Preliminary Study on Vibration Analysis of Truss Structures

Jiangping Li, Xianyun Wang*, Jiaxin Yang, Wei Jiang
North China University of Technology, Beijing 100144, China
**Corresponding Author*

Abstract: Truss structure is a common light structure, widely used in the field of engineering, often used in bridges, towers and other engineering projects. In order to study the dynamic characteristics of the truss structure and provide a more favorable basis for the design, the dynamic characteristics of the truss structure are tested in this paper, and the modal characteristics of the resonant condition are preliminarily analyzed according to the results of the test. First of all, by establishing the mathematical model of the truss structure, defining the frequency response function, and then Fourier transform, we can get the time domain signal of the excitation and the frequency of the dynamic response, and then use the finite element method to calculate the natural frequency of the structure. Then, the natural frequency and vibration mode are tested and analyzed, and the mechanism and influencing factors of resonance phenomenon are deeply discussed. Finally, the application prospect and limitation of vibration analysis of truss structure are discussed, and some improvement measures are proposed for the vibration problem of truss structure to improve the stability and anti-vibration ability of the structure. This test is of great significance for the design and optimization of the engineering based on truss structure, and provides feasible methods and ideas for researchers in related fields.

Keywords: Truss Structure; Modal Analysis; Natural Frequency; Vibration Mode

1. Introduction

The role of structure has always been recognized in the design and construction of buildings, but in reality, its function is more complex than just serving a load-bearing role [1]. Heino Engel once called the truss structure as a vector action system, that is, through the compression and tension of the linear rod in accordance with a certain law, and then connected with the hinged points, so as to achieve the compression and tension of the outside world, so as to achieve the continuous effect on the outside world [2]. It can change the original design according to different load-bearing needs, so as to achieve a variety of architectural effects. In addition, it also has a certain degree of variability, that is, to change the length, Angle or shape of the truss members, can adapt to different design requirements and functional needs.

In 1940, the Tacoma Strait suspension Bridge in the United States under the influence of extreme weather conditions, due to the stability and durability of its structure, the final 860 meters of the bridge collapsed from the height, even if the wind at that time did not reach the design wind speed limit of 1/3, but because the stability of the bridge structure itself failed to meet the standard, and ultimately caused disastrous consequences. With global warming, the approaching of tropical storms has caused serious damage to buildings. The root cause of these damages may come from the transverse force of the wind, and when the transverse force is equal to the natural frequency of the building, the so-called wind load resonance [3]. Truss structure is a kind of light structure composed of rods and joints, which has the characteristics of light weight, high stiffness and low cost, and is widely used in construction, aerospace, machinery and other fields. However, the truss structure is prone to resonance phenomenon at a specific frequency, which affects the stability and safety of the structure. This paper aims to further explore the dynamic characteristics of truss structures, as well as their natural frequencies, which not only has important theoretical value, but also has practical significance.

2. The Mathematical Model of the Truss Structure is Established

First, we propose hypotheses based on the geometry and material properties of the structure, and build a mathematical model of the structure by simplifying the truss structure into a collection of rods and nodes [4]. Then, by using the principles of statics and rigid body mechanics, we establish the balance equation of the force on the nodes and the balance equation of the whole structure. By solving these equations, we can get the stress and deformation of the structure on the nodes, and verify the accuracy of the mathematical model through examples. We choose a concrete truss structure as an example, and according to the established mathematical model for mechanical analysis. By comparing the calculation results of the mathematical model with the actual measurement data, the accuracy and reliability of the model are proved. By using the finite element analysis technique, we can divide the structure into several independent units, and then calculate its natural frequency and vibration characteristics.

2.1 Carry out Modal Analysis

Through advanced analysis systems, modal analysis can provide a better understanding of the dynamic behavior of structures and use it as an important means of identifying problems. It can help us to identify different vibration modes more accurately, so as to better understand the internal operation law of the structure. Through modal analysis, we can determine the main modes of structures in different frequency ranges, and thus infer their response to different external and internal vibration sources [5]. Therefore, modal analysis is of great significance for the dynamic planning and maintenance of structural systems.

2.1.1 A mathematical model of a hypothetical structure

When building a mathematical model of a truss structure, we can base it on several assumptions:

(1) Statically determinate hypothesis: the truss structure is a statically determinate system, that is, the constraints between the members and the nodes are enough to make the whole structure statically balanced. This hypothesis excludes the structural deformation caused by the external force and the imbalance of the node constraints. (2) Stiffness hypothesis: the rod in the truss structure is regarded as a rigid rod, that is, the length of the rod will not change during the stress process. (3) Linear elasticity hypothesis: It is assumed that the material has linear elastic properties within the force range, that is, the relationship between stress and strain is linear. (4) Mass hypothesis: ignore the mass of the truss structure members themselves, that is, only consider the influence of external forces and node constraints on the structure. (5) Plane hypothesis: the truss structure is regarded as occurring in a plane, and all the rods and nodes are restricted in this plane. This assumption is applicable to the analysis of two-dimensional truss structures.

2.1.2 Establish the modal model

By using the two-channel velocity Fourier Transform (FFT) analysis method, we can calculate the admittance function between two points. Next, we can use modal analysis theory to determine the morphology of these functions, and finally form a complete mode. By using the modal superposition method, we can use the existing load time series to infer the true vibration characteristics of the building [6], so as to obtain its response to the external environment.

2.1.3 Frequency response function

Modal studies aim to map response variables represented in traditional physical coordinate systems to a "modal coordinate system" model in order to represent them more accurately. Through modal analysis, we can find that there is an orthogonal correlation between the different characteristic variables, so that each variable can be represented singly and without any coupling. Before conducting structural test modal analysis, it is necessary to define the frequency response function, which in its original form can be described by the following formula:

$$H(\omega) = \frac{X(w)}{F(\omega)} \quad (1)$$

In the formula:

ω $X(\omega)$ $F(\omega)$ By Fourier transform, we can calculate the time domain signal f (t) of the excitation and the frequency of the dynamic response. In a linear n-degree-of-freedom vibration system, these transformations can be described by the following equations:

$$m\ddot{x}(t) + cx(t) + kx(t) = f(x) \quad (2)$$

By calculating the frequency response function matrix, the structural vibration damping can be converted to proportional viscous damping, so that the dynamic equation can be effectively decoupled, which can be achieved by exploiting the orthogonality of the modes:

$$H_{lp}(\omega) = \sum_{r=1}^{N} \frac{\varphi_{lr}\varphi_{pr}}{k_r - \omega^2 m_r + j\omega c_r} \quad (3)$$

In the equation:

k_r, m_r, ω_r, c_r Used to describe the characteristics of the R-order mode, including rigidity, mass, fixed frequency, and damping. These properties can be used to describe modes of p and l, where j is a complex number ϕ_{lr}, ϕ_{pr} $j = \sqrt{-1}$.

According to the formula, each row and each column of the frequency response function matrix contains various modal parameters, and the ratio between the modal frequency response variables in these columns is the R-order modal modes.

2.2 Transfer Function Analysis is Performed

By using excitation methods, we can perform an analysis of the motion state of the object. This analysis requires us to obtain the object's response to external stimuli and evaluate the motion properties of the object by calculating their reflectivity towards the object [7]. The core concept of this analysis is to describe the reflection of objects to external stimuli by calculating their reflectivity to external stimuli. By applying a force signal with a sine wave to i and j, and determining the propagation relationship between them by their respective reflections, we can obtain the propagation path between i and j. In addition, we can determine the path of the two points by reflecting each of them when there is a continuous change. Through innovative techniques, we can use structural models to achieve accurate vibration mode fitting, which more intuitively shows the vibration characteristics of the system. The commonly used excitation methods in structural modal tests include pulse, fast sine scan, step, pure random, transient random pseudo-random and so on. The test excitation signal is burst random excitation signal, the dynamic signal analyzer output burst random excitation signal, passed to the exciter through the power amplifier, the excitation generated by the exciter, the excitation force acts on the measured structure, the force signal and the response signal are transmitted to the dynamic signal analyzer by the force sensor and the acceleration sensor, respectively. The transfer function (Figure 1) is obtained to facilitate the subsequent analysis of the results.

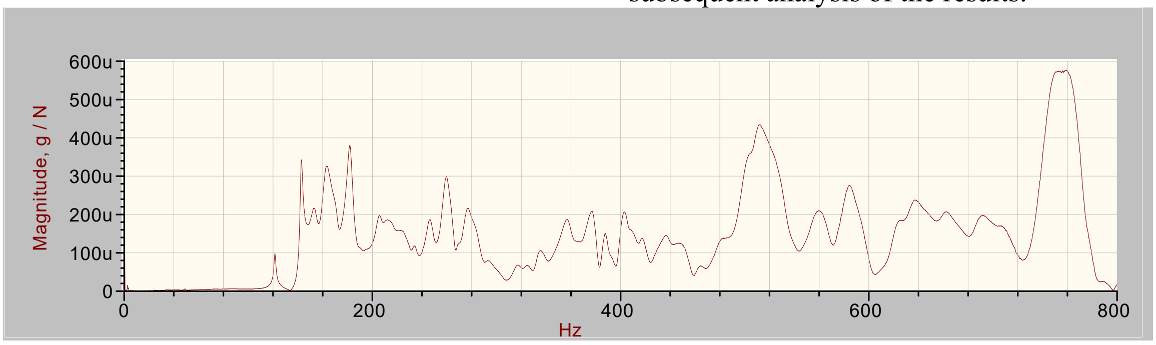

Figure 1. Tests the Resulting Transfer Function

2.3 By Using the Finite Element Method, We can Calculate and Analyze Different Truss Structures

(1) Carry out finite element calculation. According to the calculation requirements, the finite element model is established, and the original data information is integrated and processed, and the stiffness and element of the structure are locally and overall encoded. Different element stiffness matrices are formed under the corresponding coordinate system, and the integral stiffness matrix and the joint load of the whole structure are formed by the effective use of the element integration method. By listing the equations to solve, we can calculate the displacement of the joint and the internal force of the rod end of each member [8].

(2) Finite element program frame analysis. The analysis of finite element program framework needs to be carried out in accordance with certain steps, including input original data, result data, call the main control subroutine SPMAIN for operation, and output data. The main control subroutine finite element analysis also needs to be carried out in a certain way,

that is, start to input the original data, by calling the subroutine STIFFS to form the total rigidity matrix, the overall stiffness equation right end item load matrix, and then the program to solve the equations, the output node displacement, you can calculate the unit axial force and stress.

(3) A case study. According to the structure of the truss (Figure 2), under the condition that the bar materials are the same and the cross-sectional area and size are the same, calculations of the joint displacements, stresses and axial forces of the truss have been made (its cross-sectional area is $A=3cm^2$ and its elastic modulus is $E=2.1\times10^8 kN/m^2$)

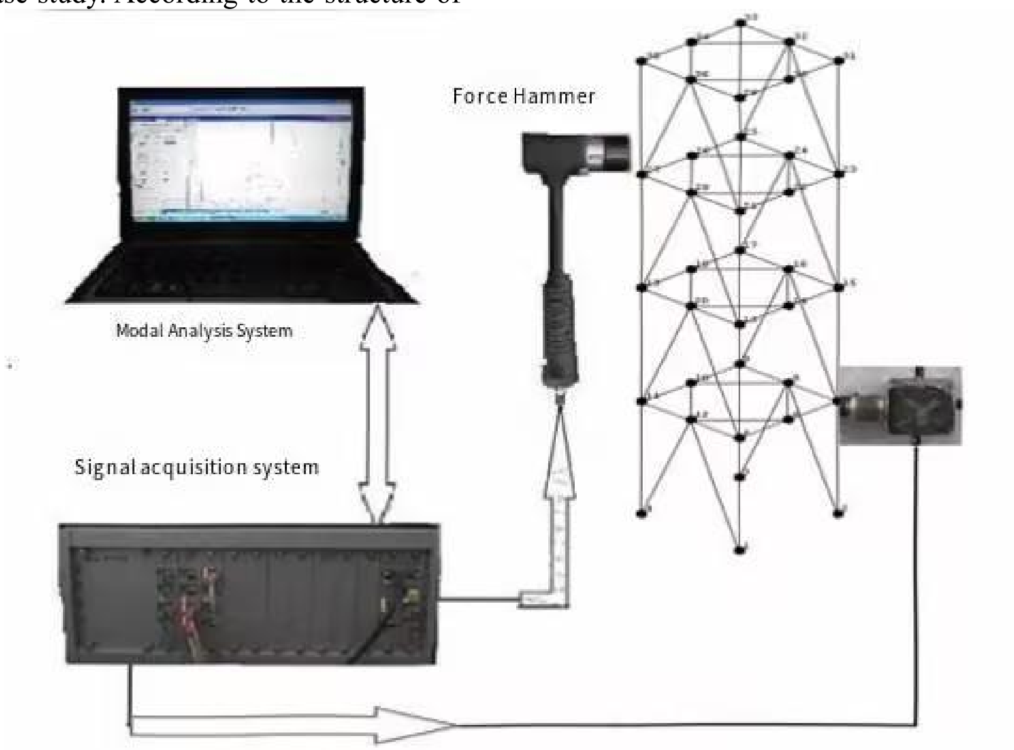

Figure 2. Test Flow Chart

Calculate the natural frequency of the structure

(1) Based on the mathematical model, the finite element software is used to calculate the natural frequency of the structure under different frequencies. Natural frequency is the basis of structural resonance, and its value reflects the characteristics of structural vibration. Table 1 shows the test results of natural vibration frequency of the basic structure.

(2) Analyze the natural frequency and vibration mode, and use the modal analysis software of LMS company to analyze the natural vibration characteristics. According to the modal judgment criteria, if the modal scale factor between the two modes is zero, there is no linear relationship between the two vectors, indicating the orthogonality between the different modes of the structure.

(3) Through the analysis of natural frequency and mode, the mechanism and influencing factors of resonance phenomenon are studied. Including the calculation of resonance frequency, the graphic display of vibration pattern and the analysis of resonance characteristics.

Table 1. Test Results of Natural Vibration Frequency (Hz)

Order	Y-direction			x-direction	
	Frequency (Hz)	Damping ratio (%)	Rank	Frequency (Hz)	Damping ratio (%)
1	17.4331	5.09	1	9.5981	4.00
2	35.9211	1.13	2	33.8701	0.16
3	157.3116	0.88	3	35.7421	0.45
4	196.4508	1.07	4	73.7085	0.10

5	211.8302	0.28	**5**	105.8024	0.09
6	284.3692	0.15	**6**	*	*
7	290.9700	0.03	**7**	*	*
8	307.8472	0.03	**8**	*	*
9	354.3348	0.23	**9**	*	*
10	679.7607	0.02	**10**	*	*

Judging from the mode, the first frequency in the Y direction is 17.4331Hz, and the first frequency in the X direction is 9.5981Hz, both of which are translational. Due to the diagonal support in the Y direction, the stiffness is large, so the first order natural vibration frequency is high (Figure 3). The following vibration modes appear in turn, such as torsion, first-order bending, second-order bending, etc. The other higher order modes are complex deformation.

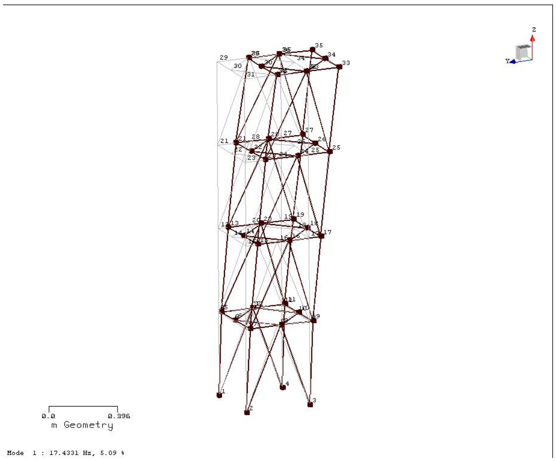

Figure 3. First Order Mode Diagram

4. Discussion

This paper simplifies the research model, through the excitation test of ordinary truss structures, hammer method is a method of force hammer excitation, one point hammer, multiple points measurement, using the method of "fixed hammer point moving measuring point" for testing [9]. This test is concerned with the vibration mode of the structure in the horizontal direction, so one hammer point is selected in the horizontal X direction and the Y direction respectively. The hammer point is selected on the test structure, and the force hammer is used to hammer at the point, and the excitation response of the structure is measured at the measuring point. The hard force hammer acts on the surface of the structure, the input force of the hammer is close to the Dirac pulse, the contact time is short, only a small part of the sampling time, the frequency bandwidth is wide, which can meet the requirements of the test, the structure under the dynamic load, always produce a certain vibration response, the acquisition and analysis system will discretize the signal and estimate its frequency response function. The frequency response function will have a peak value in the position of the natural vibration frequency of the test structure, and find the natural vibration frequency point from all the peaks. After determining the natural vibration frequency, the ratio of the amplitude of the frequency response function can be obtained by using different measuring points at the natural vibration frequency, and the damping ratio can be calculated by half power point method. Finally, after unified analysis by the system, the dynamic characteristic data of the structure can be obtained intuitively, that is, the frequency, the mode and the damping ratio. Finally, according to the modal judgment criterion, if the modal scale factor between the two modes is zero, there is no linear relationship between the two vectors, indicating the orthogonality between the different modes of the structure [10]. With the rapid development of production technology, the dynamic structure gradually develops to large-scale, high-speed, complex and lightweight, which brings more prominent vibration problems. However, the vibration caused by the structure is often the main cause of engineering accidents such as structural damage, environmental deterioration, and the reduction of the accuracy or reliability of equipment. Therefore, the study of the dynamic characteristics and resonance characteristics of the structure has increasingly become an important part of the structure design [11].

5. Conclusion

Through the resonance modal analysis of the truss structure, we can obtain the natural frequency and vibration mode of the structure. It is found that when the truss structure is at a specific frequency, resonance phenomenon may occur. The occurrence of resonance depends on the rigidity of the frame, the position of the center of gravity, and the state of the supporting system. The resonance will cause the vibration amplitude of the structure to increase, and then affect the stability and safety of the structure. Through the resonance mode analysis of the truss structure, we can deeply explore the mechanism and influencing factors of the resonance phenomenon, and propose improvement measures to improve the stability and anti-vibration ability of the structure. For truss structures, the study of resonance characteristics is challenging and requires in-depth analysis from multiple perspectives, including but not limited to design, manufacturing, installation, use, maintenance and operation management. In order to improve the stability and anti-vibration ability of the truss structure, the following improvement measures can be taken: (1) Optimize the stiffness distribution of the structure to avoid the stiffness being too concentrated in some parts to improve the anti-resonance ability of the structure. (2) Strengthen the connecting nodes of the structure to improve the overall stiffness and stability. (3) Use frequency reduction measures, such as increasing the damping material of the structure, to reduce the occurrence of resonance frequency.

Acknowledgment

This work was supported in part by a grant from Research business expenses of Beijing Municipal Education Commission in 2020. And this work was supported in part by a grant from College Student Innovation and Entrepreneurship Training Program in 2023

References

[1]. Gao Qing-Xian. Optimization design of long-span steel truss. Engineering construction and design, 2019 (8): 14-15. DOI: 10.13616 / j.carol carroll nki gcjsysj. 2019.04.207.

[2]. Ma Siqi, Li Yue-Yan, Kong Zimeng. A study on the relationship between structural form and architectural modeling -- taking truss structure as an example. City building, 2022, 12 (7): 137-141. DOI: 10.19892 / j.carol carroll nki CSJZ. 2022.07.31.

[3]. Cheng Pei-Ling. Study on wind vibration response characteristics of super high-rise building structures. Shijiazhuang Railway University, 2017.

[4]. Wang Zhe. Application analysis of mathematical model in architectural structure design. Industrial Architecture, 201, 51(08):262.]

[5]. Li Yuxue, Yang Qingshan, Tian Yuji et al. Time domain partitioning of background and resonance response and simplified analysis of modal coupling. Journal of vibration engineering, 2015, 28 (02): 269-276. The DOI: 10.16385 / j.carol carroll nki. Issn 1004-4523.2015.02.013.

[6]. Wang Jia-Hui. Research on active modal fuzzy control algorithm for structural vibration. North China University of technology, 2021. DOI: 10.27108 /, dc nki. Ghelu. 2020.000709.

[7]. Nie Weijian, Wang Jinshun, Tang Guang et al. Test method for rotor vibration characteristics of aero-engine under impact load. Vibration and impact, and 2023 (19): 1-6. DOI: 10.13465 / j.carol carroll nki JVS. 2023.19.001.

[8]. Lin Aijin. Finite Element analysis and optimal design of truss structures. Engineering and technology research, 2018 (01): 200-201 + 223. DOI: 10.19537 / j.carol carroll nki. 2096-2789.2018.01.099.

[9]. Ding Yewei, Fu Haiyan, Wang Zheng et al. Vibration test and comfort analysis of wooden roof under environmental excitation and impact excitation. Building structures, 2020, 50(16): 100-106. The DOI: 10.19701/j.jZJG. 2020.16.017.

[10]. Chang Ting-Ting. Research on numerical algorithms for dynamic problems of frame structures based on improved Fourier series. Suzhou University of Science and Technology, 2023. DOI: 10.27748 /, dc nki. GSZKJ. 2022.000475.

[11]. Wu Ti, Xiao Chengbo, Xiong Feng. Vibration problems and countermeasures in building structures. Sichuan Building Science Research, 2006(06):142-144.

