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Research on Wind-Induced Vibration of the Steel Tower on High-Rise Buildings

高层建筑楼顶突出物风致振动问题研究

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Abstract

An analysis on dynamic characteristics and wind-induced response of a high-rise building with a steel tower on the roof was conducted by ANSYS. It shows that the wind direction have a great influence on the steel tower. When the frequency of vortex-induced vibration is close to the frequency of the steel tower, it will result in serious coupling vibration of steel tower. The vibration reaches to the top when two of the factors above (particular wind direction, particular wind speed) appear at the same time. The wind-resistant performance of steel tower should be made full use in actual design, and its adverse effects should be avoided, so that the whiplash effect of structure and across-wind sympathetic vibration could be minimized.

Keywords: High-Rise Building, Wind-Induced Vibration, Numerical Wind Tunnel Test, Whiplash Effect

摘要

本文采用有限元软件建立了一带钢塔的高层结构模型，通过数值风洞获得了作用于结构的风荷载。研究了不同风振作用下的结构动力响应。计算表明: 楼顶钢塔的振动对风向角的变化较为敏感; 不同方向、不同的来流风速将会引发不同频率的横风向漩涡脱落，当涡激振动的频率与带钢塔的结构频率接近时将会引起钢塔发生较大的耦合振动。在实际设计中，应充分考虑钢塔的自身抗风性能，避开不利影响，尽量减小结构的鞭梢效应和横风向振动。

关键词: 高层建筑，风致振动，数值风洞，鞭梢效应

Foreword

Steel towers protruding from the roofs of buildings are sensitive to both wind load and earthquake activity, as has been proved by the one on top of the Shanghai Information Tower in Lujiazui, Shanghai, which experienced an intense fit of vibration on February 7, 2013. The question of what caused the vibration is in question, however. Was it seismic activity, strong winds or perhaps a subway train? Experts from various sectors have given different explanations and theories on this matter. Based on a numerical-wind-tunnel approach, this paper intends to verify whether it was wind that had caused the intense vibration. The first part of this paper focuses on the establishment of a 1:1 ratio numerical wind tunnel model for the Shanghai Information Tower and the surrounding area by using CFD technology. This is in addition to the establishment of the wind field environment of the surrounding area and the time-history data of wind load acting on the Tower's structure through an "unsteady-state" calculation. The second part of this paper provides an analysis of the transient response of the building's structure when a wind load is

引言

楼顶钢塔是对风荷载和地震作用都较敏感的一种突出物。2013年2月7日，位于上海陆家嘴地区的上海信息大厦建筑楼顶的钢塔发生了一次感官强烈的振动。究竟是地震、风、还是地铁运营引发的此次振动，各领域专家都发表了各自的猜测。本文采用数值风洞方法，试图从风振的角度还原当时的现场，找出引起钢塔大幅振动的原因。文中首先采用CFD技术建立了信息大厦及其周边环境1:1的数值风洞模型，经过非稳态计算得到了建筑周边风场环境以及作用于大楼结构的风荷载时程数据。其次，将上述风荷载时程数据定点加载到该楼的有限元结构模型上，并进行结构的瞬态响应分析。文中研究了不同风向角、不同来流风速以及周边环境等因素对结构风振的影响。分析计算表明: 本文的研究对象上海信息大楼楼顶钢塔的振动对风向角的变化较为敏感，其中在西风下出现的涡激尾流频率与结构自身第三阶自振频率接近，容易在该风向的低风速下出现涡激共振，但该风向又正好属于大风概率较小的风向，因此实际出现楼顶钢塔大幅振动的现象成为小概率事件。

applied to selected points of the finite element structure model, based on the time-history data. In the rest of the paper, the effect of wind angle, wind speed and the surrounding environment of the structure's vibration are discussed. Findings of analyses and calculations shows that: The vibration of the steel tower on the Shanghai Information Tower's roof is more sensitive to wind angles than to other factors; the frequency of the vortex-induced wake is similar to the 3rd stage self-vibration frequency of a steel tower when western winds are blowing. A vortex-induced resonant vibration may be easily caused when a wind blows from the west, even at a low speed. This is in despite of the fact that there's only a small probability for a western wind to be strong enough to cause the steel tower to vibrate with a large amplitude.

Numerical Wind Tunnel Computation

Wind load is an important parameter for structural design and plays a decisive role for flexible structures, including that of high-rise buildings. Structures protruding from high-rise buildings are more sensitive to wind load than the architecture itself, and are likely to suffer from drastic oscillation. This may result in damage or even detachment under the impact of strong winds. With the development of urbanization, high-rise agglomerations are emerging constantly in cities and urban spaces are becoming increasingly complicated every day. Under such circumstances, wind-induced interference among high-rise buildings has become an outstanding problem. There are three major ways to measure the effect of this particular interference: on-site surveys, wind tunnel model testing and numerical computations. On-site surveys, however, may be restricted by tight time schedules, undesirable on-site conditions or tricky weather characteristics. Wind tunnel tests may also be negatively affected, but by the scale effect or inappropriate measuring devices. Nowadays, with constant progress in computer capabilities, it is now possible to calculate and apply numerical wind tunnel computations for the wind resistance designs of construction projects. This is especially true now, since the speed and accuracy of computational methods, coupled with easiness in model modification, are more advanced (Wang, 2004). In this paper, the CFD method and WAWS (Weighted Amplitude Wave Superposition) were adopted for calculating the time series of wind turbulence velocity. They were then used as the boundary conditions at the inlet of the numerical wind tunnel for computing the loading time-history of each floor, and were based on an unsteady-state calculation and wind pressure integral method which was applied to the building surface. The result will, in turn, provide data for subsequent computations related to the structure's response to wind-induced oscillation.

Figure 1 provides a 1:1 ratio model of the Shanghai Information Tower and other high-rise-buildings in the surrounding area within a range of 1km.

The computational domain is 8000m long, 6000m wide and 1000m high, with a 2.5% blocking rate, which meets standardized requirements. The grid density at some of the local areas near the building is increased, with a total grid number of about 15 million. Figure 2 shows the grid generation and definition of wind angle.

The wind speed time-history curve, which is based on a numerical method, is widely applied in practical computations of engineering design because it meets certain statistical features of wind. Generally, there are two methods of numerical "wind-speed time-series" simulations: WAWS and AR (Auto Regressive). As WAWS is based on

数值风洞计算

风荷载是结构设计的重要参数,对于高层建筑等柔性结构起着决定性作用，而高层建筑突出物比高层建筑主体结构对风荷载更为敏感，在强风作用下容易产生大幅振动直至脱落或损坏。另一方面，随着城市化的发展，城市中高层建筑群也不断涌现，城市空间的构成日趋复杂，各高层建筑间的风致互扰问题也非常突出。研究高层建筑物风致效应的主要方法有现场实测，风洞模型试验和数值模拟计算三种方法。现场实测存在周期长、现场条件限制、难以捕捉特定天气特征等缺陷; 风洞实验则存在缩尺效应、测量设备干扰等不足。当前，随着计算机性能和计算方法的改进，数值风洞计算的准确性日趋提高，加之其计算速度快、模型修改效率高等特点，采用数值风洞计算进行项目的抗风设计已经成为可能。本文基于计算流体动力学 (CFD) 方法，利用谐波叠加法模拟获得脉动风速时程，随后将其作为数值风洞入口边界条件，运用非稳态计算、通过建筑表面风压积分方法得到楼层的时程荷载，为后续的结构风振响应计算提供荷载数据。

本文按1:1比例建立的上海信息大楼及其周边1公里范围内的主要高层建筑，请见图1。

计算域大小为长8000m，宽6000m，高1000m，阻塞率2.5%，满足要求。对建筑物附近网格进行局部加密，网格总数约1500万。网格划分及风向角定义请见图2。

Figure 1. The numerical wind tunnel models
图1 数值风洞模型 (出自: 李亚明)

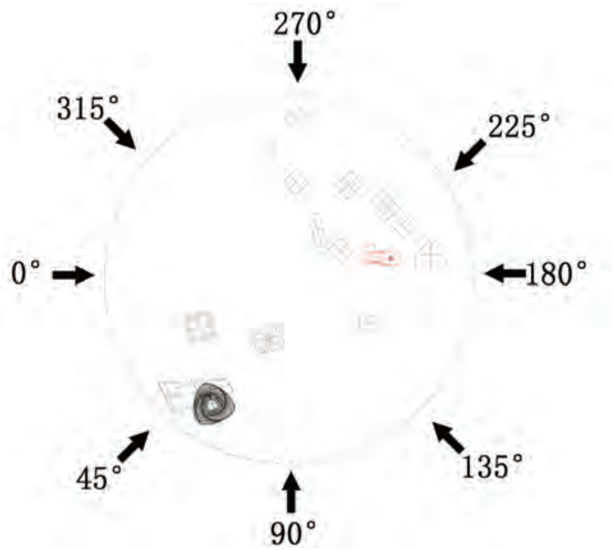

Figure 2. The definition of wind angle
图2 风向角定义 (出自: 李亚明)

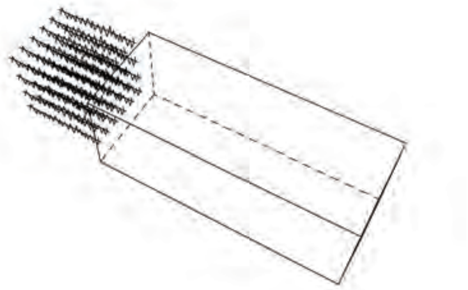

Figure 3. The simplified schematic of fluctuating wind entrance
图3 脉动风入口简化示意图 (出自: 李亚明)

the summation of trigonometric series, which are relatively simple and direct (Ma et al., 2009), this paper has adopted this method to simulate wind turbulence. The basic idea is a discrete numerical simulation approach, namely, to use a discrete spectrum to help get close to the target stochastic model (Liu & Zhu, 2005). Stochastic signals may be analyzed into a series of sinusoidal or other harmonic waves of different frequencies and amplitudes through DFT (Discrete Fourier Transform). Spectral density equal to the squared amplitude of these harmonic waves (Le, et al., 2008), are decided by band width. The stationary Gaussian process can be simulated with different kinds of trigonometric series; in this paper, the cosine wave is adopted for the purpose of describing the process.

5,363 turbulence wind curves were obtained through the simulation process. These curves were used as the boundary conditions at the inlet of a numerical wind tunnel, as indicated in Figure 3. For wind speed simulation, the sampling time step is 0.1 seconds and the step number is 1,200. The total simulation covers 120 seconds, which is long enough to figure out the turbulence characteristics of the wind, which helps to get long-period wind data. Figure 4 shows wind speed time-history curves at different heights. As shown by the figure, the wind speed time-history curves at 10m and 15m are quite similar, and so are those at 200m and 205m; but the curve at 10m and that at 200m are significantly less similar. This gives evidence to the correlation between wind turbulence and space. Figure 5 provides a comparison of the analog values of the inlet wind profile and turbulence intensity as well as their theoretical values. It clearly shows that the average wind speed and turbulence intensity values obtained through numerical simulation is very consistent with the theoretical target value.

Computations Related to Wind-Induced Oscillation of the Structure

The main body of the Shanghai Information Tower is 196m high, consisting of 47 reinforced concrete layers of a framed-tube structure, with a core tube on the right and left respectively, which is connected by a frame structure in the middle. The steel tower on top is 90m high, consisting of a tower column, horizontal bars, inclined struts and transverse diaphragms, etc. Figure 6 describes the finite element model. The damping ratio of the shown structure is 0.0035. Table 1 shows the frequency and period of natural vibration for the first 6 stages of modal analysis.

Modal analysis is used to help establish the vibration indexes of the structure, namely, the natural frequency (period) of the structure and the mode of vibration. This is essential for studies on structural systems afflicted with a dynamic load, as well as other dynamic

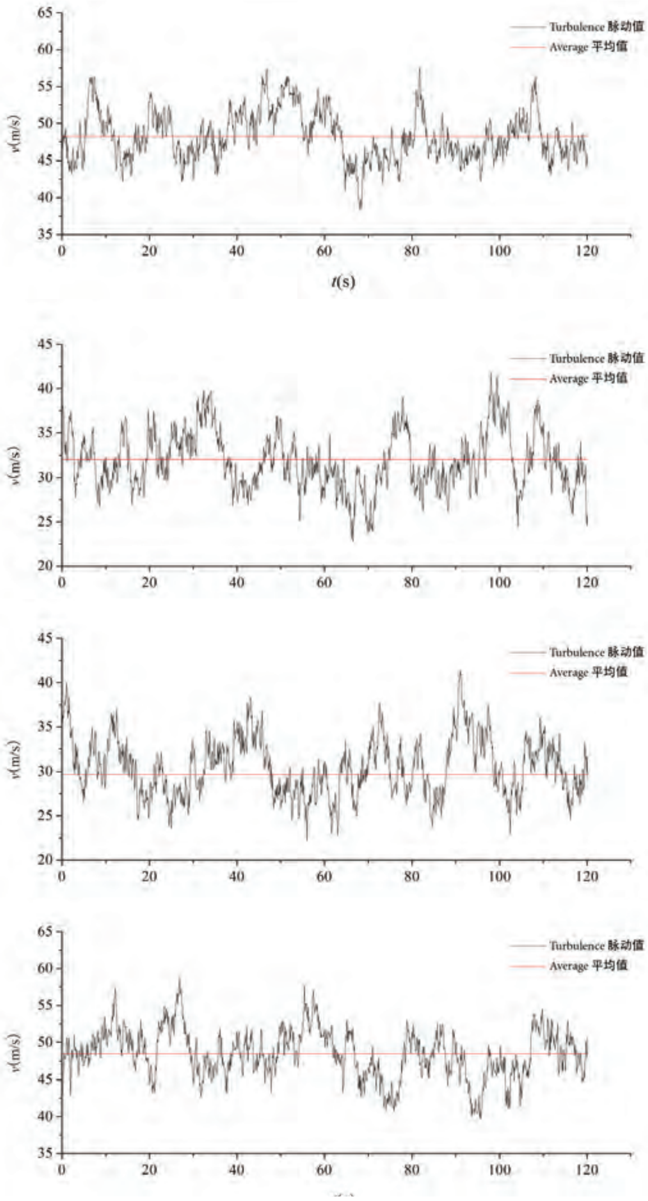

Figure 4. The time history of fluctuating wind speed at different heights (a)10m, (b)15m, (c)200m, (d)205m
图4 不同高度处的脉动风速时程 (出自: 李亚明)

阶数	1	2	3	4	5	6
频率值 (Hz)	0.29512	0.48956	0.63348	0.74528	0.87177	0.874826
周期 (s)	3.39	2.04	1.58	1.34	1.15	1.14

Table 1. Natural frequency and period of structure
表1 结构自振频率和周期 (出自: 李亚明)

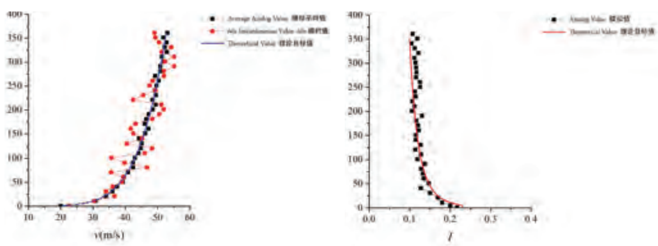

Figure 5. The section of wind inlet velocity and turbulence
图5 入口风速与湍流度剖面 (出自: 李亚明)

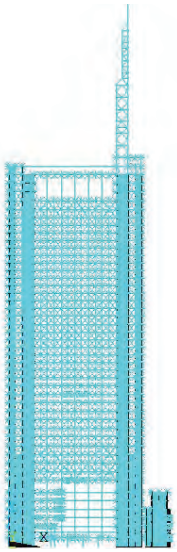

Figure 6. The structural finite element model
图6 结构有限元模型 (出自: 李亚明)

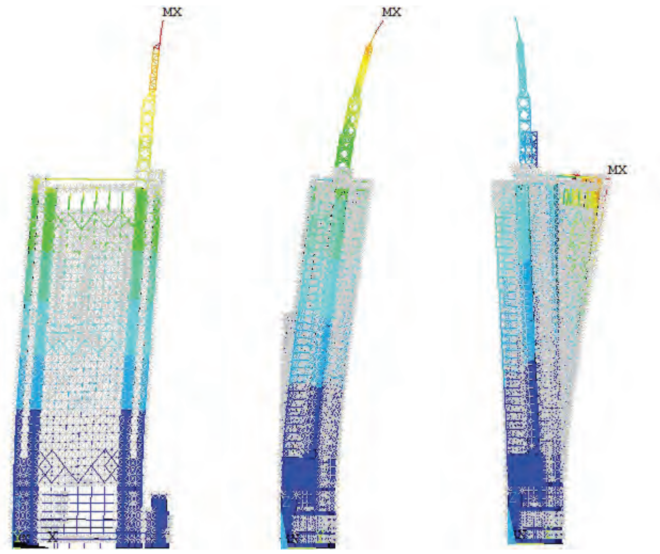

Figure 7. The structural modal shape
图7 结构模态振型 (出自: 李亚明)

analyses. Figure 7 illustrates the vibration mode of the steel tower. More specifically, the figure shows that the first stage is mainly characterized by an x-ward bend, the second stage a y-ward bend and the third stage by a twist and deformation.

There are generally two ways to analyze the response of complicated wind-sensitive structures to wind-induced oscillations, namely through frequency domain and time domain analysis. In frequency domain analysis, the oscillation equation is transformed from time domain to frequency domain through DFT, before the analysis of the power spectrum is carried out for working out the answer. In time domain analysis (Chen et.al, 2012), the time series of wind pressure obtained from the tunnel test or wind loading time-history gained from computer simulation is directly applied to the structure for analyzing the time series of the structure's response to wind-induced oscillation, which is based on dynamic computation. The working theory of time domain analysis works like this: the time series of wind load is first divided into a few load steps, then calculation is conducted step-by-step until working out the time series of the response, in which process, the response under the current load step is used as the initial condition for calculating the next step. Wilson-θ and Newmark-β are the most well-known among all the time domain methods which are famous for their high accuracy and wide applicability for computations related to the dynamic response of structures. Current researches show that steel towers placed on top of high-rise buildings always experience vibrations that are far more intensive than those occurring to the main body of the buildings themselves. This phenomenon is called the "whiplash effect." In order to analyze the wind-induced oscillation of the structure more accurately, this paper adopts the time domain method for computation.

Analysis of Computational Result

When wind interacts with a structure, alternate whirlpools will be caused behind both sides of the structure. The vortexes shed alternately from one side toward the other, which lead to the Kármán vortex street. The Kármán vortex street may lead to a periodic change of pressure which is imposed on a building's surface. The changeable force, which is vertical to wind flow, is called the "across-wind force."

基于数值方法的风速时程曲线可满足风的某些统计特性，因而广泛应用于实际工程设计的计算中。风速时程数值模拟方法大体上分为两类: 谐波叠加法(Weighted Amplitude Wave Superposition, WAWS)和线性滤波法(Auto Regressive method, AR)。其中谐波叠加法基于三角级数求和，算法简单直观。因此本文采用谐波叠加法来模拟脉动风，其基本思想是采用以离散谱逼近目标随机过程模型的一种离散化数值模拟方法。随机信号可以通过离散傅立叶分析变换，分解为一系列具有不同频率和幅值的正弦或其他谐波。谱密度就等于由带宽划分的这些谐波幅值的平方。平稳高斯过程可用不同形式的三角级数模拟，本文采用余弦波形式加以描述。

通过脉动风模拟得到入口5363条脉动风速曲线，作为数值风洞入口边界条件，请见图3。风速模拟采样的时间步长为0.1s，采样步数为1200，总共模拟了120s内的风速时程，足以捕捉到脉动风的脉动特征和风速的长周期信息。图4反映的是不同高度处的风速时程曲线。从图中可以看出10m和15m及200m和205m高度处的风速时程曲线相似度较高，而10m和200m高度处的风速曲线相似度较低，表明了脉动风的空间相关性。请见图5所示为入口风速剖面值和湍流强度剖面模拟值与理论值的比较，可见，数值模拟得到的平均风速及湍流强度值均很好地拟合了理论目标值。

结构风振计算

上海信息大厦下部主体结构高196m，为47层钢筋混凝土框筒结构，分为左右两个核心筒，中间由框架结构相连。上部钢塔高90m，由塔柱、横杆、斜撑、横隔等构件组成。结构有限元模型请见图6所示结构阻尼比为0.0035。结构模态分析的前6阶自振频率和自振周期请见表1。

模态分析用于确定结构的振动特性，即结构的固有频率 (周期) 和振型，它是对承受动态荷载结构体系进行分析研究的基础，同时也可以作为其他动力学分析问题的基础。本项目带钢塔结构振动模态请见图7。

从图中可以看出，第一阶模态主要以x方向弯曲变形为主; 第二阶模态主要以y方向弯曲变形为主; 而第三阶模态主要以扭转变形为主。

Wind Angle (Degree) 风向角 (度)	Wind Speed 风速 (m/s)					
	5	10	15	20	25	30
0	0.12	0.23	0.35	0.47	0.58	0.7
45	0.04	0.09	0.13	0.18	0.22	0.27
90	0.05	0.1	0.15	0.2	0.25	0.3
135	0.06	0.12	0.18	0.24	0.3	0.36
180	0.08	0.16	24	0.32	0.48	0.48
225	0.04	0.09	0.12	0.17	0.21	0.26
270	0.05	0.09	0.14	0.19	0.24	0.29
315	0.03	0.08	0.11	0.16	0.21	0.25

Table 2. The frequency of across-wind vortex-excited force of the building subjected to wind and flow of different directions
表2 不同风向与来流下建筑物所受横风向涡激力的频率 (Hz) (出自: 李亚明)

Oscillation caused by an alternative vortex and an operating vertically-against wind flow, is called a "vortex-induced vibration."

As air has mass, flowing air generates inertial force. Inertial force and viscous force are the two most powerful forces in air flow. They combine to determine the characteristics of air flow. The following is a discussion about the characteristics of incoming air flow in the surrounding area of a building when wind speed is between 5m/s-30m/s. The Reynolds number is 1.07-1.48, which is within a transcritical range. Despite that the wake flow moves in a very irregular pattern now, regular shedding of vortexes still exist. Table 2 provides a description of the wake shedding frequency for the Shanghai Information Tower under different wind angles and speeds obtained from numerical wind tunnel computations.

It may be observed, with the help of Table 1 that the vortex wake frequency is very close to the natural vibration frequency under the above wind angles and speed. They are likely to lead to a resonance between the structure and the wake flow. Figure 8 provides a power spectrum of displacement response at the tower tip under a wind angle of 0°, 45°, 90°, 180°, 225° and 315°. It can be seen from the chart that:

1. There is a low stage wave peak in the power spectrum for some of the wind angles and the frequency when the peak is about 0.3Hz. Obviously, this is in line with the first stage of a natural vibration period of the structure while the following peaks correspond to the higher stages respectively.
2. A notable wave peak which is even higher than the first stage peak is seen near the spot of 0.6Hz in the 0° power spectrum. This means that this wind angle has witnessed a larger vibration while the frequency is very close to that of the third stage natural vibration and across-wind vortex-induced frequency.
3. The peak near the spot of 0.6Hz as stated above is not seen at 45°or 315° where the peaks are relatively low, indicating that the phenomenon is extremely sensitive to wind angles. In this paper, the 0° angle points to the west. According to the wind rose map, in regards to Shanghai, the likelihood strong western winds in Shanghai is very low. This suggests that the probability for the two factors to concur at the same time, causing a large amplitude vortex-induced vibration of the steel tower on the Shanghai Information Tower, is even lower. Calculation results show that: the response amplitude for across-wind vibration (0.16m) is remarkably larger than that of the downwind vibration (0.03m). By comparing the response amplitude with the acceleration time history witnessed at the building's top at the same time, it can be concluded that:

对于对风敏感的复杂结构风振响应分析方法，可以大致分为频域分析法和时域分析法。其中，频域法是通过傅里叶变换将结构振动方程从时域转换到频域，利用功率谱分析进行求解。时域分析法是直接将风洞试验的风压时程或计算机模拟的风荷载时程作用于结构，进行风振响应时程分析，通过动力计算得到结构动力响应。其原理是将风荷载的时间序列分为若干荷载步，以当前荷载步作用下的结构响应作为下一个荷载步计算的初始条件，逐步求解获得结果响应的时间序列，Wilson-θ法和Newmark-β法是两种最为著名的时域计算法。时域法计算精度高、适用范围广，可以获得结构动力响应的全过程。现有研究表明，高层建筑楼顶钢塔在强风作用下常发生比主体结构大得多的强烈振动，这种现象称之为鞭稍效应。为精确分析结构风振机理本文采用时域分析法进行计算。

计算结果分析

当结构物上有风作用时，就会在该结构物两侧背后产生交替的漩涡，且将由一侧然后向另一侧交替脱落，形成所谓的卡门涡列。卡门涡列的发生会使建筑物表面的压力呈周期性变化，其结果是使结构物上作用有周期性变化的力，作用方向与风向垂直，称为横风向作用力。这种由交替涡流引起且与风向垂直的振动，按发生原因称为涡激振动。

由于空气具有质量，在流动中，空气具有惯性力作用。空气流动中影响最大的两个作用力是惯性力和粘性力，它们的相互关系成为确定可能出现何种流动特性或现象的依据。以下将讨论来流风速在5m/s~30m/s之间建筑物周边的流动现象。此时对应的雷诺数Re在1.0e7~1.4e8，流动处于跨临界范围，此时尽管尾流仍然十分紊乱，但仍然存在有规律的漩涡脱落。请见表2所示为不同风向角、不同来流风速下，由数值风洞计算得到信息大楼尾流脱落的频率。

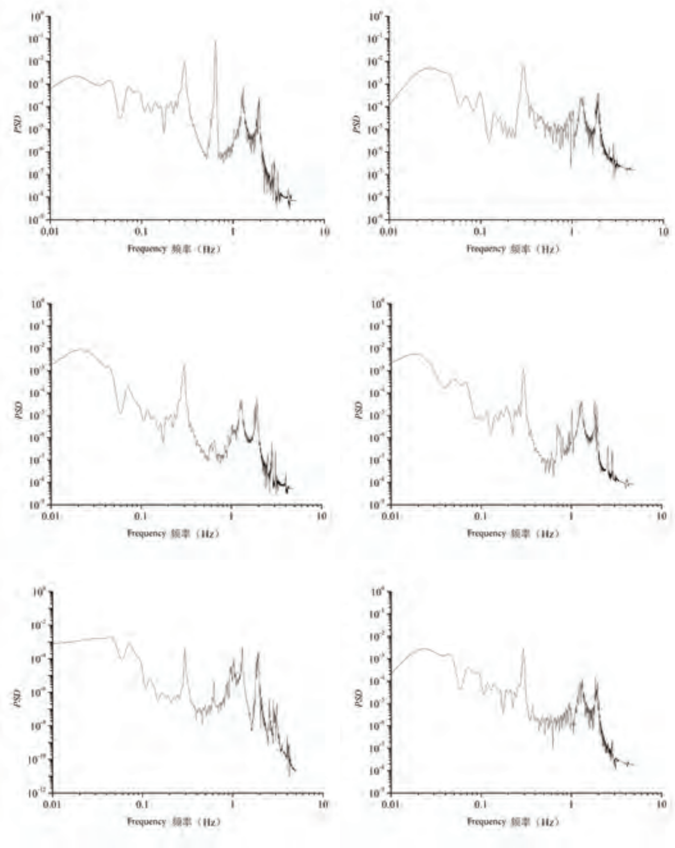

Figure 8. The displacement response power spectrum for each wind angle
图8 各风向角下位移响应功率谱 (出自: 李亚明)

- Across-wind oscillation response is notably larger than downwind oscillation response.
- The maximum acceleration response to the across-wind oscillation has exceeded the threshold value (5gal) and hence can be perceived by the human body.

The maximum downwind displacement value of a tower tip increases with the accruement of fundamental wind pressure, manifesting an obvious correlation with it. However, the gradient of displacement increase is going down at the same time. When the fundamental wind pressure is at 0.65kPa, the maximum displacement reaches 141mm, which leads to a notable whiplash effect. Therefore, it is advised here that when designing a steel tower, wind-resistance design should be carefully considered and planned in order to avoid the negative effects of wind pressure and bringing the whiplash effect to a minimum. On the other hand, the maximum across-wind displacement value of a tower tip fluctuates irregularly, displaying a weak correlation with fundamental wind pressure.

Conclusion

This paper uses numerical wind tunnel and discrete finite element structure dynamic time history analysis methods to analyze a target building of a high-rise agglomeration. By simulating the wind turbulence in the atmospheric boundary layer, a wind speed time series is obtained; wind speed time series is then added to hydrodynamics software as the boundary conditions at the inlet of numerical wind tunnel for wind pressure unsteady-state analysis; the wind pressure integral method is applied to get the wind loading time history of the building; finally, the finite element time series analysis method is used to work out the dynamic time-history response of the steel tower atop the building. The research concludes that:

1. Analysis of parameters shows that different wind angles and speeds may lead to across-wind vortex shedding at different frequencies. When the frequency of vortex-induced oscillation is close to the frequency of the structure bearing a steel tower, it may lead to large amplitude of coupled oscillation of the steel tower. When the factors act in conjunction (a certain wind angle and speed), the vibration of the steel tower will reach peak value.
2. Computations based on a numerical wind tunnel model shows that the steel tower on the Shanghai Information Tower is very sensitive to the change of wind angles. The frequency of the vortex-induced wake flow under the 0° angle is close to the third stage natural vibration frequency of the structure, which means there is a likelihood of vortex-induced resonance under low wind speeds.
3. It is advised here that when designing a steel tower, wind-resistance should be fully taken into account so as to avoid the negative effects of wind pressure which is critical in reducing whiplash effects and keeping across-wind oscillation to a minimum. In this case study, the wind direction that may witness a vortex-induced resonance is less likely to be affected by a strong wind, which means the probability for the steel tower to vibrate with large amplitude is lows.

结合表1可以看出，在上述风向和风速范围内涡激尾流频率与结构自振周期频率非常接近，比较容易引起结构与尾流的共振。请见图8给出了0°、45°、90°、180°、225°和315°风向角下塔尖位移响应功率谱图。从图中可以看出:

1. 几个风向角的功率谱中均存在一个低阶波峰，对应频率为0.3Hz附近，很明显这一频率对应结构第一阶自振周期，而随后的几个波峰分别对应结构的高阶振动;
2. 在0度风向角的功率谱中，在0.6Hz频率附近出现了一个明显的波峰，其峰值甚至超过了一阶波峰，证明在该风向角下出现了较大能量的振动，而这一频率恰好接近结构的第三阶自振频率以及此时的横风向涡激频率;
3. 上述0.6Hz附近的波峰在临近180度的其他两个角度45度和315度均未出现或波峰能量较低，由此说明该现象对风向角极为敏感。本文中的0度对应地理方位的西风，结合上海地区风玫瑰图分析，上海地区该方向出现大风的概率较低。由此说明能够使信息大厦楼顶铁塔发生大幅度涡激共振的两个因素同时出现的概率更低。

计算表明: 横风向的振动响应幅值 (0.16m) 明显大于顺风向的幅值响应 (0.3m) 。对比此时楼顶的加速度时程数据可以得到以下结论:

- 横风向风振明显大于顺风向风振响应;
- 横风向风振最大加速度响应已经超出了人体的感知水平 (5 gal) ，已经能被人体所察觉。

顺风向塔尖极值位移随基本风压增大而增加，二者具有明显的相关性，但是位移增加的梯度在减小，当基本风压为0.65kPa时，塔尖极值位移达到141mm，鞭梢效应十分明显，因此，在设计时应充分考虑钢塔自身的抗风性能，避开不利影响，尽量减小结构的鞭梢效应; 而横风向塔尖极值位移没有明显规律，呈现波动性变化，与基本风压相关性较弱。

结论

本文联合利用数值风洞和离散有限元结构动力时程分析法对高层建筑群中目标建筑进行了协同分析。通过模拟大气边界层中脉动风，得到脉动风速时程; 将风速时程作为数值风洞入口边界条件加载到流体力学软件中，进行风压非稳态分析; 通过结构风压表面积分方法得到楼层时程荷载，最后利用有限元时程分析法获得楼顶钢塔的动力时程响应。研究得出以下结论:

1. 参数分析表明，不同风向、不同的来流风速将会引发不同频率的横风向漩涡脱落，当涡激振动的频率与带钢塔的结构频率接近时将会引起钢塔发生较大的耦合振动。当上述两个因素同时出现时 (如特定风向角、特定风速) 钢塔的振动达到峰值。
2. 通过数值风洞计算表明，本文的研究对象上海信息大楼楼顶钢塔的振动对风向角的变化较为敏感，其中在0度风向角下出现的涡激尾流频率与结构自身第三阶自振频率接近，容易在低风速下出现涡激共振。
3. 建议设计楼顶钢塔时应充分考虑利用钢塔自身的抗风性能，避开不利影响，尽量减小结构的鞭梢效应、横风向风振等影响。本项目发生涡激共振的风向正好位于大风概率较小的风向，因此实际出现楼顶钢塔大幅振动的现象成为小概率事件。

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