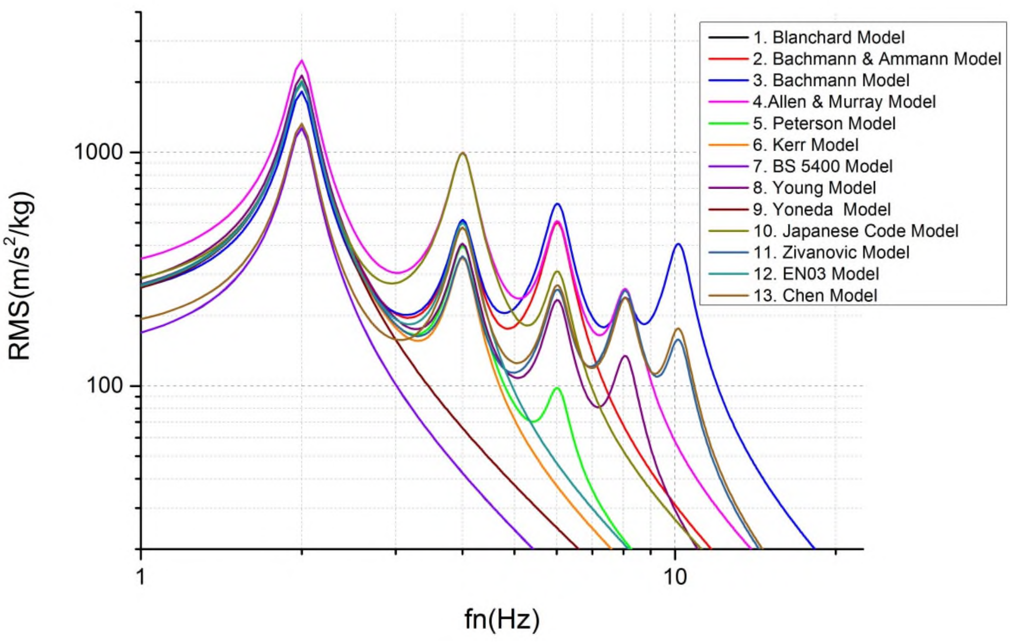

Fig. 4 Structural response of RMS of different models

4. ANALYTICAL INVESTIGATION

A single degree of freedom system with the mass of unit one is utilized to calculate the response, same with chapter 3, and the time duration is assigned 9 sec. If there is no information of phase angle provided, it is taken to be zero uniformly.

4.1. The influence of orders of the models

Kerr's and Živanović's models share the same first two dynamic load factors, and

Živanović's model has three additional harmonic components. When the step frequency is 2Hz, the DLFs are $\alpha_1 = 0.405$, $\alpha_2 = 0.07$ (Kerr's model), $\alpha_1 = 0.405$, $\alpha_2 = 0.07$, $\alpha_3 = 0.05$, $\alpha_3 = 0.05$ $\alpha_4 = 0.05$ $\alpha_5 = 0.03$ (Živanović's model). To exclude the effect of phase angle, here all the phase angles are assigned zero, the load time history and RMS response spectrum are shown in Fig.4 and Fig.5.

It is shown in Fig. 5 that the DLFs of the higher orders have an effect on load time history; as for Živanović's model, twin peaks occur; for Kerr's model there is only one peak value in every load cycle. In the response spectrum (Fig.6), when the system is at one and two times of step frequency, the peaks appear and roughly share the same value; when the system is at three, four and five times of step frequency, there exist peaks in Živanović's model while no peak in Kerr's; this is because there are five harmonics in Živanović's model while only the same first two in Kerr's. Therefore, for system frequency corresponding to the same contributing harmonic components of different models, there is rarely distinction; for that of higher orders, there are obvious distinctions.

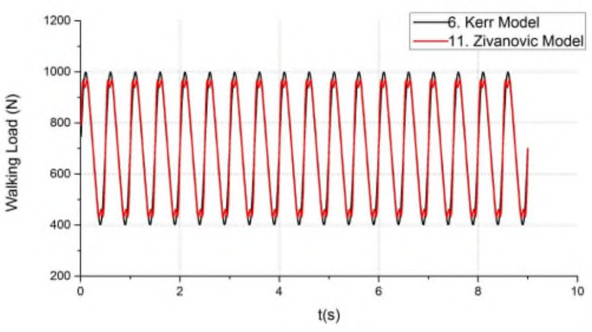

Fig. 5 Simulated walking load time histories of Kerr's and Živanović's models

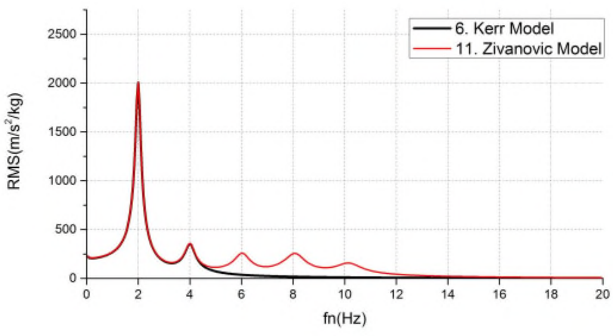

Fig. 6 Structural response of RMS of Kerr's and Živanović's models

4.2. The influence of phase angles

Take different phase angles of Peterson's model (Peterson 1996) to carry on an analysis. The proposed value of this model is $\varphi_1 = 0, \varphi_2 = \varphi_3 = \pi / 5$; here supposing $\varphi_1 = \varphi_2 = \varphi_3 = \pi / 5$ (Phase One) and $\varphi_1 = \varphi_2 = \varphi_3 = 0$ (Phase Two). The result is presented in Fig. 7 and Fig.8.

Comparing Phase One and the proposed phase in Fig. 7, apparently, the effect of the first order of phase angle respects on phase shift of load time history and the load amplitude; moreover, after contrasting Phase Two and the proposed phase in Fig. 7, phase angles of higher order only cause tiny impact on load amplitude. Besides, as shown in Fig. 8, there is scarcely any difference in structural response. Consequently, in case that no information of phase angle provides, it is feasible to treat it as zero.

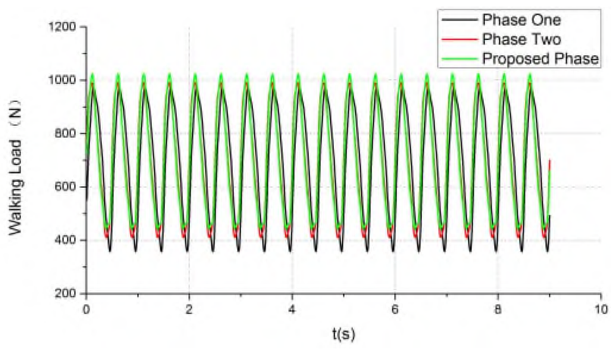

Fig. 7 Simulated walking load time histories of different phase angles for Peterson's model

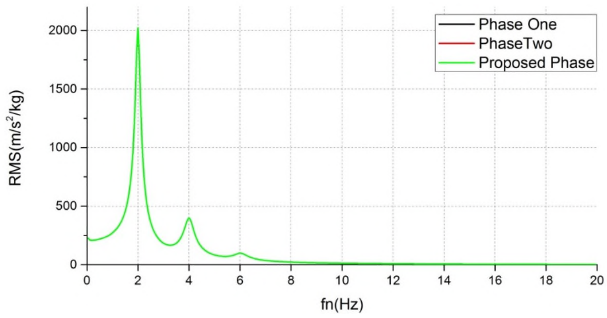

Fig.8 Structural response of RMS of three different phase angles for Peterson's model

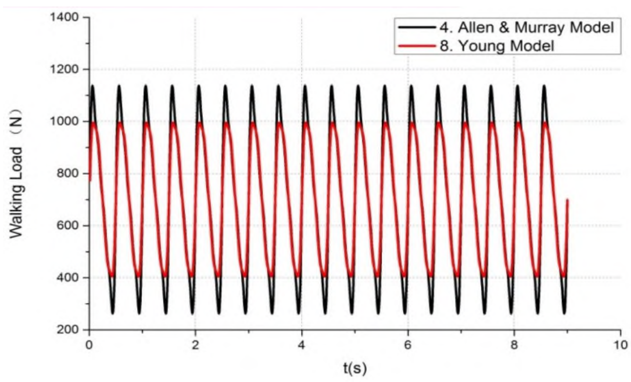

Fig. 9 Simulated walking load time histories of Allen's and Young's models

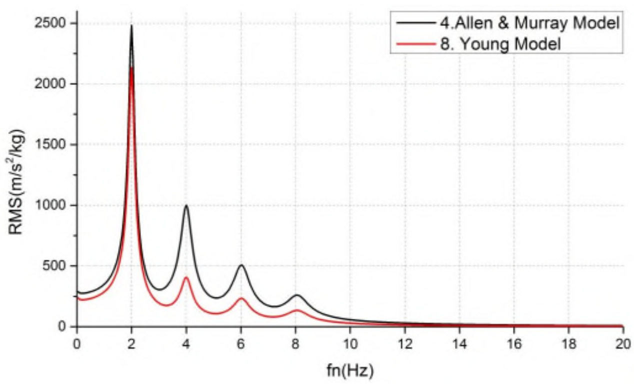

Fig. 10 Structural response of RMS of Allen and Murray's and Young's models

Table 2 Ratios of DLF and RMS at the points of frequency multiplication (4. Allen and Murray's model and 8. Young's model)

Order		1			2			3			4	
Model	4	8	Ratio	4	8	Ratio	4	8	Ratio	4	8	Ratio
DLF	0.5	0.431	1.16	0.2	0.08	2.5	0.1	0.046	2.174	0.05	0.026	1.923
RMS	4.323	3.737	1.157	1.91	0.83	2.301	1.01	0.506	1.996	0.546	0.321	1.701

4.3. The influence of dynamic load factors

To make a comparison of Allen and Murray's model (Allen 1993) and Young's (Young 2000), here DLFs for Allen and Murray's model are $\alpha_1 = 0.5$, $\alpha_2 = 0.2$,

$\alpha_3 = 0.1, \alpha_4 = 0.05$, while for Young's are $\alpha_1 = 0.431, \alpha_2 = 0.08, \alpha_3 = 0.046, \alpha_4 = 0.026$. All phase angles are set zero. The results are shown in Fig. 9 and Fig. 10, based on which Table 2 is produced.

Noting that in accordance with Table 2, the ratios of DLFs are approximately equal to the corresponding ratios of RMS. In other word, when the frequency of system is multiple of step frequency, RMS of the multiple system is in proportion to DLF of the same load order.

4.4. The influence of the initial load

Almost all the walking load models have been proposed based on Fourier decomposition. However, some of these models are composed of the individual's weight and a combination of harmonic forces while some doesn't have the composition of individual's weight such as BS 5400 Code, Yoneda's and EN03 Code models. This leads to the difference in initial load. Take Blanchard's and BS 5400 Code models as an example. The amplitudes of the two Fourier decomposition expressions are the same (180N). Results are shown in Fig. 11 and Fig. 12.

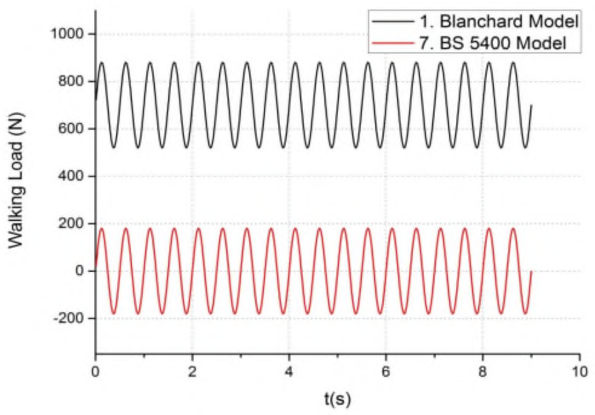

Fig. 11 Simulated walking load time histories of Blanchard' and BS 5400 Code models

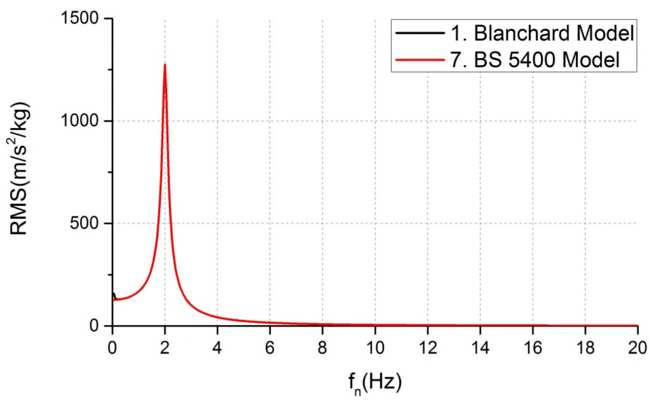

Fig. 12 Structural response of RMS of Blanchard' and BS 5400 Code models

In Fig. 11, though the two walking load time histories seem entirely different, they have barely any disparity in shape. That's because only the initial loads are not the same. In addition, the structural responses have substantially the same tendency. Evidently, the difference in response cannot account for the form of expressions, and has nothing to do with the initial load. On the other hand, it proves that DLF contributes largely to the structural response.

5. CONCLUTION

This paper has presented a comparison study of the effectiveness of different walking load models to structural response on the basis of SDOF system. Every element of the expression, including orders of models, dynamic load factors, load orders, phase angles and initial load, has a certain extent of effect on the structural response, especially DLFs. This research is fairly practical and deserves great attention for one reason that if designers neglect the importance of selecting walking load models, then whether the design is rational will be in dispute and this may lead to some unnecessary divergence.

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