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A Review of Wind Tunnel Test Technologies for High-Rise Buildings: Classification, Principles, and Engineering Applications

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Abstract

With super high-rise buildings developing towards characteristics of low damping, light weight, and high flexibility, their wind-induced vibration and aeroelastic effects have become key challenges in structural wind-resistant design. Due to the complex fluid-structure interaction phenomena involved in aeroelastic effects, theoretical derivation and computational fluid dynamics (CFD) methods have limitations. Wind tunnel test technology remains the core means for studying the wind-induced response of high-rise buildings. This paper systematically reviews the classification system, core principles, and engineering applications of wind tunnel test technologies for high-rise building models: based on whether aerodynamic feedback between the incoming flow and the structure is considered, the technologies are divided into two major categories—rigid model tests and aeroelastic model tests—which are further subdivided into sub-technologies such as high-frequency force balance (HFFB) base force measurement, synchronous multi-point static pressure measurement (SMPSS), aeroelastic vibration measurement, synchronous vibration-pressure measurement, and forced vibration tests. The test principles, typical research cases, and applicable scenarios of various technologies are elaborated in detail, and their advantages and limitations are compared and analyzed. Finally, aiming at the current technical bottlenecks, future optimization directions are proposed to provide theoretical references and engineering bases for the wind-resistant design of high-rise buildings and the iteration of wind tunnel test technologies.

Keywords

High-Rise Buildings, Wind Tunnel Tests, Rigid Models, Aeroelastic Models, Aeroelastic Effects, Wind-Induced Response

1. Introduction

1.1. Development Background of Super High-Rise Buildings

Rapid socio-economic development has accelerated urbanization. The rising population density in large cities and soaring land prices in core areas have driven the continuous growth in the number of super high-rise buildings [1]. Statistics show that among the top 10 tallest super high-rise buildings worldwide, 8 have been completed in the past 10 years; in the next 5 years, another 22 super high-rise buildings with a height exceeding 400 m will be completed globally [2] [3]. China has launched a boom in super high-rise building construction since the 1990s. As of 2022, it has 101 super high-rise buildings over 300 m in height, making it the country with the largest number of super high-rise buildings in the world. Representative buildings include China Zun (528 m), Guangzhou East Tower (530 m), Ping An Finance Center (599 m), and Shanghai Tower (632 m).

1.2. Wind Load Challenges for Super High-Rise Buildings

Newly built super high-rise buildings widely adopt new building materials, innovative structural systems, and advanced construction technologies, generally exhibiting structural characteristics of low damping, light weight, and high flexibility, which significantly increases their sensitivity to wind loads [4]. Under extreme wind conditions such as strong winds and typhoons, super high-rise buildings are prone to large-amplitude wind-induced vibrations and even vortex-induced resonance. At this time, the coupling effect between the structure and the incoming flow is significantly enhanced, and the aeroelastic effects, defined as the phenomenon where structural motion alters the aerodynamic forces acting upon it, creating a feedback loop in fluid-structure interaction, becomes a key factor affecting structural safety and service comfort, which cannot be ignored [5]-[7].

1.3. Necessity of Wind Tunnel Test Technology

Aeroelastic effects are deeply associated with complex flow field phenomena such as vortex shedding, flow separation, and fluid-structure interaction [8] [9]. It is extremely difficult to achieve accurate description through rigorous theoretical derivation and apply it to engineering design. Although computational fluid dynamics (CFD) methods have been used in the study of aeroelastic effects [10]-[13], their applicability to super high-rise buildings with complex shapes is still limited due to constraints in grid accuracy, turbulence inlet condition settings, and computational resource consumption. Therefore, relying on its ability to scale-simulate the actual wind environment and structural characteristics, wind tunnel test technology remains the main means for studying the aeroelastic effects and wind-induced responses of high-rise buildings [14] [15]. It should be noted, however, that CFD continues to serve a valuable complementary role, often employed in preliminary design stages for rapid aerodynamic form-finding and qualitative flow visualization around complex geometries before committing to more resource-intensive wind tunnel tests.

1.4. Technical Classification Framework

The core of wind tunnel test technology for high-rise buildings is to scale-simulate the actual atmospheric boundary layer wind environment, building aerodynamic shape, and dynamic characteristics in a wind tunnel laboratory based on the similarity ratio criterion, and infer the wind effects of the prototype building from the test results [16] [17]. According to whether aerodynamic feedback between the incoming flow and the structure is considered, it can be divided into two major categories: rigid model tests and aeroelastic model tests.

1) Rigid model tests: Only simulate the actual wind environment and the aerodynamic shape of the building, without directly simulating the structural dynamic characteristics. The wind-induced response needs to be calculated by combining the structural dynamic parameters after obtaining the aerodynamic forces. They are further subdivided into high-frequency force balance (HFFB) base force measurement wind tunnel tests and rigid model synchronous multi-point static pressure measurement (SMPSS) wind tunnel tests.

2) Aeroelastic model tests: Simulate the wind environment, building aerodynamic shape, and structural dynamic characteristics simultaneously, and can directly measure the model dynamic response to infer the wind-induced response of the prototype building. They are further subdivided into aeroelastic model vibration measurement tests, aeroelastic model synchronous vibration-pressure measurement tests, and forced vibration model wind tunnel tests.

These two categories of technologies together form a complete technical system covering the needs of high-rise building wind-resistant design at different stages.

2. Rigid Model Wind Tunnel Test Technology

Rigid model tests focus on simulating the wind environment and the aerodynamic shape of the building. They derive the wind-induced response by measuring aerodynamic forces and combining them with structural dynamic parameters [18]. They have the advantages of simple model fabrication and low test cost, and are suitable for wind load evaluation in the conceptual design stage and preliminary design stage of high-rise building wind-resistant design [19].

2.1. High-Frequency Force Balance (HFFB) Base Force Measurement Wind Tunnel Test

2.1.1. Technical Principles and Development History

The HFFB base force measurement wind tunnel test technology was proposed in the early 1970s [18]. Its core idea is: fabricate a rigid test model that only simulates the aerodynamic shape of the prototype building, install a multi-component high-frequency force balance at the bottom of the model, and directly measure the overall aerodynamic forces acting on the model through the balance; based on the assumption that "the first-order mode shape of the structure is a linear mode shape" [20] [21], derive the linear conversion relationship between the overall aerodynamic forces and the generalized aerodynamic forces, and then calculate the wind-induced response by combining the dynamic parameters of the prototype structure [22]. Due to its short model fabrication time, convenient test process, flexible data processing, and strong economy, this technology has gradually developed into the mainstream technology for evaluating the overall wind load of high-rise buildings [23] [24] (**Figure 1**).

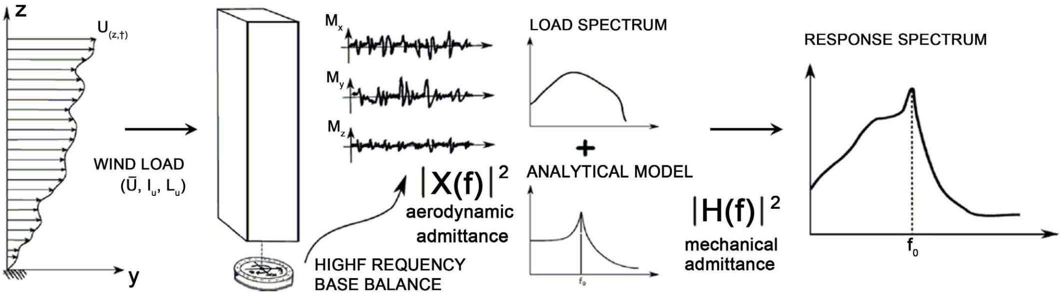


Figure 1. Principle of HFFB base force measurement wind tunnel test [23].

2.1.2. Engineering Applications and Typical Studies

The HFFB base force measurement technology is widely used in the study of wind loads and wind-induced responses of high-rise buildings. Typical related research results include: Kareem *et al.* [25] measured the mean wind load and fluctuating wind load of high-rise buildings based on HFFB technology, systematically compared the accuracy differences between the HFFB method and other wind load estimation methods, and verified the reliability of this technology in overall wind load evaluation; Marukawa *et al.* [26] conducted HFFB tests on square-section high-rise buildings with approximately 40 different length-width ratios and height-width ratios under open wind fields and urban wind fields, and proposed empirical formulas for cross-wind acceleration response, torsional acceleration response, and cross-wind base bending moment power spectral density that can be used in engineering design; Xie *et al.* [27] proposed a multi-high-frequency force balance measurement base combination (MHFFB) method, determined the overall wind load of multi-tower buildings through wind tunnel tests, and found that the inter-tower structural connection significantly increases the wind vibration response of low towers while reducing that of high towers; Quan *et al.* [28] [29] carried out wind tunnel tests on 15 typical high-rise building models using HFFB technology, established calculation formulas for cross-wind aerodynamic force power spectrum, base bending moment coefficient, and base shear coefficient, clarified the influence laws of various factors on wind loads through parametric analysis, and verified the accuracy of the cross-wind wind load calculation formula by combining with aeroelastic model tests; Zhang [30] systematically studied the influencing factors of wind load characteristics of rectangular-section high-rise buildings based on HFFB technology, proposed an empirical formula for base bending moment, and deeply analyzed the regulatory effects of aerodynamic optimization measures such as corner treatment, building opening, and tapering on the base aerodynamic forces of square and rectangular-section high-rise buildings; Li *et al.* [31] studied the wind loads and wind-induced responses of kilometer-level super high-rise buildings under monsoon and typhoon climate wind fields using the HFFB method, and found that the vortex shedding intensity of super high-rise buildings increases with height under monsoon climate, while the vortex-induced resonance effect weakens with increasing height under typhoon climate; Zhang *et al.* [32] derived the calculation process of wind effects of multi-tower structures based on HFFB technology from the frequency domain perspective, and analyzed the wind load characteristics, wind-induced response laws, and inter-tower interference effects of double-tower structures through wind tunnel tests on weakly connected double-tower super high-rise buildings.

2.1.3. Technical Limitations and Improvement Directions

The core limitation of HFFB technology stems from the assumption that “the first-order mode shape of the structure is a linear mode shape”: this assumption has good applicability for high-rise buildings with low height and regular cross-sections; however, with the increase in building height and the complexity of shape and facade, the distribution of structural mass and stiffness gradually deviates from uniformity, and the first-order mode shape of most super high-rise buildings is no longer a simple linear mode shape [33]-[35]. Although Holmes [36], Chen and Kareem [37], Tse *et al.* [19], and Huang *et al.* [38] have proposed mode shape correction factors or correction formulas to optimize the linear mode shape assumption, such methods still have significant uncertainties in the calculation of generalized aerodynamic forces. In addition, when the stiffness center of the prototype structure does not coincide with the mass center, it is also necessary to consider the influence of three-dimensional coupled wind vibration on the test results [39] [40].

HFFB technology has high requirements for the “light weight and high frequency” characteristics of the test model, which requires that the model frequency is much higher than the main frequency band of the wind load spectrum density to avoid the interference of model vibration on the base aerodynamic force measurement results. However, due to the limitations of material properties and manufacturing processes, the model frequency of some super high-rise buildings and tall structures (such as transmission line towers) is difficult to meet the requirements, resulting in significant resonance effects [41]-[43]. To address this issue, Cui and Luca [44] derived the dynamic equation of the “balance-model” coupling system based on classical dynamics theory, which can effectively eliminate the “false resonance peak” in the base aerodynamic force power spectrum. However, this method still relies on the deterministic assumption of the coupling system mode shape, and the correction effect will be affected when the actual mode shape deviates from the assumed one; Zhang *et al.* [45] introduced the blind source separation method into HFFB technology to realize the correction of the base aerodynamic force spectrum; Hu *et al.* [46] proposed a time-domain correction method based on adaptive blind source separation, which can perform real-time decoupling and filtering of the base aerodynamic force signal of the coupling system to obtain the corrected base aerodynamic force time history.

In summary, HFFB technology can quickly and effectively obtain the overall aerodynamic forces of the structure. Only one wind tunnel test is required to determine the wind-induced responses of structures with the same aerodynamic shape but different dynamic parameters, making it widely used in the conceptual design stage of structural wind-resistant design. However, it cannot obtain the local wind load distribution, and is limited by the linear mode assumption, insufficiently considering coupled modes, nonlinear modes, and higher-order modes. At the same time, it ignores the influence of aeroelastic effects, so it needs to be supplemented and verified by other technologies in refined wind-resistant design.

2.2. Rigid Model Synchronous Multi-Point Static Pressure Measurement (SMPSS) Wind Tunnel Test

2.2.1. Technical Principles and Core Advantages

The rigid model SMPSS wind tunnel test uses multi-channel high-speed pressure acquisition equipment to arrange pressure measurement points reasonably at different heights of the rigid model, obtain the spatiotemporal variation characteristics of wind pressure on the building surface [47], and then determine the wind load distribution law. The core assumption of this technology is that "the pressure within the area to which the pressure measurement point belongs is completely correlated", based on which the base aerodynamic force can be calculated through high-frequency pressure integration technology [48]; when the pressure measurement points are arranged reasonably, the base aerodynamic force obtained by SMPSS integration is consistent with the test results of HFFB technology [49].

Compared with HFFB technology, the core advantage of SMPSS lies in that it can calculate the generalized aerodynamic forces of each order through the combined integration of wind pressure time history and each order of mode shape. Therefore, it can not only consider nonlinear mode shapes but also analyze the contribution of higher-order modes to the overall wind-induced response [50] [51], breaking through the limitation of the linear mode assumption of HFFB technology and being more suitable for the refined evaluation of wind loads on super high-rise buildings with complex shapes.

2.2.2. Engineering Applications and Typical Studies

Restricted by the development of pressure measurement test equipment technology, SMPSS technology has gradually been applied to wind load evaluation of high-rise buildings since the 1980s. Typical related studies include: Kareem and Cermark [52] conducted wind tunnel tests on square-section high-rise buildings with a height-width ratio of 4 under rural and urban wind fields based on SMPSS technology, and analyzed in detail the distribution characteristics and variation laws of cross-wind aerodynamic force spectra; Liang *et al.* [53] carried out wind tunnel tests on rectangular-section high-rise buildings with various height-width ratios and length-width ratios using SMPSS technology, and proposed empirical calculation formulas for cross-wind aerodynamic force spectra, root-mean-square lift coefficients, and Strouhal numbers, providing references for the wind-resistant design of rectangular-section buildings; Lin *et al.* [54] conducted wind tunnel tests on 9 typical rectangular-section high-rise building models using SMPSS technology, and simultaneously carried out HFFB tests on models with unequal cross-sections. Through comparative analysis, they clarified the variation laws of layer wind force coefficients, aerodynamic force power spectra, vertical correlation, and coherence, and revealed the influence mechanisms of height-width ratio and length-width ratio on wind load characteristics from the perspective of bluff body flow around; Kim *et al.* [55] [56] conducted SMPSS wind tunnel tests on high-rise buildings adopting aerodynamic treatment measures such as tapering and setbacks. The study found that tapering and setback measures can effectively disrupt the vertical coherence of vortex shedding along the height direction, reduce the root-mean-square lift coefficient, and make the peak of the cross-wind aerodynamic force spectrum decrease and the bandwidth increase, thereby significantly mitigating the cross-wind wind-induced response of the structure; Tanaka *et al.* [57] conducted systematic experimental studies on high-rise building models with different cross-sectional shapes (square, circular, elliptical, rectangular) and different aerodynamic optimization measures (corner treatment, setback, spiraling, opening, and their combinations) based on SMPSS and HFFB technologies, and compared the effects of various aerodynamic optimization measures in detail. The results showed that the 180˚ spiraled model exhibited extremely weak broadband vortex shedding characteristics in the full height range, making it the optimal aerodynamic optimization scheme; based on the research of Tanaka *et al.* [57], Kim *et al.* [58] further analyzed the variation law of peak stress of high-rise buildings with atypical cross-sections, and found that the model adopting the setback measure had the smallest peak stress among the single aerodynamic optimization measures, while the model with the combined measure of convex corner treatment + tapering + 360˚ spiraling had the smallest peak stress among all aerodynamic optimization models; Li *et al.* [59]-[61] conducted a series of systematic wind tunnel tests on L-shaped cross-section high-rise buildings based on SMPSS technology, and deeply analyzed their wind load characteristics. The study found that unlike square cross-sections, the correlation of pressure measurement points inside the concave corners of L-shaped high-rise buildings increased significantly, which was closely related to the incoming flow turbulence, internal recirculation of concave corners, and their interaction; at the same time, they proposed cross-wind and torsional wind load calculation formulas for L-shaped high-rise buildings, and verified the applicability of the formulas through wind tunnel tests.

2.2.3. Technical Limitations and Improvement Directions

Although SMPSS technology is widely used in the evaluation of wind loads and wind-induced responses of high-rise buildings, it still has inherent limitations [62]:

1) Pressure signal distortion: Wind pressure signals are usually transmitted to pressure sensors through PVC pipes. The inevitable coupling effect between the pipes and the pressure signals causes distortion of fluctuating pressure, affecting the accuracy of wind pressure measurement. Currently, this problem is mainly solved in two ways [63]: one is to pre-calibrate the frequency response characteristics of the pressure measurement pipes and perform targeted corrections in the test data processing stage; the other is to add restrictors (dampers) in the pressure measurement pipes to suppress the resonance effect between the pressure measurement pipes and the pressure signals.

2) Difficulty in arranging measurement points for complex shapes: For buildings with complex geometric shapes such as attached balconies, facade screens, or large curvature changes, it is extremely difficult to arrange pressure measurement points, and it is difficult to obtain accurate wind load distribution through SMPSS technology.

3) Ignorance of aeroelastic effects: Similar to HFFB technology, the wind load obtained by SMPSS technology is essentially a “quasi-static wind load”, which does not consider the aerodynamic feedback between the structure and the incoming flow and cannot reflect the influence of aeroelastic effects on the wind-induced response.

In practical engineering applications, SMPSS technology is often used in combination with HFFB technology: HFFB is used to quickly obtain the overall wind load, and SMPSS is used to supplement the local wind load distribution and the influence of higher-order modes. The two work together to achieve a comprehensive evaluation of the wind load of high-rise buildings.

3. Aeroelastic Model Wind Tunnel Test Technology

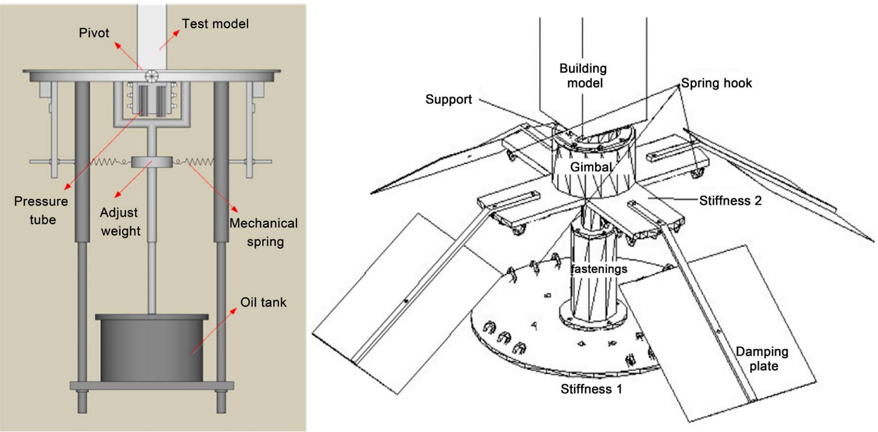
Aeroelastic model tests focus on simulating the wind environment, building aerodynamic shape, and structural dynamic characteristics (stiffness, mass, damping) simultaneously [64]. They can directly measure the dynamic response of the model under wind action and consider the aerodynamic feedback between the structure and the incoming flow [65] [66]. They are key technologies for studying the wind-induced effects of wind-sensitive structures with high flexibility and low damping, and are suitable for the evaluation of aeroelastic effects in the refined stage of high-rise building wind-resistant design.

3.1. Aeroelastic Model Vibration Measurement Test

The aeroelastic model vibration measurement test simulates the aerodynamic shape and dynamic characteristics of super high-rise buildings through specific fabrication methods, considers the aerodynamic feedback between the structure and the incoming flow, and infers the wind-induced response of the prototype building by measuring the wind-induced response of the model [64] [67]. This technology can fully reflect the unsteady effects caused by structural vibration. According to whether the contribution of higher-order modes to the wind-induced response is considered, it can be divided into single-degree-of-freedom (SDOF) aeroelastic model tests and multi-degree-of-freedom (MDOF) aeroelastic model tests [68] [69]. The SDOF approach is typically sufficient for buildings where the fundamental mode dominates and the mode shape is approximately linear. Conversely, an MDOF model becomes necessary for slender super-tall buildings (often with aspect ratios > 7), those with significant structural irregularities, or when mass/stiffness distributions are highly non-uniform, as these conditions lead to substantial contributions from higher-order modes.

3.1.1. Single-Degree-of-Freedom (SDOF) Aeroelastic Model Test

For most high-rise buildings, the fundamental mode component of the wind-induced response dominates the total response, and the fundamental mode shape is close to a linear mode shape [70]. Based on this characteristic, the SDOF aeroelastic model test does not need to consider the distribution characteristics of mass and stiffness. It uses lightweight materials such as aerospace wood to fabricate the building aerodynamic shape, simulates the structural frequency by adjusting the stiffness of elastic components (such as springs) at the bottom support, and adjusts the damping ratio by changing the height and immersion area of the bottom damping plate in the damping oil tank [71].



(a) Chen Zengshun [65] (b) Quan Yong [28]

Figure 2. Typical SDOF aeroelastic model test bases.

The fabrication difficulty of SDOF aeroelastic models is lower than that of MDOF models, and the damping ratio can achieve gradient changes, making them widely used in scientific research on wind-induced vibration of high-rise buildings. Typical SDOF aeroelastic model test base designs include the schemes proposed by Chen Zengshun [65] and Quan Yong [28] (**Figure 2**): the base designed by Chen Zengshun provides stiffness through mechanical springs and realizes damping ratio adjustment by combining with oil tank damping; the base designed by Quan Yong optimizes the integration of the elastic support and damping system, improving the simulation accuracy of the model dynamic characteristics.

3.1.2. Multi-Degree-of-Freedom (MDOF) Aeroelastic Model Test

For slender super high-rise buildings, the contribution of higher-order modes to the wind-induced response cannot be ignored, and slight differences in vibration forms can lead to large errors in wind-induced response analysis results [72]. At this time, the SDOF aeroelastic model test is no longer applicable, and the MDOF aeroelastic model test emerges as the times require. This technology simulates wind-induced vibration by fabricating an elastic model similar to the dynamic characteristics of the prototype building. The model needs to meet the similarity of aerodynamic shape, mass distribution, stiffness distribution, and damping characteristics simultaneously. For the study of wind-induced vibration of super high-rise buildings, it is only necessary to ensure the similarity of the first few orders of modes [69].

MDOF aeroelastic models can fully reflect the interaction between wind and structures, and consider factors such as nonlinear modes, higher-order mode vibrations, and mode coupling, making them irreplaceable in wind-resistant research of complex super high-rise buildings. Scholars such as Isyumov [67], Yoshie [68], and Quan Yong [17] pioneered the design of MDOF aeroelastic models for high-rise buildings and conducted wind tunnel test studies (**Figure 3**).

The model designed by Yoshie [68] uses a lightweight skeleton to provide stiffness, realizes mass distribution similarity through layered mass blocks, and adjusts the damping ratio with oil dampers.

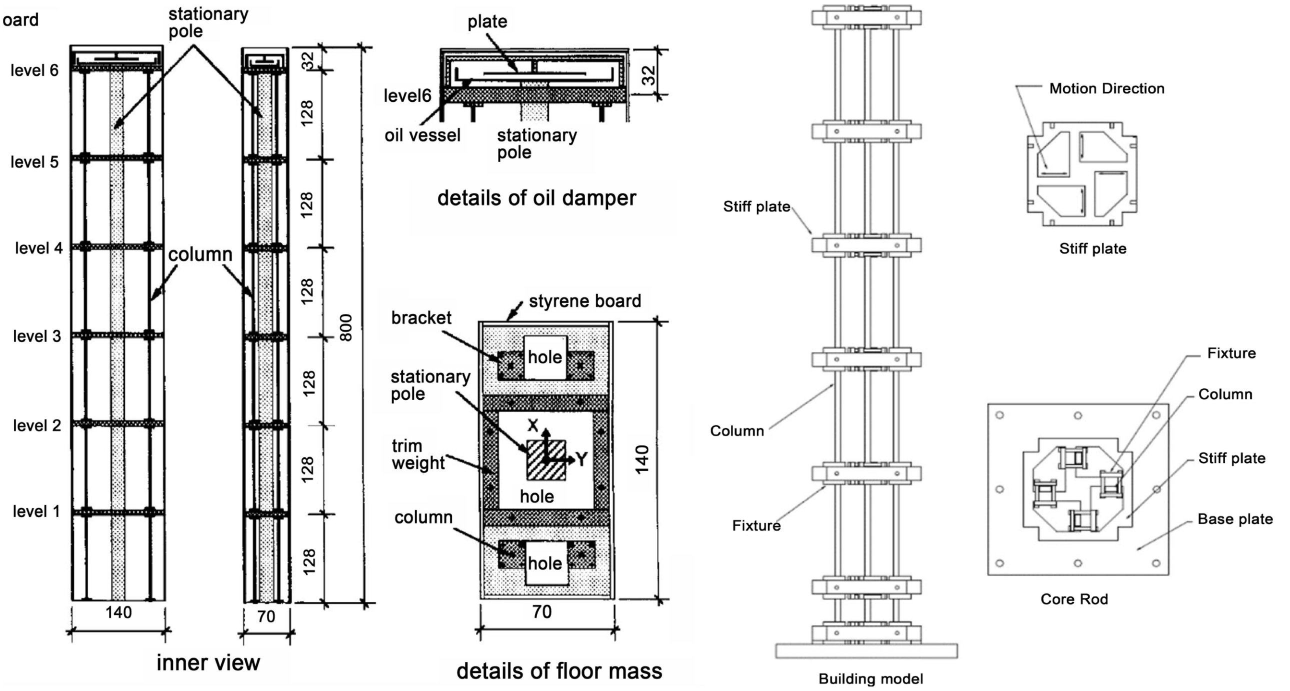
The model proposed by Quan Yong [17] uses an aluminum core skeleton to ensure stiffness, aerospace wood to make the outer covering to simulate the aerodynamic shape, optimizes the stiffness distribution by adjusting the spacing of columns, and realizes mass distribution similarity by adding local mass blocks, effectively improving the simulation accuracy of dynamic characteristics.

Based on the model design scheme of Quan Yong [17], Wang *et al.* [69] proposed an MDOF aeroelastic model fabrication method that can flexibly adjust the structural frequency and mode shape. By replacing skeleton components with different stiffness and adjusting the position of mass blocks, it adapts to the dynamic characteristic requirements of different buildings.

For high-rise buildings with relatively low requirements on mode shapes, Zhang Lele [70] and Hao Wei [71] respectively designed new two-degree-of-freedom pendulum-type aeroelastic test models based on electromagnetic induction dampers, simplifying the damping adjustment process while ensuring the measurement accuracy of wind-induced responses (**Figure 3(c)**, **Figure 3(d)**).

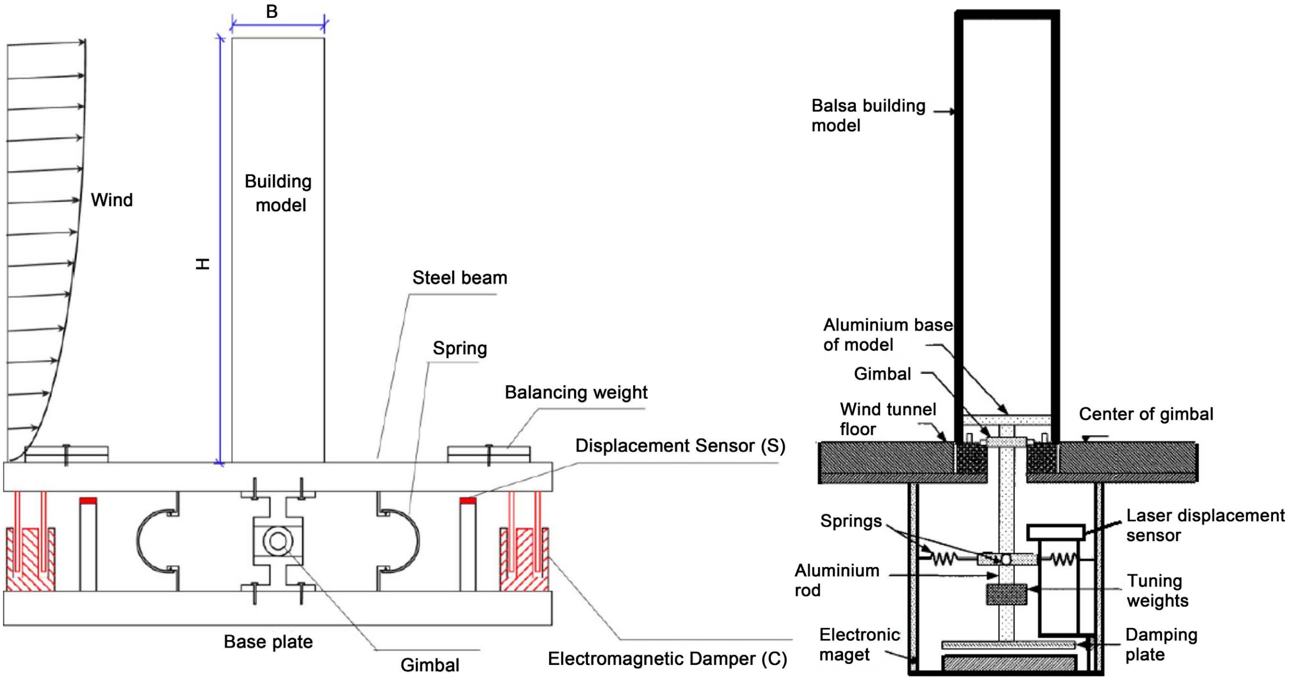
3.1.3. Technical Limitations

Both SDOF and MDOF aeroelastic model vibration measurement tests have significant limitations:



(a) Yoshie [68]

(b) Quan Yong [17]



(c) Zhang Lele [70]

(d) Hao Wei [71]

Figure 3. Typical MDOF aeroelastic model designs.

SDOF models: Only the contribution of the first-order mode can be considered, and they rely on the linear mode shape assumption, resulting in large analysis errors for wind-induced vibration of super high-rise buildings and tall structures; at the same time, the spring suspension system of the test base is prone to the influence of nonlinear factors (such as friction of connecting parts, interaction of damping oil molecules), leading to amplitude dependence of the structural damping ratio, which interferes with the identification accuracy of the aerodynamic damping ratio.

MDOF models: The fabrication process is complex, the economic cost is high, and the time consumption is long. The simulation accuracy of dynamic characteristics (such as the damping ratio of each order mode, the mode shape of higher-order modes) is difficult to ensure accurately; in addition, the gaps (about 1 - 2 mm) between the rigid outer coverings of each segment of the model will interfere with the wind pressure field on the structure surface, affecting the measurement results of wind-induced responses.

Common limitations: Both methods cannot obtain the unsteady aerodynamic force information on the model surface during vibration, so it is difficult to intuitively analyze the coupling mechanism between the model and the surrounding wind field, and cannot reveal the essential influence laws of aeroelastic effects.

3.2. Aeroelastic Model Synchronous Vibration-Pressure Measurement (HAPT) Test

3.2.1. Technical Principles and Development History

The high-rise building aeroelastic model synchronous vibration-pressure measurement (HAPT) wind tunnel test technology is a new type of wind tunnel test technology that has been gradually developed and improved in the past decade. Its core idea is: under wind load excitation, the test model undergoes wind-induced vibration, and at the same time, the wind load signals on the model surface are obtained through a synchronous acquisition system [72]. This technology integrates the two functions of “wind-induced response measurement” and “unsteady aerodynamic force measurement”. It can not only accurately simulate the aeroelastic effect between the structure and the incoming flow but also intuitively observe the dynamic changes of wind load on the model surface, providing a new perspective for in-depth understanding of the aerodynamic characteristics of high-rise buildings and the evolution laws of the surrounding flow field [73].

3.2.2. Engineering Applications and Typical Studies

Currently, wind tunnel test research based on HAPT technology is still in the development stage. Typical related results include: Hayashida *et al.* [74] conducted synchronous vibration-pressure wind tunnel tests on square column models, compared and analyzed the differences in layer aerodynamic force coefficients, base lift coefficient power spectra, and phase spectra between static models and vibrating models, and initially revealed the influence of vibration on aerodynamic force characteristics; however, limited by the technical conditions at that time, the influence of nonlinear factors such as the amplitude dependence of aeroelastic base dynamic parameters and pressure measurement pipe signal distortion was not fully considered, and the accuracy of the test conclusions needs further verification; Chiara [75] developed a set of HAPT test devices in his doctoral research, which can simultaneously measure the surface wind pressure, base aerodynamic force, acceleration, and displacement response of the aeroelastic model. The device is composed of an external skin and an internal skeleton assembled together; however, due to defects in the test design, the amplitude dependence curve of the modal damping ratio is disordered (e.g., the first-order modal damping ratio is as high as 8% at low amplitudes), which is inconsistent with the actual structural damping characteristics, making it difficult for the model to generate large-amplitude vibration under wind action. In addition, the model fabrication is time-consuming and labor-intensive, which is not conducive to application in practical scientific research; Huang *et al.* [76] developed a set of MDOF HAPT test devices and conducted a series of wind tunnel tests based on square prism models. They systematically analyzed the influence of aeroelastic effects on structural responses, mean wind pressure coefficients, fluctuating wind pressure coefficients, base aerodynamic force power spectral density, and coherence functions, and clarified the action laws of aeroelastic effects; Kim *et al.* [8] studied the influence of low-turbulence wind fields and boundary layer wind fields on unsteady wind pressure based on a set of SDOF HAPT test devices. The results showed that within the vortex-induced resonance wind speed range, the aeroelastic effect has a significant influence on cross-wind aerodynamic forces, while its influence on along-wind aerodynamic forces can be ignored. Based on the SDOF aeroelastic model test base (**Figure 2(a)**), Chen *et al.* [77] improved and designed a HAPT test device. Aiming at the problem of "amplitude dependence of aeroelastic model dynamic parameters (damping ratio, stiffness)" in HAPT technology, they proposed an equivalent linearization method using the Krylov-Bogoliubov averaging method [78] [79] to simulate the characteristics of nonlinear systems, and combined with the improved wavelet transform method [80] to realize the accurate identification of dynamic parameters [81]; Aiming at the problem of "non-wind-induced pressure interference caused by model vibration" in HAPT technology (**Figure 4**), Chen *et al.* [81] proposed a method for identifying non-wind-induced nonlinear damping and stiffness based on forced vibration wind tunnel tests, successfully identifying the non-wind-induced aerodynamic parameters of vertical prisms and inclined prisms, and solving the two core defects of HAPT technology; on this basis, Chen *et al.* [82] obtained the unsteady aerodynamic forces on the surface of square prisms using HAPT technology, decomposed them into aerodynamic damping forces, aerodynamic stiffness forces, and random buffeting forces based on the principle of energy equivalence, established a nonlinear mathematical model of unsteady aerodynamic forces using polynomial functions, and verified the accurate prediction ability of this model for the galloping response of square prisms through wind tunnel tests.

Chen *et al.* [82] discovered a new aerodynamic phenomenon in the HAPT test of tapered prisms: after separation, the shear layer will partially reattach to the building surface, suppressing vortex shedding in this area and forming a separation bubble, and this phenomenon will transform into a fully reattached state with the change of wind direction angle; they also found that the tapering aerodynamic

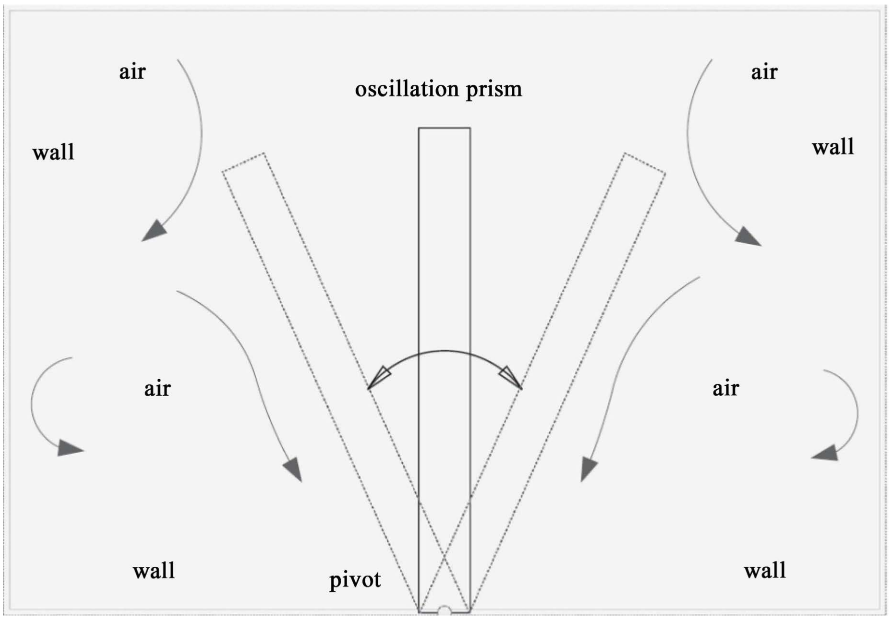


Figure 4. Principle of non-wind-induced aerodynamic interference in HAPT technology.

measure will enhance the sensitivity of the building's top area to wind loads; Fu *et al.* [83] explored the influence of incoming flow turbulence intensity on the unsteady aerodynamic forces of square columns based on HAPT technology, and analyzed the mechanism of aeroelastic effects and the variation law of aerodynamic damping ratio. The results showed that aeroelastic effects have a significant influence on unsteady aerodynamic forces and wind-induced responses; increasing the incoming flow turbulence intensity will weaken the correlation between unsteady aerodynamic forces, thereby suppressing aeroelastic effects, and both the positive and negative peaks of the aerodynamic damping ratio decrease with the increase of incoming flow turbulence intensity.

3.2.3. Technical Limitations

Although HAPT technology solves the problem of synergistic research on aeroelastic effect simulation and unsteady aerodynamic force measurement, it still has significant limitations:

1) Interference of nonlinear factors: This technology relies on the aeroelastic base (spring suspension system) to simulate the model dynamic characteristics, which inevitably suffers from the influence of factors such as friction of connecting parts and nonlinearity of damping oil. Especially when the structure undergoes large-amplitude vibration (such as galloping), the interference of nonlinear damping and stiffness on the test results is significant, while the reliability of existing identification methods based on the assumption of weakly nonlinear systems is insufficient.

2) Poor repeatability of test results: The vibration of the model under random wind load excitation is greatly affected by test environment factors (such as airflow uniformity, temperature) and equipment status, resulting in low repeatability of

test results. Furthermore, inherent variabilities in the experimental setup itself contribute to this issue. These include mechanical wear in the suspension system's components (e.g., hinges, springs) over time and calibration drift in sensors and acquisition systems, which collectively introduce non-linear, time-variant errors that are difficult to isolate and control.

3) Signal-to-noise ratio problem: When the vibration amplitude is small, the ratio of unsteady aerodynamic force signals to background noise (signal-to-noise ratio, SNR) is low, making it difficult to accurately extract effective signals and affecting the accuracy of test results.

Despite the above limitations, by synchronously obtaining wind-induced responses and unsteady aerodynamic forces, HAPT technology provides a key means for revealing the wind-structure coupling mechanism and remains a highly promising wind tunnel test technology.

4. Forced Vibration Model Wind Tunnel Test Technology

4.1. Technical Principles and Core Advantages

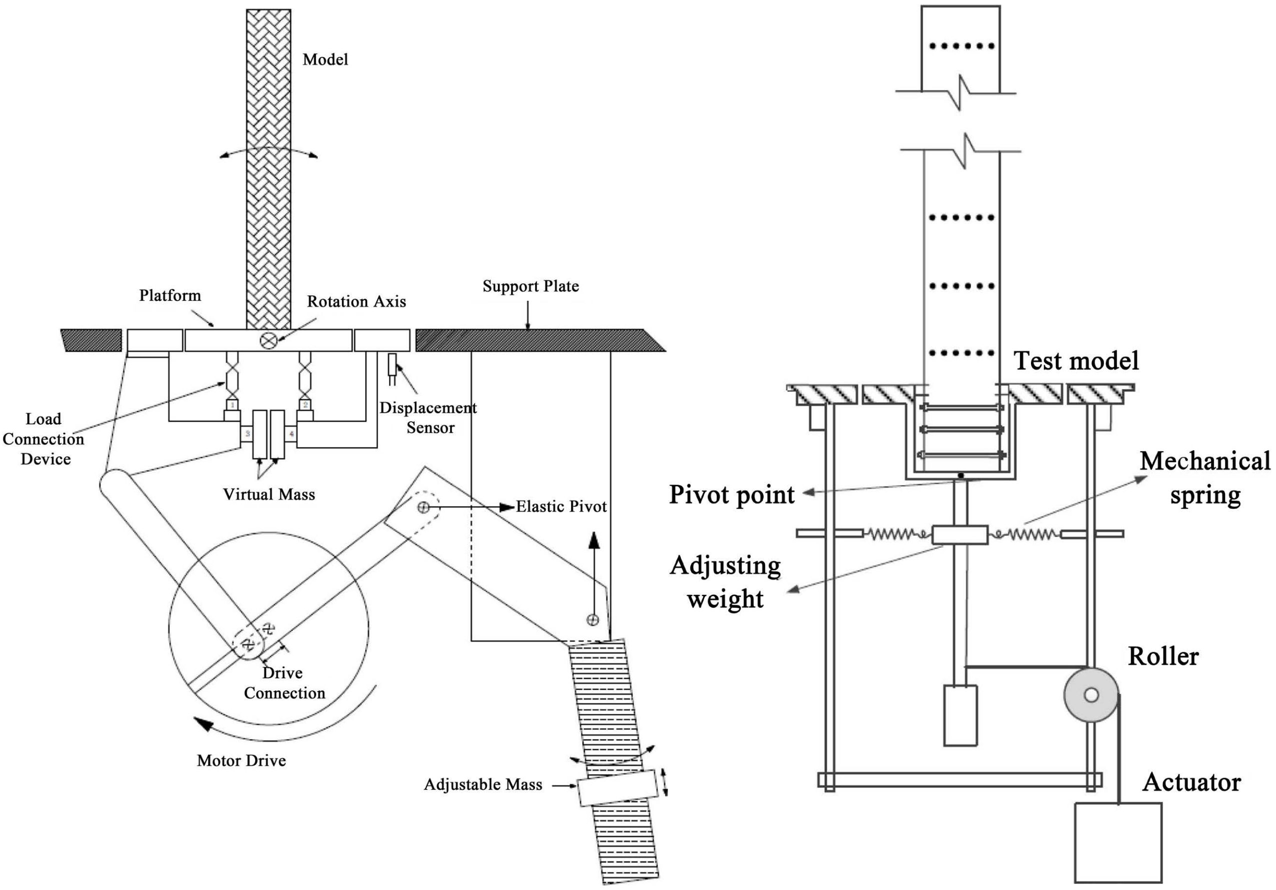
Different from the "random wind load excitation" mode of rigid model tests and aeroelastic model vibration measurement tests, the forced vibration model wind tunnel test actively controls the vibration amplitude and frequency of the model during the wind tunnel test through special driving equipment, making the model perform harmonic vibration, thereby accurately and quantitatively studying the aeroelastic effects and aeroelastic parameters of high-rise buildings [84]. The core advantages of this technology are: large signal-to-noise ratio of test signals, good stability of test results, and high accuracy in identifying aeroelastic parameters. It can effectively avoid the interference of random wind load uncertainty and provide accurate test data support for the study of aeroelastic effect mechanisms.

In the 1960s, Bishop and Hassan first proposed the forced vibration test method and applied it to the study of flow around circular cylinders [85]; subsequently, Bearman *et al.* [86]-[88] used this method to compare the surface aerodynamic force characteristics of static cylinders and vibrating cylinders in detail and conducted a large number of studies on the mechanism of bluff body vortex shedding. In the field of civil engineering, forced vibration model wind tunnel test technology has been widely used in the identification of flutter derivatives of bridge segment models [89]-[94]. However, due to the high complexity of the design and manufacturing of test devices for high-rise buildings, its application in wind-resistant research of high-rise buildings is still relatively limited.

4.2. Engineering Applications and Typical Studies

4.2.1. SDOF Forced Vibration Devices and Tests

Steckley [84] was the first to conduct forced vibration wind tunnel test research on high-rise buildings and tall structures, and developed a set of classic SDOF forced vibration devices (**Figure 5(a)**): the upper part of the device is a rigid test model that only simulates the aerodynamic shape of the building, and the lower part is an active excitation system, including transmission bearings, drive motors, displacement sensors, and force measurement equipment, which can realize the harmonic vibration of the model along a specific direction and measure the base aerodynamic force; however, this device can only obtain the overall aerodynamic force and cannot obtain the local wind load distribution.



(a) Steckley [84]

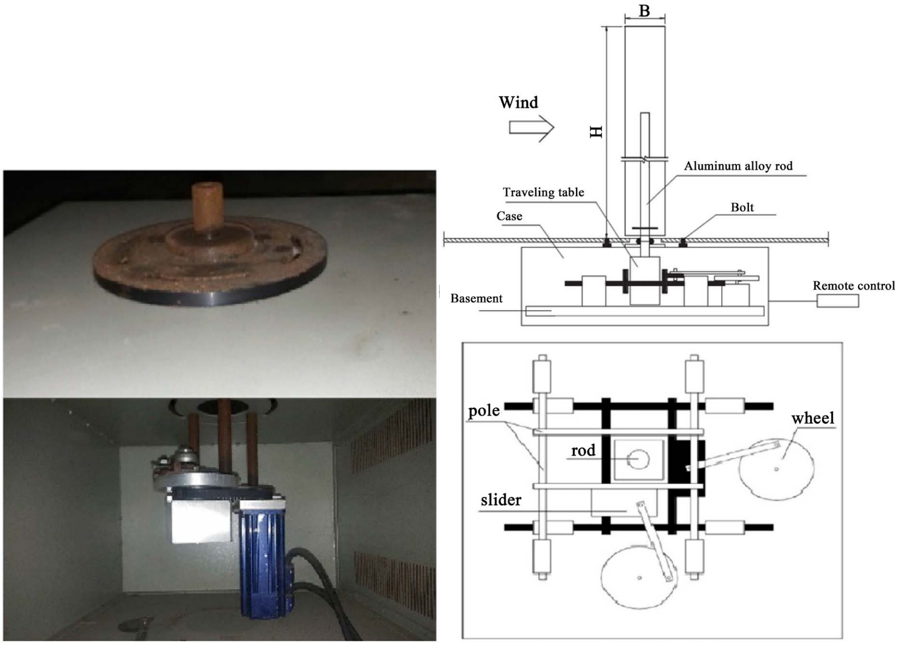
(b) Chen [65]

Figure 5. Principles of typical SDOF forced vibration devices.

To supplement the local wind load information, Chen *et al.* [65] improved and designed a SDOF forced vibration test device based on the Steckley device (**Figure 5(b)**): pressure measurement channels are arranged on the surface of the upper test model to obtain the spatiotemporal distribution of surface wind pressure; the lower part retains the drive motor system (actively driving the model to perform harmonic vibration), mechanical springs (providing hysteretic force), and displacement response measurement system, realizing the synergy of "vibration control-aerodynamic force measurement-response monitoring"; this device requires the test model to have sufficient rigidity to ensure the simulation accuracy of the aerodynamic shape. During the test, the actual dynamic characteristics of the structure are not directly simulated, and only the linear mode shape of the model vibration is considered [95].

4.2.2. MDOF and Special-Direction Forced Vibration Devices and Tests

With the in-depth study of aeroelastic effects of high-rise buildings, forced vibration in a single direction can no longer meet the research needs of complex coupling effects. Scholars have gradually developed MDOF and special-direction (such as torsional) forced vibration devices: Zou *et al.* [96] developed a new torsional forced vibration test device (**Figure 6(a)**) specifically for studying the torsional aeroelastic effects of high-rise buildings. The test results showed that the vibration amplitude has no significant influence on the torsional aeroelastic effect, and the torsional aerodynamic stiffness ratio can be ignored when there is no structural eccentricity; Liang *et al.* [97] and Song *et al.* [98] jointly developed a biaxial forced vibration device (**Figure 6(b)**). This device can realize SDOF harmonic forced vibration in two horizontally orthogonal directions, and can also realize coupled forced vibration in the two directions. The vibration amplitude, frequency, and phase can be flexibly adjusted, providing key equipment support for the study of biaxial coupled aeroelastic effects of high-rise buildings.



(a) Zou *et al.* [96] (b) Song *et al.* [98]

Figure 6. Typical MDOF and special-direction forced vibration devices.

4.3. Technical Limitations

The limitations of the forced vibration model wind tunnel test technology are mainly reflected in three aspects:

1) Complex device design and manufacturing: The mechanical structure and control system integration of MDOF and special-direction forced vibration devices are difficult, and the manufacturing cost is high, which limits the wide application of this technology in conventional wind-resistant research of high-rise buildings.

Difference between vibration form and reality: Most existing forced vibration devices drive the model to perform harmonic vibration, while the vibration of actual high-rise buildings under natural wind is random vibration. There is an essential difference between the two vibration forms, which may lead to deviations between the test results and the actual wind-induced response.

2) Insufficient consideration of modes: Currently, this technology can only consider the influence of the first-order linear mode shape, ignoring the contribution of higher-order modes and nonlinear modes to the aeroelastic effect, resulting in limited accuracy in the research of slender and complex-shaped super high-rise buildings.

Despite the above limitations, relying on its ability to accurately control vibration parameters, the forced vibration test technology has irreplaceable value in basic research such as the identification of aeroelastic parameters of high-rise buildings and the mechanism of vortex shedding. In the future, through device optimization and vibration form innovation, its application scope will be further expanded.

5. Technical Summary and Future Outlook

5.1. Summary of the Technical System

The wind tunnel test technology for high-rise building models has formed a complete system centered on "rigid model tests-aeroelastic model tests". Various technologies have clear applicable scenarios, core advantages, and limitations (Table 1), which can cover the needs of high-rise building wind-resistant design from the conceptual stage to the refined stage:

Table 1. Various technologies have clear applicable scenarios, core advantages, and limitations.

Type of Test Technology	Core Function	Applicable Stage	Core Advantages	Main Limitations
HFFB	Measuring overall aerodynamic forces	Conceptual Design	Simple model fabrication, high test efficiency	Linear mode assumption, no local wind load, ignorance of aeroelastic effects
SMPSS	Measuring surface wind pressure and local wind load	Preliminary Design	Considering nonlinear modes and higher-order modes	Pressure signal distortion, difficulty in arranging points for complex shapes, ignorance of aeroelastic effects
SDOF	Measuring first-order mode wind-induced response	Preliminary Design	Considering aeroelastic effects, low fabrication difficulty	Only first-order linear mode, nonlinear damping interference
MDOF	Measuring multi-order mode wind-induced response	Refined Design	Considering coupled modes and nonlinear modes	Complex fabrication, high cost, no unsteady aerodynamic forces

Continued

HAPT	Synchronously measuring response and unsteady aerodynamic forces	Refined Design	Revealing wind-structure coupling mechanism	Nonlinear interference, poor repeatability, low SNR
Forced Vibration Test	Identifying aeroelastic parameters	Basic Research	High SNR, stable results, high accuracy	Complex devices, large difference between vibration form and reality, insufficient mode consideration

1) Conceptual design stage: Priority is given to HFFB technology to quickly obtain the overall wind load, compare the wind-induced response characteristics of different aerodynamic shape schemes, and realize the preliminary optimization of the scheme.

2) Preliminary design stage: Combine SMPSS technology to supplement the local wind load distribution and the influence of higher-order modes, and use SDOF aeroelastic model tests to verify the significance of aeroelastic effects, providing a basis for the design of structural wind-resistant parameters.

3) Refined design stage: Use MDOF aeroelastic model tests, HAPT technology, or forced vibration tests to conduct in-depth analysis of the mechanism of aeroelastic effects, unsteady aerodynamic force characteristics, and the influence of coupled modes, ensuring the wind-resistant safety and service comfort of the structure.

5.2. Future Development Directions

Aiming at the current limitations of wind tunnel test technologies for high-rise building models and combining with the development trend of super high-rise buildings towards “taller, more flexible, and more complex”, future technical development needs to focus on four directions:

1) Optimization of model fabrication and similarity: Develop new model materials with light weight, high stiffness, and low damping, and combine advanced manufacturing technologies such as 3D printing to improve the geometric accuracy of complex-shaped models and the simulation accuracy of dynamic characteristics; at the same time, improve the similarity criterion, break through the limitation of the “linear mode shape assumption”, and establish a similarity system considering nonlinear modes and multi-field coupling (wind-structure-temperature).

2) Innovation of measurement and acquisition technology: Develop pressure sensors and displacement measurement equipment with high sampling frequency and low noise, and combine wireless synchronous acquisition technology to eliminate the interference of cables on model vibration; at the same time, integrate particle image velocimetry (PIV) technology with HAPT technology to realize synchronous measurement of “flow field structure-unsteady aerodynamic forces-

wind-induced response", and in-depth reveal the wind-structure coupling mechanism.

3) Upgrading of data processing methods: Introduce artificial intelligence technologies such as machine learning and deep learning to optimize the aeroelastic parameter identification algorithm and eliminate the interference of nonlinear factors on test results. For example, ML algorithms can be leveraged to develop highly accurate surrogate models from wind tunnel data, enabling rapid wind load predictions for parametric design studies. Alternatively, AI-driven real-time signal processing techniques could be developed to correct for nonlinear interference in HAPT systems. At the same time, establish a fusion model of multi-source test data (HFFB, SMPSS, HAPT) to improve the prediction accuracy of wind-induced responses.

4) Enhancement of extreme wind environment simulation capability: Develop special wind tunnel equipment capable of simulating extreme wind environments such as typhoons and tornadoes, optimize the wind field simulation accuracy, and combine forced vibration tests and HAPT technology to study the aeroelastic effects and wind-resistant safety reserves of high-rise buildings under extreme wind conditions, providing technical support for the design of super high-rise buildings in extreme wind areas.

6. Conclusions

The wind tunnel test technology for high-rise building models is the core means to solve the problems of wind-induced vibration and aeroelastic effects of super high-rise buildings. Its technical system is constantly improved with the increase in building shape complexity and the upgrading of wind-resistant requirements:

1) Rigid model tests, centered on HFFB and SMPSS, realize the rapid measurement of overall and local wind loads, respectively, providing a basis for the aerodynamic shape optimization and preliminary wind-resistant design of buildings.

2) Aeroelastic model tests, through SDOF/MDOF vibration measurement and HAPT technology, gradually realize the synergistic research of aeroelastic effects and unsteady aerodynamic forces, providing mechanism support for refined wind-resistant design.

3) Forced vibration tests, relying on their ability to accurately control vibration parameters, have become a key technology for the identification of aeroelastic parameters and basic mechanism research.

In the future, through the innovation of model materials, the upgrading of measurement technology, the optimization of data processing, and the enhancement of extreme wind simulation capabilities, the wind tunnel test technology for high-rise building models will further break through the existing limitations and provide more powerful technical support for the safe, economical, and comfortable design of super high-rise buildings.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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