Acceleration response research of large span floor under pedestrian load

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Abstract. With the progress of technology and the constant improvement of the requirement for the quality of life, people tend to choose light and long-span structure. Due to damping of the long-span floor is small, the fundamental frequency is low, which will produce vertical vibration which exceed a certain limit will affects the security of buildings under the action of pedestrian vibration. Firstly, the large-span floor vertical vibration comfort control standards and design methods were introduced in this paper. Next, the research status of walking load model was summarized. Then, the critical calculation methods of the vibration response were summed up. Finally, the existing problems of comfort control standards, design methods, walking load model and the floor response analysis were discussed and possible research directions were also pointed out.

1. Introduction
Large span floor have the characteristics of light weight and low damping, when there are large crowds across the floor, it will produce obvious dynamic response which beyond a certain range that can make users feel uncomfortable or even panic and will significantly reduce the applicability of the structure; Once producing comfort problem on the built floor, the cost of maintenance will be large and the technical problems will be complex. Therefore, large span floor design should not only meet the requirements of strength, deformation, but also take the vibration comfort problem into account adequately. So this paper will introduce the vibration comfort problem from three aspects: 1) the vertical vibration comfort control standards and design methods of large span floor; 2) the research status of walking load model; 3) the critical calculation method of the vibration response.

2. Comfort evaluation standard
Floor rigidity and resonance problems are attached great importance by international scholars, standard for structural deformation of finite values are various in different countries, Such as limits the ratio of deflection to span or the smallest depth-span ratio of flexural member section. These standards can only ensure the stiffness of structure and solve the problems of the structure of the static deformation, but not directly ensure the comfort requirements of floor vertical vibration. Researchers solve the problem of large span floor vertical vibration mainly by two ways: 1) stipulating that floor frequencies surpass a certain threshold; 2) Limiting the response of floor under walking load, namely. The first method has been widely used because it is simple and easy to implement during the design phase, but it cannot directly contain the pedestrian excitation elements; The second approach based on the acceleration is widely applied on vibration comfort evaluation at present stage.

Vibration control permission value was given by $KB$ which could be calculate by one of acceleration, velocity and displacement on 1975’s DIN4150 standard [1].
Walking load model

Human walking is actually a process in which the left and right legs alternately support the body weight and moving forward, and the process is divided into stance phase and swing phase. Support phase refers to the state that the feet keep in contact with the ground; Swing phase refers to the state that the feet off the ground and swing forward. Pedestrians walking process can be summed up the repeat of the two phases. Scholars had begun to study pedestrians walking load model and put forward using Fourier series to approximate the continuous walking load in the 1960s [4].

\[
F(t) / G = c_0 + \sum_{n=1}^{N} c_n \left[ \cos \left( 2nf / \pi \right) \cos \phi_n + \sin \left( 2nf / \pi \right) \sin \phi_n \right] = c_0 + \sum_{n=1}^{N} c_n \cos(2nf / \pi - \phi_n)
\]

Where \( G \) is weight; \( c_n \) is the nth order resonance dynamic load factor; \( f \) is walking frequency.

When using walking load model we should determine a reasonable calculation of harmonic order \( N \) in order to truncate the Fourier series. Ji [5] and Racic [6] pointed out that the determination of Fourier series harmonic order depend on the accuracy of the load curve and the structural vibration response.

Scholars also studied on the key parameters of walking load model. But due to the physical meaning of the phase angle and statistical regularity was not obvious, therefore continuous walking load model had certain difficulty in practical application. The methods of dealing with the current specification was only taking the first order dynamic load factor, namely only take the first item of Fourier series to analyze structural response, such as the UK standard BS5400 specification [7] and Canada OHBDC (1991) [8]. Jiansheng Fan[9] put out simple form standard single walking load model on the basis of existing research results, and demonstrated the model to be feasibility and practicability by combining with the measured walking load curves provided by Kerr.

\[
f(t) = \sum_{n=1}^{S} A_n \sin \left( \frac{n \pi t}{T_e} \right), \quad t \in [0, T_e]
\]

Where \( A_n \) is the coefficient; \( T_e \) is the cycles of single step load, \( T_e=1 / (0.76f_o) \).

Theoretical analysis method

The calculation method of vibration response of floor can be roughly classified into the following categories: Fixed on Foot Force Method, Moving on Foot Force Method, Equivalent Number of Synchronization Method, and Response Spectrum Method.

Fixed On Foot Force Method [10,11] supposed on foot force exerting on a fixed position on the floor, the natural frequency of vibration and pedestrian walking pace and the same, in order to inspire the most unfavorable resonance response of the floor, Load applying the role position of the points is
maximum floor displacement, but there are the following disadvantages: 1) Fixed Single Foot Force Method assumes that the single foot force exerting on the floor of a fixed point. When a large number of crowded through the floor, vibration response is greater than the vibration response of the single person to walk; 2) Fixed Multiplayer Force On Foot Method is equivalent with formed stable flow on the floor to uniform distribution in fixed point load on the walking route. But all pedestrians may not walk with the same frequency and phase. So this method is very conservative in the design phase.

Moving On Foot Force [12] first apply force to simulate the change with time of the step of the point, then carry out dynamics calculation with the ANSYS analysis software etc, finally get the floor response according to the results of calculation. This method is more precise in theory, but difficult to be applied in actual engineering because of the troublesome calculation.

The Equivalent Number of Synchronous Method [10] is simplify to force method for fixed people walking, suppose there are N pedestrians were distributed evenly on the floor, the length of Y direction is S, the length of X direction is L, Area is A, δn \((x_n, y_n)\) is the location of individual of \(i_{th}\) of the \(n_{th}\) order modal displacement, then get the response of structure \(γ_n\) (t) according to higher structural dynamics steady-state vibration mode and vibration acceleration response by derivative \(γ_n\)(t) twice.

Response Spectrum Method first standardized load \(F(t)\) curve, next loaded \(F(t)\) to the standard incentive system, then obtained the acceleration response \(u''(t)\), finally changed frequency and damping ratio of the single degree of freedom system, which can obtain the response spectrum curve. Wei-Liang Jin [13] carried out the maximum beam slab structure vibration acceleration response spectrum based on the vibration equations of the beam with selecting multiple sets of measured single step foot fall curve and adopting method to construct incentive function. Jianguo Nie[14,15] built the standard pedestrian incentive model and get root mean square response spectrum of single span simply supported the pedestrian bridge and the acceleration of 2~4 continuous footbridge according to the vibration differential equation of beam on the basis of walking load model. Chen Juan [16] first got the standard calculation incentive system of floor response under walking load according to the vibration differential equation of rectangle thin plate. Then, the acceleration response of the incentive system under the measured load curve of the 3 motion capture technology was calculated. Finally, the acceleration response spectrum by adjusting the floor frequency was determined.

5. Summary

1) Generally, evaluation of the vibration comfort caused by walking load based on the vibration acceleration RMS was in the entire time which may ignore the malaise during the middle period. Comfort evaluation should take the space of three direction acceleration into account; Therefore vibration comfort problem caused by walking load on space and time effect remains to be research.

2) Accurate pedestrian load model is the premise of the response calculation. Using the traditional force plate or a force measuring device for laboratory measurement is different to actual pedestrian load model, and not considering the coupling relationship with the floor vibration. So, the same as biological and medical science, a new experimental method, including graphics processing using a new type of motion tracking (such as three-dimensional gait analyzer) and load inversion technology of indirect measurement were introduced. It’s important research direction of load modeling.

3) The acceleration response is an important index of comfort evaluation system. At the same time, it is very important to calculate the acceleration response quickly and effectively because of the frequent changes in the design stage. The response spectrum analysis method only need modal analysis for the structure to get the structural self vibration frequency and generalized mass structure. And then, by using the maximum acceleration response spectrum envelope, we can obtain the approximate value of maximum acceleration response of the structure, which is convenient for engineering application. However, based on the numerical analysis, the following problems are established: ①In the differential equation of vibration, use the beam deflection function to displace lateral displacement. The basic equation is not accurate enough, so the numerical results are inaccurate; ②Instead of the acceleration response of the structure, the first order vibration acceleration response is used, and the result is too small; ③The statistical law and the physical meaning of the
phase angle of the load model function of some scholars are not obvious. The finite element analysis method can eliminate the error of numerical analysis by the beam deflection function instead of lateral displacement reaction, and resolved of the problem of small results caused by using first vibration acceleration response instead of structural acceleration response. Therefore, it is necessary to establish the calculation model of the long-span structure under the standard excitation model and establish the acceleration response spectrum by using the finite element analysis method.

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