

Dynamic Characteristic Analysis of an Arch-String Structure

Wei Su¹, Fengliang Xiang², and Hua Li¹

¹ School of Aeronautical Engineering, Jilin University of Chemical Technology, Jilin 132102, China

² School of Mechanical and Electrical Engineering, Jilin University of Chemical Technology, Jilin 132102, China

Abstract

A finite element model of a single arch-string structure was established, and the dynamic characteristics of the structure were investigated using ANSYS. Taking an arch-string structure with a span of 30m and a rise-to-span ratio of 1/2 as the research object, the effects of several key parameters, including the rise-to-span ratio, cable prestress level, arch cross-sectional area, and cable arrangement, on the natural frequencies and mode shapes of the structure were systematically analyzed under self-weight only. In addition, a comparative analysis between the arch-string structure and a conventional pure arch structure was conducted under the same span, loading, and support conditions in order to clarify the dynamic advantages of the arch-string structural system. The results indicate that, within the parameter range considered in this study, the cable arrangement, cable prestress level, and arch cross-sectional area have relatively limited influence on the dynamic characteristics of the structure, whereas the geometric parameters of the outer arch, especially the rise-to-span ratio, have a much more significant effect on the natural frequencies. As the rise-to-span ratio decreases, the overall dynamic stiffness of the structure increases, leading to a notable increase in the natural frequencies. The results of this study can provide a useful reference for the dynamic performance evaluation and optimal design of arch-string structures.

Keywords

Arch-string Structure; Cable-Arch Structure; Dynamic Characteristics; Parametric Analysis; Prestressed Steel Structure.

1. Introduction

Arch-string structure is a spatial structural system composed of cable elements and beam elements, combining the mechanical characteristics of both arch structures and cable structures[1,2]. Although substantial research has been conducted on the static performance and stability of pure arch structures and cable-arch structures, systematic studies on the dynamic characteristics of arch-string structures remain relatively limited. In particular, in-depth investigations into the influence of key factors such as cable prestress, cable arrangement, and geometric parameters are still lacking.

The study of structural dynamic characteristics mainly involves two aspects: natural frequencies and mode shapes[3]. Through modal analysis, the natural frequencies and corresponding mode shapes of a structure can be obtained. These parameters are not only important in structural dynamic design, but also provide the basis for subsequent studies on seismic response, wind-induced response, and structural vibration control.

In this paper, an arch-string structure with a span of 30m and a rise-to-span ratio of 1/2 is selected as the research object, and its dynamic characteristics are analyzed using the general finite element

software ANSYS. The effects of the principal parameters influencing the dynamic behavior of the arch-string structure, including the rise-to-span ratio, cable arrangement, cable prestress level, and member cross-sectional area, are systematically investigated. Meanwhile, under the same span, loading, and support constraint conditions, the dynamic performance of the arch-string structure is compared with that of a conventional pure arch structure, so as to reveal the advantages of the arch-string structure in terms of dynamic behavior and to provide a theoretical basis for the dynamic performance evaluation and optimal design of arch-string structures.

2. Finite Element Modeling of the Arch-String Structure

2.1 Model Establishment

The model was established and simplified using SOLIDWORKS 2023 and ANSYS 2021 R1. A single arch-string structure consists of the inner and outer steel arches, inner and outer steel cables, joints(nodes), and web members[4]. During the modeling process, all joints were assumed to be rigidly welded, while the effects of weld details and chamfers of hollow square steel tubes on the overall mechanical behavior were neglected, so as to improve modeling efficiency and maintain the relevance of the analysis.

The arch axes of both the inner and outer steel arches were defined as circular curves. And the two arches are connected by web members arranged in groups of three. Both the arches and the joints are made of hollow square steel tubes with a cross-sectional size of $\square 60\text{mm} \times 60\text{mm} \times 3\text{mm}$, while the web members are made of hollow square steel tubes with a cross-sectional size of $\square 50\text{mm} \times 50\text{mm} \times 3\text{mm}$. The initial structure has a span of 30m and a rise of 15m, corresponding to a rise-to-span ratio of 1/2. The cables are arranged between the inner and outer arches in a non-crossing pattern, connecting every two adjacent nodes in sequence. A schematic diagram of the structure is shown in Fig. 1.

The single arch-string structure in this study is modeled using ANSYS beam188 elements, while the cables are simulated using cable280 elements[5,6]. The initial prestress in the cables is applied through an initial strain method. Primary material parameters are summarized in Table 1.

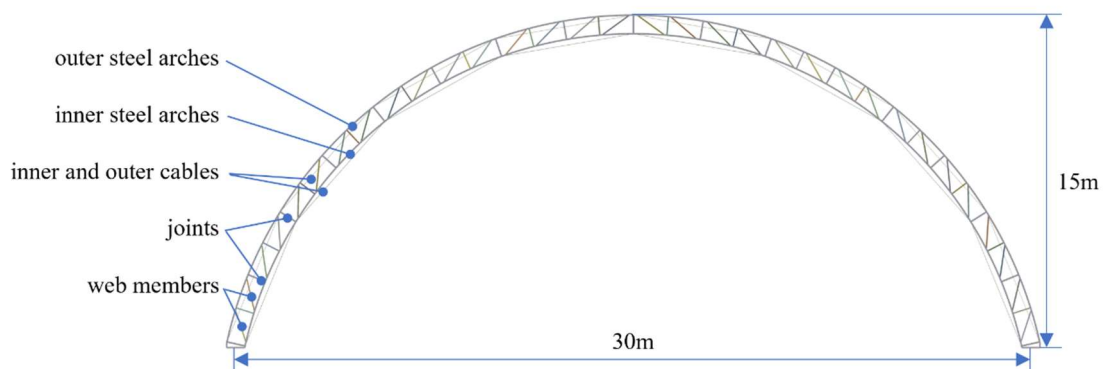


Fig. 1 Diagram of a single arch-string structure

Table 1. Material properties and cross-sectional dimensions of arch-string structure

Component	Elastic Modulus / $\text{kN} \cdot \text{mm}^{-2}$	Poisson's Ratio	Design Strength / $\text{N} \cdot \text{mm}^{-2}$	Density / $\text{kg} \cdot \text{m}^{-3}$	Cross-Section / mm	Type
Arch (Chord)	206	0.3	215	7850	$\square 60 \times 60 \times 4$	Square Tube
Web Member	206	0.3	215	7850	$\square 50 \times 50 \times 3$	Square Tube
Cable	115	0.3	1350	7850	$\Phi 10$	Steel Strand

2.2 Analysis Methods

Structural natural frequency analysis is a fundamental problem in structural dynamics, aiming to determine the natural frequencies and corresponding mode shapes of the structure. The natural frequencies reflect the structure’s inherent ability to resist vibration, while the mode shapes characterize the deformation patterns of the structure in each free vibration mode. For large-span prestressed spatial structures, natural frequency characteristics are not only related to the magnitude of the dynamic response but also indicate the overall structural stiffness and the effectiveness of prestress, making their study of significant importance.

The determination of structural dynamic characteristics essentially involves solving the eigenvalue problem:

$$[K] - \omega^2[M] = 0 \quad (1)$$

where $[K]$ is the stiffness matrix, $[M]$ is the mass matrix, ω is the natural circular frequency of the structure[7].

In the finite element program ANSYS, eigenvalue problems for frequencies and mode shapes are solved using modal analysis. The software provides multiple solution methods, including Block Lanczos, Subspace, Power Dynamics, and Reduction Method, among others. Since the Subspace method is particularly suitable for large-span structures, it is adopted in this study.

The finite element analysis is performed within the elastic range of the materials, assuming that the arches deform only within their plane. The cables are modeled as tension-only elements obeying Hooke’s law, with no compressive capacity. Two types of boundary conditions are considered, which have minimal influence on low-order mode shapes, the main focus of this study:

Simply supported at both ends – used when comparing horizontal thrust, as arch structures generate significant horizontal reactions at supports.

One end simply supported, the other end allowing horizontal movement – used when comparing horizontal displacement. In this case, one end of the structure is pinned and constrained in both horizontal and vertical directions in-plane, while the other end is constrained only vertically, allowing free horizontal sliding.

Table 2. Comparison of the first five natural frequencies under two boundary conditions (Hz)

Rise-to-Span Ratio	Boundary Condition	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5
1/2	Simply Supported at Both Ends	0.61594	1.4176	2.39	3.6357	4.0722
1/2	One End Pinned, One End Horizontal Move	0.60759	1.4101	1.5358	2.3887	3.6231
1/3	Simply Supported at Both Ends	0.87306	1.7482	2.9374	4.3095	5.5107
1/3	One End Pinned, One End Horizontal Move	0.84	1.7344	2.426	2.9441	4.2451

3. Parameters Analysis

3.1 Effect of Rise-to-Span Ratio

The rise-to-span ratio is defined as the ratio of the rise of the inner arch to the overall span of the structure. Keeping all other parameters constant, four single arch-string structure models were established with a span of 30m and rise-to-span ratios (λ) of 1/2, 1/2.5, 1/3, and 1/4. In these models, the cross-sectional dimensions of the main structure (including arches and joints) are

□60mm×60mm×4mm, while the web members have a cross-section of □50mm×50mm×3mm. The cables have a diameter of Φ10mm, with an initial prestress of 5MPa applied.

The natural frequencies of the structure were computed for each rise-to-span ratio, and their variation with mode number is presented in Fig. 2. These results reveal the influence of the rise-to-span ratio on the vibrational characteristics of the arch-string structure.

Table 3. First 10 natural frequencies under different rise-to-span ratios (Hz)

Rise-to-Span Ratio (λ)	Mode 1	Mode 2	Mode 3	Mode 4	Mode 5
1/2	0.6056	1.4146	1.4926	2.4057	3.6710
1/2.5	0.75015	1.7014	1.9086	2.9005	4.3645
1/3	0.84158	1.7527	2.3657	2.9851	4.4002
1/4	1.0798	2.3179	2.8884	3.9697	5.7477
Rise-to-Span Ratio (λ)	Mode 6	Mode 7	Mode 8	Mode 9	Mode 10
1/2	5.0021	5.1794	6.3289	7.6280	8.9566
1/2.5	5.8390	6.2539	7.3177	8.8006	10.402
1/3	5.8089	7.2998	7.4108	8.6931	10.114
1/4	7.5040	8.5967	9.3083	11.243	13.084

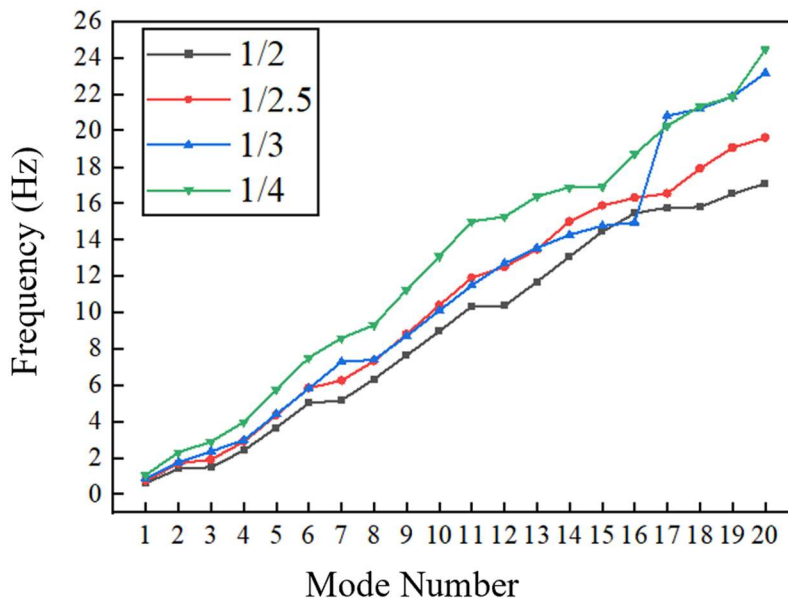


Fig. 2 Relationship between mode number and natural frequency under different rise-to-span ratios

From Table 3 and Fig. 2, it can be observed that under different rise-to-span ratios, the low-order natural frequencies of the arch-string structure are relatively insensitive to the change in rise-to-span ratio. However, as the mode number increases, the differences in natural frequencies among the various rise-to-span ratios gradually become more pronounced. Overall, smaller rise-to-span ratios correspond to higher natural frequencies, with most mode frequencies reaching the maximum at a rise-to-span ratio of 1/4, and the minimum at a ratio of 1/2. This indicates that as the structure becomes flatter, its overall dynamic stiffness increases, leading to an increase in natural frequencies.

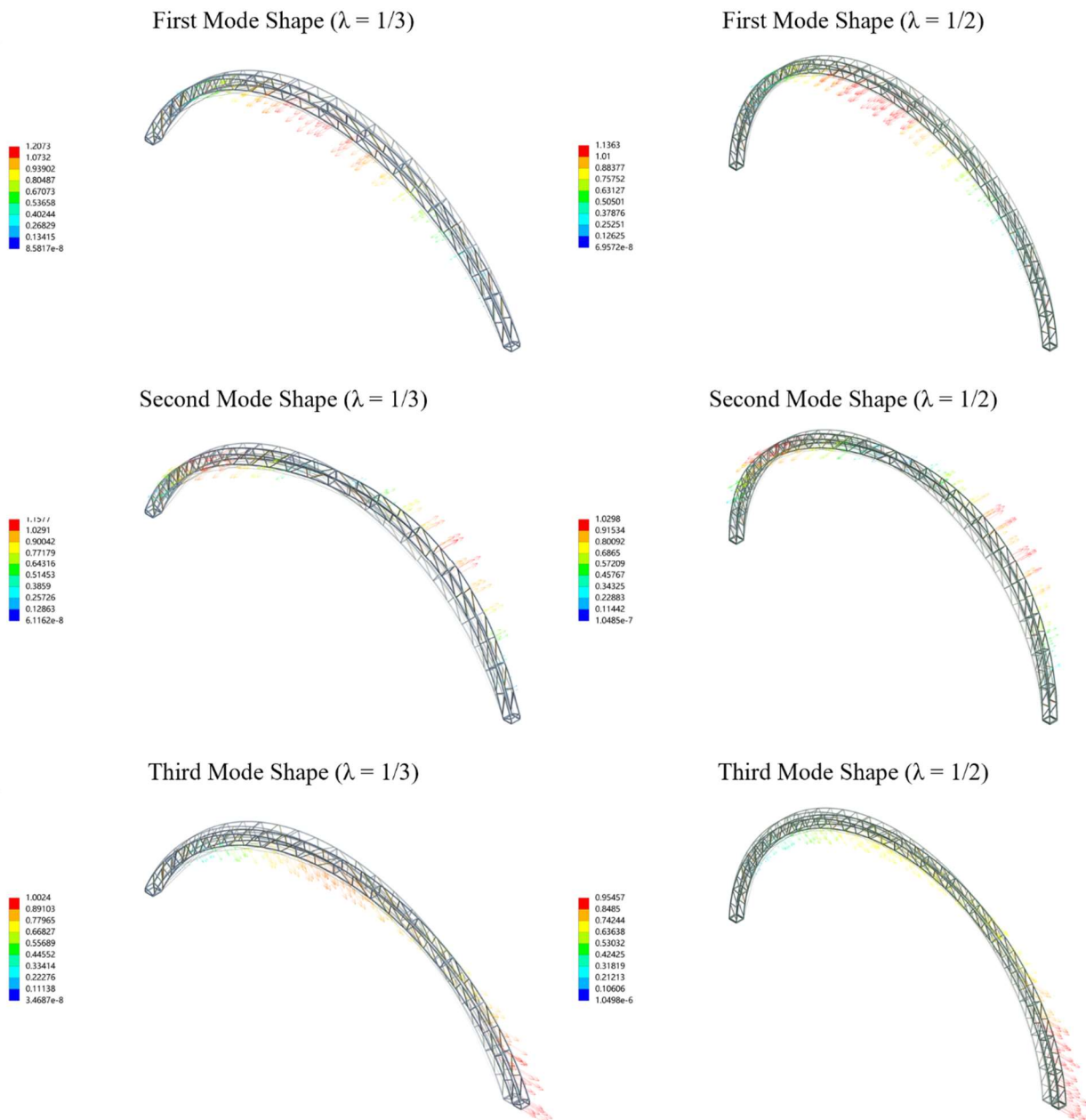


Fig. 3 Mode shape vector diagrams of the first three modes under different rise-to-span ratios

As shown in Fig. 3, the rise-to-span ratio has a limited effect on the low-order mode shapes, with the first three mode shapes remaining largely consistent across different ratios.

3.2 Effect of Arch and Web Member Cross-Sectional Dimensions

Keeping all other parameters constant, different sizes of square steel tubes were selected as the main structural members to investigate the influence of member cross-sectional dimensions on the structural response. The cross-section combinations were defined as follows: when the main arch members have a cross-section of $\square 60\text{mm} \times 60\text{mm} \times 3\text{mm}$ and the web members have $\square 50\text{mm} \times 50\text{mm} \times 3\text{mm}$, the combination is denoted as A33; when the web members are $\square 50\text{mm} \times 50\text{mm} \times 4\text{mm}$, it is denoted as A34. Similarly, the combinations A43, A44, A53, and A54 represent other variations of arch and web member dimensions. The cable arrangement follows that of the original structure. The computed results are shown in Fig. 4.

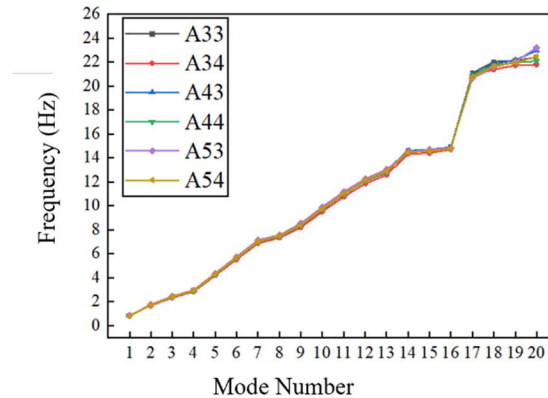


Fig. 4 First 20 natural frequencies with different member cross-section combinations

As illustrated in Fig. 4, the first 20 natural frequency curves of the structure under different cross-section combinations exhibit essentially the same overall trend, with frequencies increasing progressively with mode number. This indicates that variations in member cross-sectional dimensions do not alter the fundamental modal distribution of the structure. The A43 combination corresponds to the original cross-section. With the increase in member cross-section, the overall natural frequencies exhibit a slight upward trend, suggesting that enlarging the cross-section can modestly enhance the global stiffness of the structure.

However, from the relative spacing of the curves, the differences between cross-section combinations are not significant, particularly for mid-to-high-order modes where the curves are closely aligned. This demonstrates that the cross-sectional dimensions of the members have a relatively limited influence on the dynamic characteristics of the arch-string structure.

3.3 Effect of Cable Prestress Level

The initial prestress of the cables was selected as the variable parameter, while all other structural and geometric parameters were kept constant. A series of simulations were conducted to analyze the influence of different cable prestress levels on the static performance of the arch-string structure. The computed results are presented in Fig. 5.

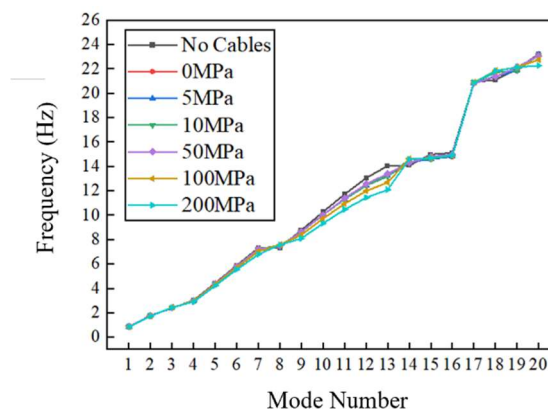


Fig. 5 First 20 natural frequencies under different initial cable prestress levels

As shown in Fig. 5, the natural frequency curves of the first 20 modes under different initial cable prestress levels are overall quite similar, indicating that the cable prestress level has a relatively limited effect on the dynamic characteristics of the structure. As the prestress increases, the changes in natural frequencies are not significant, suggesting that for a single-bay structure under self-weight only, the adjustment effect of cable prestress on the overall dynamic stiffness is relatively weak.

3.4 Effect of Cable Arrangement

Five cable arrangement patterns are considered in this study: without cables, one cable connecting two nodes of the inner arch, one cable connecting two nodes of the outer arch, one cable connecting two nodes of both inner and outer arches, and multiple crossed cables connecting both inner and outer arches, as shown in Fig. 6. All other structural parameters are kept constant. The corresponding natural frequencies under different cable arrangements were computed, and the results are presented in Fig. 7.

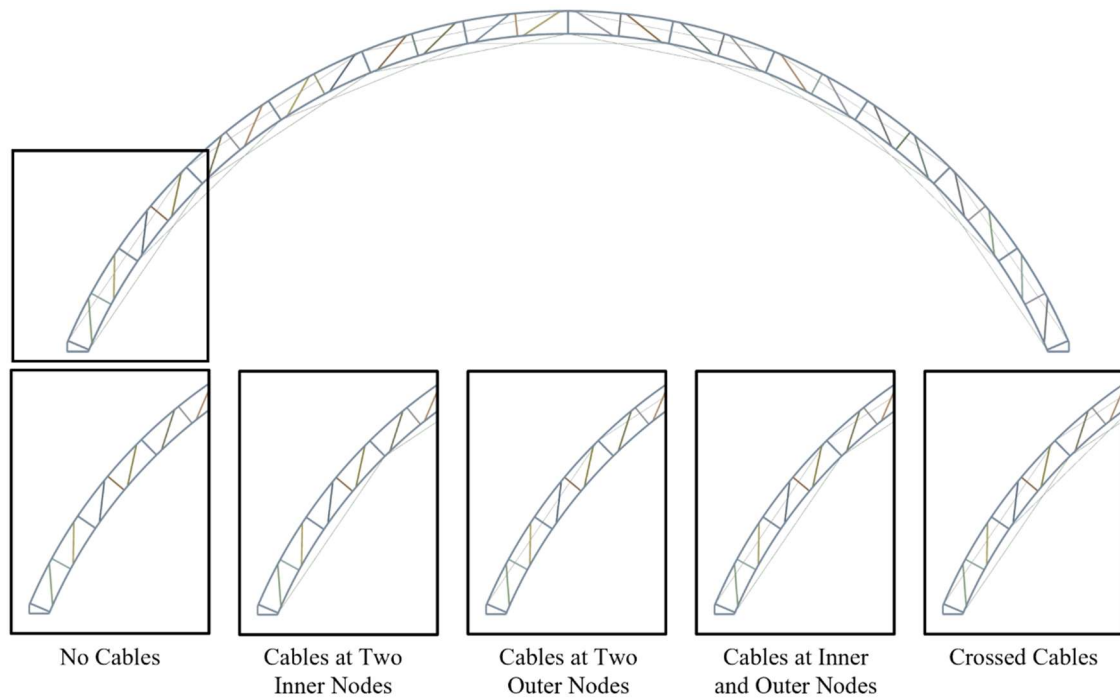


Fig. 6 Five different cable arrangement patterns

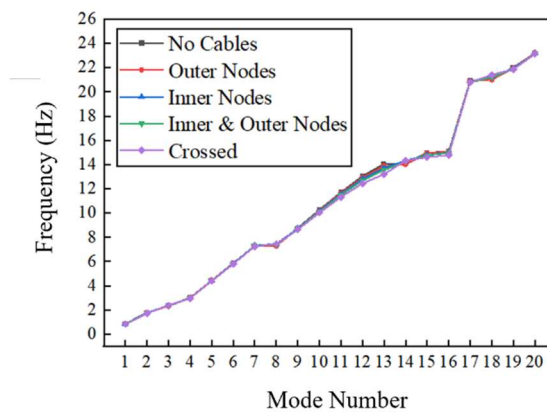


Fig. 7 First 20 natural frequencies under different cable arrangement patterns

As illustrated in Fig. 7, the first 20 natural frequencies of the structure under the five cable arrangement patterns show only minor differences, with the frequency curves nearly overlapping. This indicates that for a single arch-string structure, when considering self-weight only, the cable arrangement has a relatively limited effect on the overall dynamic characteristics of the structure.

4. Conclusion

Based on the analysis of the effects of various parameters on the dynamic characteristics of a single arch-string structure, the following conclusions can be drawn:

Within the range of parameters studied, the rise-to-span ratio has the most significant influence on the dynamic characteristics of the single arch-string structure. As the rise-to-span ratio decreases, the overall dynamic stiffness of the structure increases, and the natural frequencies of the first 20 modes generally rise. This effect is particularly pronounced in the mid-to-high-order modes.

The cross-sectional dimensions of the members have a certain influence on the dynamic characteristics, but the effect is relatively limited. Within the selected range of section sizes, increasing the cross-sectional area results in only a slight increase in natural frequencies.

For a single structure considering only self-weight, both the cable prestress level and the cable arrangement pattern have a relatively small effect on the natural frequencies of the first several modes. This indicates that their adjustment effect on the overall dynamic performance of the structure is limited.

References

- [1] CHEN Zhihua. Development and engineering practice of building cable structures in China[J]. Building Structure. 2024, Vol. 54 (No. 19), p. 44-50, 65.
- [2] Zhi-Hong Z, Shi-Lin D. Some aspects of pre-stressed spatial structures[J]. Spatial Structures. 2015, Vol. 21 (No. 04), p. 12-16, 24.
- [3] Jin Y, Yi J W, Hu L. The Dynamic Performance and Stability Analysis of Prestressed Arch-Supported Net Shell Structures[J]. Advanced Materials Research. 2013, Vol. 2195 (No. 639-640), p 149-154.
- [4] Xing C. Performance Analysis of Lower-Prestressed Fabricated Latticed Arch of Square Steel Tubes[J]. Journal of Jilin Architectural and Civil Engineering Institute. 2001, Vol. 0 (No. 02), p 15-18.
- [5] Chen X, Liu Y. Finite element modeling and simulation with ANSYS Workbench[M]. CRC press. 2018.
- [6] Lee H H. Finite element simulations with ANSYS workbench 2019[M]. SDC publications. 2019.
- [7] Chen Y J, Feng Z F, Qi A, et al. The analysis of dynamic characteristics and wind-induced displacement response of space Beam String Structure[C]. EDP Sciences. 2018, 38: 03032.