A new method of safety detection in high-rise building curtain walls based on natural vibration frequency

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Abstract. With the development of curtain wall technology, the unit curtain wall has been widely used as a decorative component of high-rise buildings, but it has brought great difficulties to the later safety inspection. Based on the theory of thin-slab vibration, the laser vibration measurement technology in this paper is used to analyze the relationship between the multi-order natural frequency and the safety status of the point-supported experimental curtain wall model. At the same time, a corresponding finite element model is established to further quantify the natural frequency and restraining force on the curtain wall. The result shows that there are different relationships between natural frequencies of different orders and the safety of the curtain wall. In actual engineering, it is more sensitive for the first-order natural frequency to changes in the safety status of the curtain wall. A new method of safety detection in high-rise building curtain walls can be achieved by the combination of remote laser vibration measurement technology.

1. Introduction

As a typical peripheral component, the curtain wall is widely used in modern building structures, especially in high-rise buildings. With the accumulation of the service life of the existing curtain wall and the influence of the external environment, some problems appear in the curtain wall, such as material aging and corrosion of the fasteners. Eventually, it will result in a gradual decline in certain safety. Once the curtain wall of a high-rise building falls off, it will bring greater safety hazards and adverse social impacts. How to establish a new method suitable for the safety evaluation in high-rise building curtain walls is an urgent problem. At present, traditional detection methods are mainly based on visual inspection, which relies on the experience of the field test staff to judge the safety of curtain walls and lacks a scientific detection principle. Some detection items are not directly related to the safety of curtain walls.

How to quantify the safety of existing high-rise building curtain walls and the organic and unified realization of scientific and time-effective detection methods require an indicator to reflect the changes in the structural safety status. By establishing the relationship between dynamic characteristic parameters and changes in the safety status of the curtain wall, it is possible to achieve the preliminary assessment of structural safety based on the field index analysis. In recent years, with the rapid
development of detection equipment and damage identification theory based on dynamic characteristic parameters [1], a new method of safety evaluation in high-rise building curtain walls based on natural vibration frequency already has an objective condition in both theoretical research and technical applications. Huang ZD et al. [2] proposed a method for judging the safety of curtain walls by using vibrations, and analyzed the applicability of remote laser vibration measurement technology in the detection of hidden frame curtain walls. Brueggeman et al. [3-5] analyzed the performance of the glass curtain wall from dynamic characteristics of the structure through dynamic tests. Liu Xiaogen et al. [6-8] carried out stability testing on frame curtain walls exposed to nut constraints, proposed a feasibility method which natural frequency is used to judge the stability of curtain walls. Structural detection based on dynamic characteristic parameters has become a new research hotspot at home and abroad [9, 10]. Kirlangıç AS [11] diagnosed the degree of corrosion-induced deterioration of prestressed concrete by transmitting vibration signals. Krishnanunni CG et al [12] used vibration data to analyze the structure sensitivity, and used mathematical algorithms to quickly and accurately calculate the crack position. In this paper, the technical idea is to analyze the relationship between frequency and safety of the curtain wall, to realize a new method for fast and remote safety detection of existing curtain wall, and to propose a site safety evaluation scheme based on the method.

2. Vibration theory

2.1. Vibration detection theory

The vibration detection of engineering structures is to measure the vibration of the structures by a portable vibrometer. According to the allowable value or the requirements of relevant vibration standards, the safety status of engineering structures is determined, and the trend analysis and life prediction of the variability of the engineering structure status are performed [13], which is based on results obtained from multiple periodic inspections. The general vibration problem can be regarded as the system responds to the input, such as environmental interference, artificial excitation, etc., as shown in Figure 1. The structural health can be diagnosed and the objective maintenance measures can be proposed by means of the analysis of the structure's vibration detection.

![Figure 1 Schematic diagram of vibration detection theory](image)

Where \( M, K, C \) are the mass matrix, stiffness matrix, and damping matrix of the structural system; \( x, \dot{x}, \ddot{x} \) are the vibration displacement, velocity and acceleration of the structural system; \( F \) is the excitation of the external environment of the structural system.

2.2. Thin-slab vibration theory

The inherent characteristic vibration phenomenon will occur in the engineering structure stimulated by the external environment [14]. Vibration is the reciprocating motion of the structural system around an equilibrium position or a physical phenomenon in which its physical quantity fluctuates back and forth between its average value. With the change of the safety status of the curtain wall, the vibration phenomenon will inevitably change, which will lead to the change of inherent properties, such as the change of natural frequency. Curtain wall can be regarded as the typical thin-slab structure with a much smaller thickness than its length and width, which conforms to the theory of thin-slab vibration. The lateral oscillation differential equation is:

\[
\nabla^4 W - \gamma^4 W = 0
\]

Where
\[ \gamma^4 = \frac{\omega^2 \bar{m}}{D} \]  \hspace{1cm} (2)

Where \( \omega \) is the inherent harmonic frequency of thin slab, Hz; \( D \) is the bending stiffness of thin slab, N·m; \( W \) is the mode function of the thin slab; \( \bar{m} \) is the mass per unit area of the thin slab, kg/m\(^2\); \( \nabla \) is the harmonic operator.

\( \gamma \) can be obtained from the known mode function \( W \) of the thin slab, and natural frequency can be obtained according to formula (2). For example, the mode function of a thin slab under the conditions of simple four-sided support and four-sided fixed support are formula (3) and (4), respectively. And its natural frequencies can be obtained by formulas (5) and (6), respectively.

\[ W_{\text{sim}} = \sin\left(\frac{m\pi x}{a}\right) \sin\left(\frac{n\pi y}{b}\right) \]  \hspace{1cm} (3)

\[ W_{\text{fix}} = \sin\left(\frac{m\pi x}{a}\right) \sin^2\left(\frac{n\pi y}{b}\right) \]  \hspace{1cm} (4)

\[ \omega_{\text{sim}}^2 = \pi^2 \left(\frac{m^2}{a^2} + \frac{n^2}{b^2}\right) \frac{D}{\bar{m}} \]  \hspace{1cm} (5)

\[ \omega_{\text{fix}}^2 = \pi^2 \left(a^4 + b^4 + \frac{4}{7}a^2b^2\right) \frac{504D}{a^4b^4\bar{m}} \]  \hspace{1cm} (6)

Where \( m, n \) are integers; \( a, b \) are the length and width of thin slab, m.

3. Experimental programs

3.1. Experimental model

By simplifying the constraint form of the curtain wall, the point-supported curtain wall experimental model is built and bound by four nuts, as shown in Figure 2. In order to highlight the experimental effect, a smooth tile panel is used to simulate the curtain wall panel. At the same time, a rubber pad is added between the nut and the panel to reduce stress concentration. By adjusting the pre-tightening force of the nut to simulate the change of the binding force of the model, the bolt numbers are sequentially set to A, B, C, and D. The pre-tightening force of the nut is decreased from working condition 1 to working condition 5, as shown in Table 1.

The test panel size is: long side * short side * thickness = 800mm * 300mm * 9mm, bolt diameter is 10mm, rubber washer thickness is 3mm. The panel is set to 24 units of 10cm * 10cm, 36 measuring points are counted, and a reflective sheet is pasted at the measuring points to increase the signal strength.

Figure 2. Laboratory experimental model
Table 1. Division of different working conditions

| working conditions | status description                  |
|--------------------|-------------------------------------|
| condition 1        | A, B, C and D nuts are fixed        |
| condition 2        | loosen the A nut on condition 1     |
| condition 3        | loosen the B nut on condition 2     |
| condition 4        | loosen the C nut on condition 3     |
| condition 5        | loosen the D nut on condition 4     |

3.2. Experimental equipment

The single-point Laser Doppler Vibration meter (LDV) with an extremely long working distance is used to detect the curtain wall test model under various working conditions, as shown in Figure 3. In the process of vibration detection, additional sensors do not need to be installed on the measured objects, and state detection and dynamic inspection on structures and systems can quickly be performed. Its technical parameters are shown in Table 2.

![Laser Doppler Vibration meter](image)

Figure 3. Laser Doppler Vibration meter

Table 2. Technical parameters of Laser Doppler Vibrometer

| model number | detection distance | frequency range | speed accuracy | displacement accuracy |
|--------------|--------------------|-----------------|----------------|----------------------|
| RSV-150      | > 300m             | 0~25kHz         | <0.5µm/s      | 0.3nm                |

The working principle of the remote laser vibrometer is shown in Figure 4. The He-Ne laser emits a polarized light with a certain frequency, which is divided into two by the beam splitter, one for reference, and the other one for the measurement. The system collects the reflected light and the reference light at the detector, which produces an interference effect because of the doppler shift caused by the object vibration. The vibration information of the measured object is carried on the interference signal. Then the signal processor converts the frequency-shifted signals into velocity and displacement signals. After obtaining velocity or displacement signals, the time-domain curve is formed, and the frequency-domain curve is obtained through the fast Fourier transform (as shown in Figure 5). Finally, the dynamic characteristic parameters such as the natural frequency of the target will be obtained.
3.3. Result and analysis

The vibration signals of the thin slab in the above five working conditions are collected by LDV, and first to fifth-order natural frequency was obtained by the fast Fourier transformation. The mean value of the natural frequencies at each measurement point of different working conditions is taken as the final result, and the following conclusions can be drawn.

3.3.1. Effect of Constraint Looseness on Natural Frequency. The test results are shown on the horizontal axis with the natural frequency as the vertical line with the natural frequency value as shown in Figure 6. It can be obtained that the natural frequency of the panel has different changing characteristics with the change of the restraining force of the panel. The first-order frequency value gradually decreases with the increase in the number of loose nuts, but the abnormal change appeared under the same conditions. Therefore, it is more sensitive for the panel’s first-order natural frequency to the decline of the constraint force on the curtain wall, which is suitable for the safety evaluation in the curtain wall.

The variation of the first-order natural frequency to evaluate the tightness of the restraint on the curtain wall can solve the problem that the restraint force of the curtain wall cannot be quantified by detection means. With the increase of the number of the loose nuts, the restraining force decreases on the curtain wall, which will lead to the decrease of the curtain wall safety. Based on the change characteristic in the first-order natural frequency of thin slab, the preliminary judgment can be made to the safety status of the curtain wall.
3.3.2. Influence of measuring point position on natural frequency. In order to study the influence of the measuring point position on the natural frequency detection result, the discrete analysis is performed on the frequency results of 36 measuring points under each working condition, as shown in Table 3. In the first-four working conditions, the difference between the maximum and minimum of natural frequencies is less than 1 and the standard deviation is less than 0.5, In the working condition 5 which is considered as the limit state of damage, the standard deviation is 1.43. The results show that the test results are reliable and relatively close in each working condition. Except for the limited state of the panel, the position of the measuring point has a little influence on the test result of natural frequency. However, for reducing error and increasing measurement accuracy, the middle part of the curtain wall in the actual measurement can be chosen as the measurement point. The average value obtained by multiple measurement results is used as the final value.

| working condition | max value | min value | max value-min value | standard deviation |
|-------------------|-----------|-----------|---------------------|--------------------|
| condition 1       | 63.80     | 63.01     | 0.79                | 0.32               |
| condition 2       | 58.92     | 58.25     | 0.67                | 0.41               |
| condition 3       | 56.12     | 55.34     | 0.78                | 0.36               |
| condition 4       | 54.90     | 54.02     | 0.88                | 0.45               |
| condition 5       | 51.12     | 49.23     | 1.89                | 1.43               |

4. Simulation programs
For the point-supported panel structure, the relationship between the natural frequency and the safety of thin slab is found by using the above-mentioned laboratory experimental model, but it is difficult to quantify the size of the nut constraint. The definite relationship between the constraint force and the vibration characteristics of thin slab cannot be observed, so it is difficult to determine the specific characteristics of natural frequency as the changes of structural security. With the help of the finite element numerical simulation, the stiffness of the constrained spring was changed by the artificial constrained spring method to simulate the constraint imposed on the nut, and the modal analysis of thin slab was performed.
4.1. Finite element model
The finite element model established in accordance with the laboratory experimental model consists of the panel and the constrained nut. As shown in Figure 7, the model is divided into 504 element bodies after fine meshing, and the high-order element Solid186 is used as the finite element.

The corresponding constraints imposed on various parts of the model according to the actual constraints. As shown in Figure 8, the lower surface of the nut is bonded with the upper surface of the panel, which makes the model a whole. At the same time, the outer surface of the screw is imposed on a displacement constraint that can limit X and Y displacement. The lower surface of the screw is imposed on an elastic constraint. By continuously changing the elastic stiffness, the change of binding force of the nut is simulated. The material parameters of each part are shown in Table 4.

| part | density (kg/m³) | elastic modulus (Pa) | poisson's ratio |
|------|----------------|----------------------|----------------|
| panel | 3000           | 7.2e+10              | 0.2            |
| nut   | 7500           | 2.06e+8              | 0.3            |

4.2. Simulation process and results
With the 10 times increase of the stiffness, 19 different safety states of the model were simulated, which the elastic stiffness is 0.001N/m³ ~ 10¹⁷N/m³. After taking the logarithm of the first-fifth-order natural frequency and the corresponding elastic stiffness, the relationship showed closer, as shown in Figure 9. As the elastic stiffness increases, the natural frequency changes from constant to gradually increased, and finally remained unchanged again. The finite element simulation also proves the relationship between natural frequency and restraining force of curtain wall again, and the safety of the curtain wall can be judged according to the change law of the vibration characteristic-natural frequency.
According to the relationship between elastic stiffness and natural frequency, the safety status of the thin slab is divided into three stages: The first stage is that the elastic stiffness is very small and the natural frequency does not change greatly with the decrease of the elastic stiffness, which is the failure stage. The second stage is that the natural frequency changes significantly with the change in elastic stiffness, which is the instability phase. The third stage is that the elastic stiffness is extremely large and the natural frequency does not change significantly with the decrease in elastic stiffness, which is the stable phase. And the statistical results are shown in Table 5. As the elastic stiffness increases, the panel state can be divided into three stages (the failure stage, the instability stage, and the stable stage). If the stage is divided by the first-order natural frequency, the instability stage obtained has the most distribution and the largest span of natural frequency. The three stages divided by the second-order and third-order, fourth-order and fifth-order frequencies respectively have the same distribution and the same frequency span. It can be concluded that the first-order natural frequency has the largest sensing range, which is easy to reflect the tightness of the nut in engineering. Therefore, the first-order
natural frequency value of the curtain wall is selected as the main indicator of safety detection in the curtain wall.

### Table 5. First-fifth-order frequency statistics of stage division

| Stage division bases | Failure stage (Log_{10})/N·m^{-3} | Instability stage (Log_{10})/N·m^{-3} | Stable stage (Log_{10})/N·m^{-3} | Frequency span (Log_{10})/Hz |
|----------------------|-------------------------------------|----------------------------------------|-----------------------------------|-------------------------------|
| 1st order frequency  | <0                                 | 0-11                                   | >11                               | 4.5                           |
| 2nd order frequency  | <6                                 | 6-12                                   | >12                               | 2.5                           |
| 3rd order frequency  | <6                                 | 6-12                                   | >12                               | 2.5                           |
| 4th order frequency  | <9                                 | 8-13                                   | >13                               | 0.2                           |
| 5th order frequency  | <9                                 | 8-13                                   | >13                               | 0.2                           |

5. Discuss

5.1. Comparative analysis

In order to further analyze the difference between the laboratory experimental model and the ideal curtain wall model established by the computer, the elastic constraints on the lower surface of the four nuts of the finite element model were replaced by fixed constraints to simulate the laboratory model under working condition 1 (the restraint imposed on the curtain wall is not loosen).

The modal analysis results of the finite element model are compared with the natural frequency detection results of the laboratory experimental model. As shown in Table 6, the relative error is only small in the first order. In other orders, the natural vibration frequency of the actual project is greatly different from the model analysis result of numerical simulation under the influence of the external environment. Therefore, the finite element simulation method can be used to estimate the first-order frequency of the actual unit curtain wall, which is the frequency value of the curtain wall in the ideal state.

### Table 6. Comparative analysis of natural vibration frequency

| Order | Natural vibration frequency /Hz | Relative error |
|-------|--------------------------------|----------------|
| 1     | 67.818                         | 0.066          |
| 2     | 122.3                          | 0.399          |
| 3     | 154.42                         | 0.385          |
| 4     | 172.85                         | 0.646          |
| 5     | 197.43                         | 0.756          |

5.2. Analysis of detection methods

Through the theoretical analysis of the thin-slab vibration, it can be found that natural frequency is the inherent property of the curtain wall and can be used as the basis for the safety evaluation in the curtain wall. The laboratory experimental model and finite element model established both further analyze the feasibility of natural frequency as an evaluation index of curtain wall safety. By comparing
the models of two different approaches, it can be found that the vibration characteristics of curtain wall in actual engineering can be predicted by using simulation software, but ensuring the accuracy of the safety detection method in curtain wall is the focus of the detection process in the face of complex actual projects.

In order to ensure the reliability and timeliness of the safety detection in high-rise curtain walls, the detection process can be divided into the following main steps:

1. To collect the data of the structural design of existing high-rise building curtain walls and daily operation and maintenance, to analyze related factors affecting the safety of curtain wall, and to perform preliminary finite element simulation based on the data to obtain the theoretical value of natural frequency of the curtain wall under ideal conditions.

2. To select the curtain wall units with the same specification for remote vibration signal collection, and to perform the vibration signal collection at least three times in the middle position of each curtain wall unit, which ensures the accuracy of the detection result.

3. Using the fast Fourier transform to obtain the frequency curve from the time-domain curve collected by the vibration signal, reading the first-order natural frequency value, and taking the average value as the final result.

4. Selecting the on-site stable unit curtain wall as the reference curtain wall, using the natural frequency of curtain wall as the reference frequency, and comparing the reference frequency with the theoretical natural frequency to verify the rationality of the selected reference curtain wall.

5. By comparing the natural frequency of the curtain wall unit of the same specification with the reference frequency, it is instability if the natural frequency is less than the reference frequency, and the larger the deviation distance is, the more unstable it is. It is stability if the natural frequency is greater than the reference frequency, and the larger the deviation distance is, the more stable it is.

6. Using GIS and other visualization tools to visually display the test results of a large number of curtain wall units, which can facilitate managers to make more scientific maintenance decisions and maintenance personnel to perform repairs or replace curtain wall operations on site.

6. Conclusion
According to the established laboratory experimental model, the dynamic characteristic parameter-natural frequency is introduced into the curtain wall vibration detection. It can be found that the natural frequency of these different orders has different correspondence with the curtain wall safety. Especially the first-order natural frequency gradually decreases as the safety of the curtain wall reduces, and the vibration detection point has little effect on the final result. The finite element model further quantifies the relationship between the restraining force on the curtain wall and the natural frequency of curtain wall, and it’s concluded that the safety status of the curtain wall can be divided into three stages: the failure stage, the instability stage, and the stable stage. By comparing with other high-order frequencies, it is more suitable for the first-order natural frequency (the important basis) to judge the curtain wall safety. At the same time, the theoretical frequency value of the curtain wall in the ideal state can be obtained by the model analysis of the finite element model, which can be regarded as the basis to select the reference curtain wall. By combining the analysis and comparison of the experimental model with the finite element model, a new method of curtain wall safety detection can be proposed. With the assistance of the remote laser vibration measurement technology, the safety detection (fast, remote and non-destructive) in high-rise building curtain walls can be achieved, which improves the efficiency of curtain wall detection, saves the cost of testing, guarantees the safety of operating personnel, and provides the new technical means for the daily operation and maintenance in the high-rise building curtain walls.

Acknowledgments
The authors gratefully acknowledge the financial support from the National Key R&D Program Project of China (No. 2016YFC0600703), the National Natural Science Foundation of China (No. 41702371, 41572274), Beijing Municipal Science and Technology Project (No. Z16110000116104),
and USTB-NTUT Joint Research Program (No. TW2019011) for providing generous funding for the project. The authors declare that there is no conflict of interests regarding the publication of this article.

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