

A Review of Research on Human-Induced Vibration and Comfort of Pedestrian Bridges

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Abstract

With the increasing prevalence of long-span, lightweight pedestrian bridges, the issue of human-induced vibration has become increasingly prominent. This problem not only affects user comfort but may even compromise structural safety. This paper first analyses the generation mechanisms and characteristics of human-induced vibrations. It then summarizes pedestrian load models, vibration response analysis methods, and comfort evaluation criteria, while discussing the effectiveness of vibration reduction design strategies. Research indicates that the acceleration response of footbridges exhibits an initial increase followed by a decrease as crowd density rises, and that comfort assessment requires comprehensive consideration of both physiological and psychological factors. Finally, it is emphasized that establishing load models tailored to the characteristics of the Chinese population and optimizing vibration reduction technologies represent key future development directions.

Keywords

Pedestrian Bridge; Human-induced Vibration; Comfort Assessment; Vibration Reduction Design; Crowd Load; Vibration Response.

1. Introduction

Pedestrian bridges, as vital components of urban transport infrastructure, not only facilitate pedestrian movement but have increasingly become significant elements of the cityscape. With rapid advances in high-strength flexible materials, continuous development of structural calculation methodologies, and ongoing breakthroughs in construction and manufacturing techniques, pedestrian bridge design is progressively evolving towards 'long-span' and 'lightweight flexible' configurations. [1] However, this structural trend has also introduced significant human-induced vibration issues. The dynamic loads generated by pedestrians walking on the bridge may trigger structural vibrations, thereby affecting pedestrian comfort and potentially compromising safety.[4]

Since the closure of London's Millennium Bridge following excessive lateral sway on its opening day, scholars both domestically and internationally have accorded significant attention to human-induced vibration in pedestrian bridges. This incident not only highlighted the complexity of human-induced vibration but also exposed shortcomings in the contemporary engineering design's understanding of this phenomenon. In truth, human-induced vibration in footbridges has long been a concern. For instance, when the Wuhan Yangtze River Bridge opened in 1957, the passage of tens of thousands of people triggered severe lateral swaying vibrations.

Human-induced vibration in footbridges constitutes a multidisciplinary research domain involving structural dynamics, biomechanics, and psychology. Its core lies in comprehensively considering multiple factors, including the dynamic characteristics of loads, structural vibration responses, and human subjective perception. This paper systematically reviews research progress on human-induced

vibration in footbridges and its comfort assessment, aiming to provide insights and references for relevant engineering practice and theoretical research.

2. Human-Induced Vibration Theory and Characteristics

2.1 Pedestrian Load Characteristics

Pedestrian loads constitute the primary excitation source for footbridge vibrations. Unlike vehicular loads, pedestrian loads exhibit three distinct characteristics: pronounced periodicity, narrow-band random processes, and human-bridge interaction. The step frequency of a normal adult walking typically ranges between 1.6 and 2.4 Hz. The resulting vertical forces exhibit a double-peak characteristic, with the first three harmonic components potentially exciting bridge vibrations. Lateral forces, however, are generally considered to involve only the first harmonic.

The three directional components of pedestrian loads exhibit distinct characteristics: vertical loads primarily result from the oscillation of the body's centre of gravity; lateral loads originate from the lateral sway of the centre of gravity caused by alternating leg movements (at approximately half the vertical frequency); longitudinal loads represent the forward-direction component required to overcome ground friction. Table 1 displays the time-history curves of the three directional components of single-step forces during normal walking.

Table 1. Frequency Range of Pedestrian Walking Forces

Direction	Frequency Range (Hz)	Harmonic Component	Primary Source
Vertical	1.6-2.4	First three harmonic orders	Centre of gravity fluctuations
Lateral	0.8-1.2	First harmonic order	Centre of gravity lateral oscillations
Longitudinal	1.6-2.4	First harmonic order	Forward friction

2.2 Mechanism of Human-Bridge Interaction

Human-bridge interaction represents a unique phenomenon within human-induced vibrations.[6] Humans are highly sensitive organisms capable of perceiving accelerations as low as 0.01 m/s^2 (0.001 g). When a bridge vibrates, pedestrians automatically adjust their step frequency and phase to synchronize with the vibrations, thereby improving their walking comfort. This phenomenon is termed 'lock-in' in vibration studies. However, this adjustment process often further intensifies the bridge's lateral vibrations, creating a positive feedback effect. The vibrations persist until pedestrians cease movement due to extreme discomfort or the number of people on the bridge decreases.

This interaction renders pedestrian bridge vibration issues far more complex than typical structural problems, necessitating consideration of multiple factors including crowd density, step frequency distribution, and synchronization. Research indicates that when crowd density reaches 1.3–1.5 persons per square meter, collective synchronization is likely to occur, leading to significant vibrations.

2.3 Vibration Response Analysis

The vibration response of footbridges under crowd loads may be analyzed using deterministic or stochastic methods. Deterministic approaches, based on worst-case load assumptions, typically employ periodic functions to simulate pedestrian loads in finite element time-history response analyses. Stochastic methods account for load randomness, such as analyses based on random walk models, which derive analytical solutions for structural vibration responses under random loads. The structural acceleration response of footbridges exhibits an initial increase followed by a decrease as crowd density rises. This nonlinear relationship reflects the complex interplay between crowd density and synchronization effects: at low densities, additional pedestrians exacerbate vibrations; at high densities, restricted pedestrian movement may paradoxically reduce vibrations.

3. Comfort Assessment Methods

3.1 Subjective Evaluation and Objective Indicators

Comfort assessment constitutes a comprehensive evaluation of pedestrians' physiological and psychological satisfaction with human-induced vibrations from footbridge structures during use.[7] Factors influencing comfort include vibration amplitude, frequency, direction, duration, and individual variations.

Research indicates that among the three vibration parameters—displacement, velocity, and acceleration—acceleration is the primary factor influencing human physiological and psychological perception. Consequently, acceleration is widely adopted as the principal indicator for comfort assessment in current international codes. However, recent studies suggest that the comfort amplification factor decreases with increasing peak vibration response and increases with rising crowd density, indicating that a single metric may be insufficient for comprehensive comfort evaluation.

3.2 Comparison of Domestic and International Standards

Current standards for pedestrian bridge comfort assessment remain inconsistent globally, primarily employing two approaches: frequency adjustment and dynamic response analysis. The frequency adjustment method involves optimizing the structure's primary vibration frequencies during design to avoid overlapping with human resonance frequencies. Its simplicity and clear conceptual basis lead most standards to priorities this approach. Typically, pedestrian bridges are required to avoid vertical frequencies within the 2.0–2.5 Hz range and transverse frequencies within the 0.8–1.2 Hz range. The dynamic response analysis method, however, is employed when the actual bridge structure's frequencies fail to meet code requirements. It assesses comfort by analyzing the maximum response of the bridge structure under primary dynamic loading, ensuring this maximum response remains below the comfort threshold. Table 2 lists the acceleration limit requirements of the principal specifications.

Table 2. Acceleration Limits for Pedestrian Bridge Comfort in Different Standards

Standard Source	Vertical Acceleration Limit (m/s ²)	Horizontal Acceleration Limit (m/s ²)	Remarks
International Organization for Standardization (ISO)	0.5-1.0	0.2-0.4	Depends on usage scenario
British BS5400 Standard	$0.5\sqrt{f}$	0.05-0.1	Frequency-dependent
German EN03 Guidelines	0.5-1.5	0.1-0.3	Varies by comfort level
Chinese Technical Standards for Urban Pedestrian Bridges	0.5	0.1	Fixed value

China's regulations concerning pedestrian bridge comfort are insufficiently comprehensive, failing to provide solutions when structural natural frequencies cannot meet specification requirements. This occasionally renders the standards inadequate for practical engineering construction needs. Consequently, domestic researchers predominantly draw upon European Union specifications while incorporating characteristics of the Chinese population for comfort assessments.

3.3 Load Characteristics of the Chinese Population

It is noteworthy that the walking characteristics of the Chinese population differ from those of Western populations. Research indicates that statistical results from over 12,000 samples reveal the average step frequency for Chinese adults is 1.825 Hz, with an average stride length of 0.715 m, both

lower than the statistical results for Western populations. This discrepancy suggests that directly adopting foreign load models may be unsuitable for the design of Chinese footbridges, making it essential to establish load models based on the characteristics of the Chinese population.

4. Vibration Reduction Design Strategies

4.1 Structural Design Optimization

Vibration reduction design should commence with structural optimization. Adjusting structural parameters can enhance dynamic performance, such as modifying the dimensions of stiffeners and main cables, or installing horizontal tie rods. Research indicates that mounting horizontal tie rods beneath stiffeners elevates the fundamental frequency and transforms the stiffener into a more enclosed, box-like structure, significantly improving its torsional resistance.

The objective of structural optimization is to increase structural stiffness or enhance structural damping. Increasing stiffness shifts the natural frequencies away from the fundamental frequency range of pedestrian forces; enhancing damping reduces resonance responses. However, for long-span footbridges, increasing stiffness often entails greater material usage and structural self-weight, which may prove uneconomical and aesthetically undesirable.

4.2 Additional Damping Systems

When structural optimization fails to meet vibration control requirements, implementing additional damping systems provides an effective solution. The vibration mitigation retrofit of London's Millennium Bridge exemplifies this approach, where viscous dampers and tuned mass dampers (TMDs) reduced vibration response by a factor of 40.

TMD systems operate by generating counteracting forces through assemblies of mass blocks, springs, and dampers, thereby dissipating a portion of vibrational energy. Research indicates that for large-span pedestrian suspension bridges, installing TMDs substantially reduces acceleration response, enabling vibration comfort levels to meet requirements.[8]

5. Conclusion and Outlook

This paper reviews research progress on human-induced vibration and comfort assessment in pedestrian bridges, yielding the following conclusions: Firstly, human-induced vibration is a critical consideration in pedestrian bridge design, particularly for large-span, lightweight structures. Pedestrian loads exhibit periodicity, narrow-band randomness, and human-bridge interaction characteristics, complicating vibration response analysis. Secondly, comfort assessment requires comprehensive consideration of vibration characteristics and multiple human perception factors. Current domestic and international standards remain inconsistent, and walking characteristics of Chinese populations differ from Western populations, necessitating load models and evaluation criteria tailored to Chinese pedestrians. Finally, vibration reduction design should adopt integrated strategies combining structural design optimization, supplementary damping systems, and operational management measures. Additional damping systems such as TMDs have proven effective in engineering practice, though precise design tailored to specific structural characteristics remains essential.

Despite significant advances in pedestrian-induced vibration research for footbridges, future investigations must deepen across multiple fronts. The foremost task is constructing load models for Chinese pedestrians based on extensive field data, providing precise foundations for domestic footbridge design. Secondly, research into human-bridge interaction mechanisms must be deepened, particularly by developing more precise theoretical descriptions and mathematical models for the 'locking' phenomenon. Finally, the comfort assessment system should evolve towards a comprehensive approach. Beyond acceleration metrics, it must incorporate multidimensional parameters such as vibration duration and directional variation, while accounting for population differences including age and gender.

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