Optimal Placement of Health Monitoring Sensor for Bridge Structure of Air-Cooled Island

Chuandi Zhou
Key Laboratory of Condition Monitoring and Control for Power Plant Equipment of Ministry of Education
North China Electric Power University
Beijing 102206, China
zcd@ncepu.edu.cn

Yibing Liu
Key Laboratory of Condition Monitoring and Control for Power Plant Equipment of Ministry of Education: North China Electric Power University
Beijing 102206, China
lyb@ncepu.edu.cn

Wei Teng
Key Laboratory of Condition Monitoring and Control for Power Plant Equipment of Ministry of Education
North China Electric Power University
Beijing 102206, China
tengw@ncepu.edu.cn

Zhiyong Ma
Key Laboratory of Condition Monitoring and Control for Power Plant Equipment of Ministry of Education
North China Electric Power University
Beijing 102206, China
mzy@ncepu.edu.cn

Ji Wu
Key Laboratory of Condition Monitoring and Control for Power Plant Equipment of Ministry of Education
North China Electric Power University
Beijing 102206, China:
wuji1738675589@163.com

***Abstract*—The air-cooled island of air-cooled thermal power unit consists of dozens of cooling units with fans and their bridges. Its structure and excitation load are complex. The health status of the air-cooled island has an impact on the safe operation of thermal power unit. In this paper, an optimal placement of health monitoring sensor for bridge structure of air-cooled island is proposed based on effective independence method. Through the finite element analysis, the main mode shapes of the bridge structure were obtained. Based on this, a given number of sensors were optimally arranged according to the Fisher information matrix. Then the optimal placement of the health monitoring sensor for the bridge structure of air-cooled island was obtained. The modal guarantee criterion was used to evaluate the placement scheme. The result shows that the sensor placement scheme can ensure the accuracy of modal identification and effectively reflect the structural characteristics of the bridge structure of the air-cooled island. The result can provide a reference for the health monitoring of the bridge structure of air-cooled island.**

***Keywords*—air-cooled island bridge, health monitoring, effective independence method, sensor placement, Fisher information matrix**

I. INTRODUCTION

In areas where water resources are scarce, the cooling system in thermal power generation mostly uses a direct air-cooled system, that is, the steam exhaust of the steam turbine is cooled by air. Direct air cooling system, also known as air cooled island, is generally built on a tens of meters high concrete column array, composed of a number of air cooling units, each air cooling unit is equipped with an air cooling fan, supported by the fan bridge. Due to environmental factors, motor and fan operation, the fan bridge is easy to generate large-scale low-frequency vibration. In the long run, it will affect the health status of the fan bridge structure, which will affect the safe and stable operation of the air-cooled island. Therefore, the health monitoring of the fan bridge is carried out. The fan bridge is a truss structure with more nodes. If the position of the health monitoring sensor is not suitable, it will directly affect the accuracy and completeness of acquiring structural modal information, resulting in the inability to accurately analyze the changes in its structural characteristics. Thus, it is important to optimize the distribution of health monitoring sensors for the fan bridge structure.

At present, the research on air-cooled islands mainly focuses on vibration characteristics. Li Hongxing [1] and Xue Feiren [2] used finite element to analyze and calculate the harmonic response of the fan bridge structure, and obtained the harmonic response characteristics of the fan bridge. Qi Zhiguang [3] and Qu Tiejun [4] compared the vibration characteristics between multiple air- cooled fan bridges and studied the interaction between different fan bridges. Dou Ruijie [5] , Shao Yun [6] , Zhou Chao [7] and so on the actual test of the fan bridge, found the vibration source and verified the results of the modal analysis. In the actual test of the fan bridge, most scholars did not consider the problem of sensor layout, resulting in large test workload or incompleteness of

978-1-7281-0860-5/19/$31.00 ©2019 IEEE

structural information in the data, it is necessary to optimize the placement of the health monitoring sensor of the fan bridge structure.

In terms of sensor optimization configuration methods, traditional algorithms are mainly divided into effective independent method [8] , modal kinetic energy method [9] and modal confidence criterion [10]. In 1991, Kammer [8] proposed an effective independent method based on the Fisher information matrix, which sorts the degree of contribution of the degree of freedom of the candidate set to the linear independence of the target modal vector to realize the optimal arrangement of the sensor. Subsequently, Poston and Tolson [11] demonstrated that deleting potential sensor locations with the smallest effective independent distribution value would result in a minimum relative change in the determinant of the Fisher information matrix. The method is effective for optimally locating the sensor. Chen Y [12] and Kim T [13] improved the effective independent method and optimized the arrangement of bridges, trusses and other structures, and achieved good results.

In this paper, the finite element model of bridge structure of air-cooled island is established and the modal analysis is carried out. The optimal placement of the sensor is studied by means of effective independent method, and the modal confidence criterion is used to evaluate the optimal placement results of the sensor. The results provide a certain basis for the structural health monitoring sensor arrangement of the fan bridge of the air-cooled island.

II. THEORETICAL BASIS

A. Effective Independent Method

The core idea of the Effective Independent Method (EI) is to rank each degree of freedom based on its contribution to the linear independence of the target modality (Fisher Information Matrix). Through iterative method, the degree of freedom with the least contribution degree is gradually deleted, and the degree of freedom with greater contribution is retained, thereby realizing the optimal arrangement of the sensor.

The dynamic equation of a multi-degree-of-freedom linear time-invariant system is

$$\boldsymbol{M}\ddot{\boldsymbol{u}}(t)+\boldsymbol{C}\dot{\boldsymbol{u}}(t)+\boldsymbol{K}\boldsymbol{u}(t)=\boldsymbol{F}(t) \tag{1}$$

where M, C, and K are the mass matrix, damping matrix, and stiffness matrix of the system, u(t) is the displacement response vector, and F(t) is the external excitation vector. According to the modal analysis theory, the solution of equation (1) can be expressed as

$$\boldsymbol{u}(t)=\boldsymbol{\Phi}\boldsymbol{q}(t) \tag{2}$$

where Φ is a mode shape matrix and q(t) is a modal coordinate. Since s is arranged on a position m sensors (m<s), the number of degrees of freedom system is s . If the influence of noise is considered, the output response U_s of the sensor can be expressed as:

$$\boldsymbol{U}_s=\boldsymbol{\Phi}_s\boldsymbol{q}+\boldsymbol{\psi} \tag{3}$$

The estimated value of the generalized modal coordinate vector q is :

$$\hat{\boldsymbol{q}}=\left[\boldsymbol{\Phi}_s{}^{\boldsymbol{T}}\boldsymbol{\Phi}_s\right]^{\boldsymbol{-1}}\boldsymbol{\Phi}_s\boldsymbol{U}_s \tag{4}$$

For a complex structure with s degrees of freedom, if m sensors are to be deployed for health monitoring, the modal information acquired by m sensors is linearly independent. The best estimate of the generalized coordinate q needs to be obtained. The covariance matrix of the estimated deviation is:

$$\begin{aligned}\boldsymbol{P}=\boldsymbol{E}\left[(\boldsymbol{q}-\hat{\boldsymbol{q}})(\boldsymbol{q}-\hat{\boldsymbol{q}})^{\boldsymbol{T}}\right]&=\left[\left(\frac{\partial\boldsymbol{\Phi}_s\boldsymbol{q}}{\partial\boldsymbol{q}}\right)^T\left[\sigma^2\right]\left(\frac{\partial\boldsymbol{\Phi}_s\boldsymbol{q}}{\partial\boldsymbol{q}}\right)\right]^{-1}\\&=\left[\boldsymbol{\Phi}_s{}^{\boldsymbol{T}}\left(\boldsymbol{\sigma}^{\boldsymbol{2}}\right)^{-1}\boldsymbol{\Phi}_s\right]^{\boldsymbol{-1}}=\boldsymbol{Q}^{-1}\end{aligned} \tag{5}$$

where E represents the expected value; Q is the Fisher information matrix. In order to minimize the covariance matrix to get the best estimate , you need to maximize the determinant of Q. To simplify the analysis, assuming that the noise is uncorrelated and has the same statistical properties in each sensor, the Fisher information matrix Q can be expressed by equation (4) as:

$$\boldsymbol{Q}=\boldsymbol{\Phi}_s{}^{\boldsymbol{T}}\left(\boldsymbol{\sigma}^{\boldsymbol{2}}\right)^{-1}\boldsymbol{\Phi}_s=\frac{1}{\sigma_0^2}\boldsymbol{\Phi}_s^{\boldsymbol{T}}\boldsymbol{\Phi}_s=\frac{1}{\sigma_0^2}\boldsymbol{A}_{\boldsymbol{0}} \tag{6}$$

it can be seen that the Fisher information matrix Q can be represented by the matrix A_0. The A_0 written in matrix form

$$\begin{aligned}\boldsymbol{A}_{\boldsymbol{0}}=\boldsymbol{\Phi}_s^{\boldsymbol{T}}\boldsymbol{\Phi}_s&=\begin{bmatrix}\varphi_{11}&\varphi_{21}&\cdots&\varphi_{s1}\\\varphi_{12}&\varphi_{22}&\cdots&\varphi_{s2}\\\vdots&\vdots&\ddots&\vdots\\\varphi_{1N}&\varphi_{2N}&\cdots&\varphi_{sN}\end{bmatrix}\begin{bmatrix}\varphi_{11}&\varphi_{12}&\cdots&\varphi_{1N}\\\varphi_{21}&\varphi_{22}&\cdots&\varphi_{2N}\\\vdots&\vdots&\ddots&\vdots\\\varphi_{s1}&\varphi_{s2}&\cdots&\varphi_{sN}\end{bmatrix}\\&=\begin{bmatrix}\boldsymbol{\Phi}_{\boldsymbol{1}}^{\boldsymbol{T}}&\boldsymbol{\Phi}_{\boldsymbol{2}}^{\boldsymbol{T}}&\cdots&\boldsymbol{\Phi}_s^{\boldsymbol{T}}\end{bmatrix}\begin{bmatrix}\boldsymbol{\Phi}_{\boldsymbol{1}}\\\boldsymbol{\Phi}_{\boldsymbol{2}}\\\vdots\\\boldsymbol{\Phi}_s\end{bmatrix}=\sum_{i=1}^{s}\boldsymbol{\Phi}_s^{iT}\boldsymbol{\Phi}_s^{i}\end{aligned} \tag{7}$$

Φ_s^i represents the arrow in Φ_s associated with the i-th degree of freedom (the position of the i-th sensor), and therefore, the increase or decrease of the degree of freedom (sensor position) reflects the increase or decrease of information in A_0 . To maximize Q, the information in A_0 can be deleted step by step, thereby removing the degree of freedom (sensor position) that contributes less to the target modal independence, maximizing A_0 .

In order to delete the information in A_0 , it is necessary to determine the contribution values of the respective degrees to the target modality. The determination of this value is given by the following procedure:

For the matrix A_0 , its characteristic equation is:

$$(\boldsymbol{A_0} - \lambda \boldsymbol{I})\boldsymbol{\Psi} = 0 \tag{8}$$

where λ are the eigenvalues of A_0; Ψ are the eigenvectors of A_0.

It can be introduced by formula (8) :

$$\boldsymbol{\Psi^T A_0 \Psi = \lambda, \Psi^T \Psi = I} \tag{9}$$

Suppose F is a contribution matrix of degrees to target modalities, and F can be expressed as

$$\boldsymbol{F} = [\boldsymbol{\Phi_s \Psi}] \otimes [\boldsymbol{\Phi_s \Psi}]\boldsymbol{\lambda}^{-1} \tag{10}$$

where ⊗ represents multiplication by one of the same dimension of the matrix, and therefore the matrix F is s * N order matrix, where in the first i of row j term represents the i-th degrees of freedom of j contribution eigenvalues, if each row of F is added, and a column vector E_D can be obtained, each of which represents the contribution of the i-th degree of freedom to the linear independence of the entire mode matrix.

$$\boldsymbol{E_D} = \left[\sum_{j=1}^{N} F_{1j} \quad \sum_{j=1}^{N} F_{2j} \quad \cdots \quad \sum_{j=1}^{N} F_{sj} \right]^T \tag{11}$$

In addition to equation (11) , the contribution matrix of degrees to target modalities can also be represented by another matrix E :

$$\boldsymbol{E} = \boldsymbol{\Phi_s} \boldsymbol{\psi} \boldsymbol{\lambda}^{-1} \left(\boldsymbol{\Phi_s \psi}\right)^T = \boldsymbol{\Phi_s A_0^{-1} \Phi_s^T} \tag{12}$$

Using equation (7) , you can get:

$$\boldsymbol{E} = \boldsymbol{\Phi_s A_0^{-1} \Phi_s^T} = \boldsymbol{\Phi_s} \left[\boldsymbol{\Phi_s^T \Phi_s}\right]^{-1} \boldsymbol{\Phi_s^T} \tag{13}$$

i-th element of the diagonal of E represents the contribution of i-th degree of freedom to the target mode matrix F. Therefore, if m sensors are arranged at n node positions, the degree of freedom that contributes the least to the linear independence of the target mode is gradually deleted, and m sensor positions are obtained after n-m iterations.

B. *Evaluation of layout effects*

The modal confidence criterion MAC [10] is an important tool for evaluating the intersection angle of modal vectors, which can reflect the correlation of two space vectors. The calculation formula is:

$$MAC_{ij} = \left| \frac{\Phi_i \Phi_j}{(\Phi_i^T \Phi_i)(\Phi_j^T \Phi_j)} \right| \tag{14}$$

where F_i and F_j represent the i-th and j-th order modal vectors, respectively. The value of MAC_{ij} is between 0 and 1 where 0 means that the two vectors are orthogonal and 1 means that the two vectors are completely correlated. The smaller the value of MAC_{ij} , the smaller the correlation between the two modes, and the stronger the structural characteristics of the modal reflection. Otherwise, the correlation between the two modes is large, and the two modes are close. It is generally considered that when MAC_{ij} is greater than 0.9 , the two modal vectors are completely related and cannot be distinguished.

III. Analysis of an Example of an Air-Cooled Island Fan Bridge

A. *finite element modal analysis*

In this paper, the optimal layout of the health monitoring sensor of a bridge structure an air-cooled island is studied. The three-dimensional model of the air cooling unit is shown in Figure 1 . The fan bridge is located in the upper part of the air-cooled steel truss. It not only carries the motor, gearbox and fan, but also the walking path of the engineering personnel. It is an important structure in the air-cooling unit.

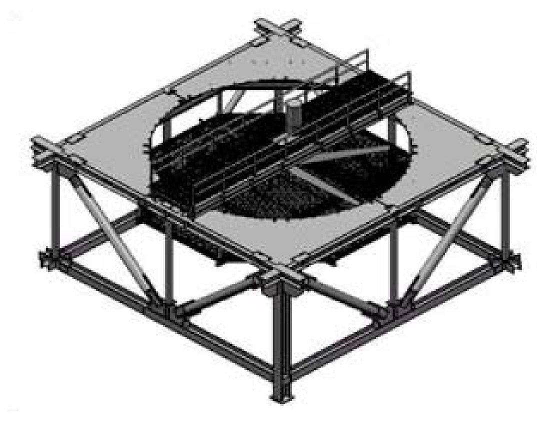


Figure. 1. 3D model diagram of air cooling unit

The finite element model of the fan bridge is shown in Figure 2 , and the main node numbers are shown in Figure 3 . The number of model nodes is 24 and the number of units is 36. All components are beam unit Beam 188 . The bridge structure adopts Q235 steel, and the material parameters are: elastic modulus is 2.06e11, Poisson's ratio is 0.3 , and density is 7850 kg/m^3 . The imposed constraint is that nodes 1 , 10 , 11, and 20 constrain the displacement constraints of all degrees of freedom. The mass of the fan, motor and gearbox totals 4000 kg and is applied to nodes 5 , 6 , 15, and 16 with concentrated mass .

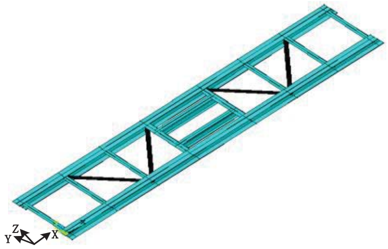


Figure. 2. Fan bridge finite element model

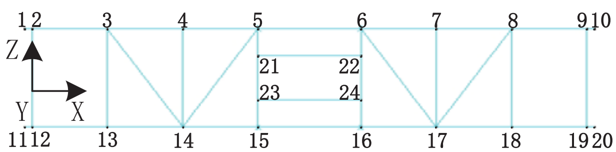
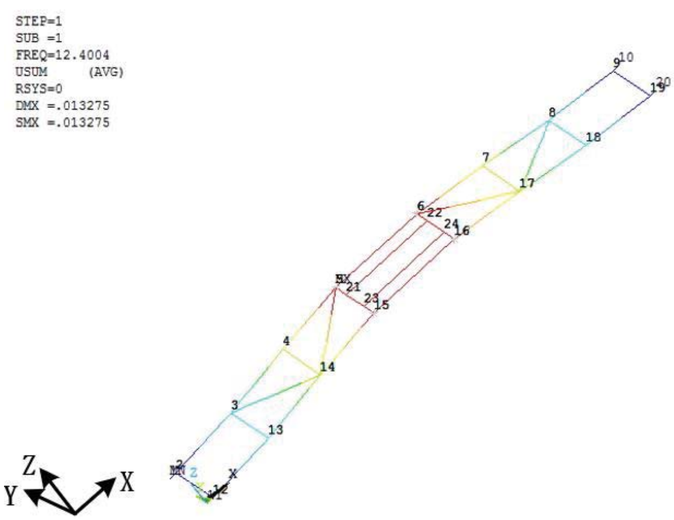
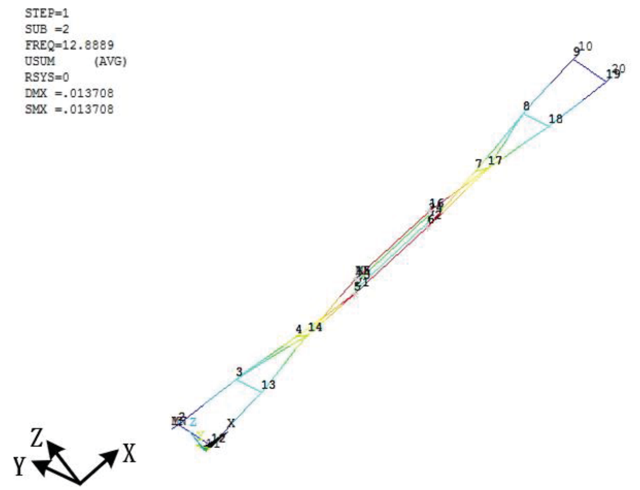


Figure. 3. main node number map

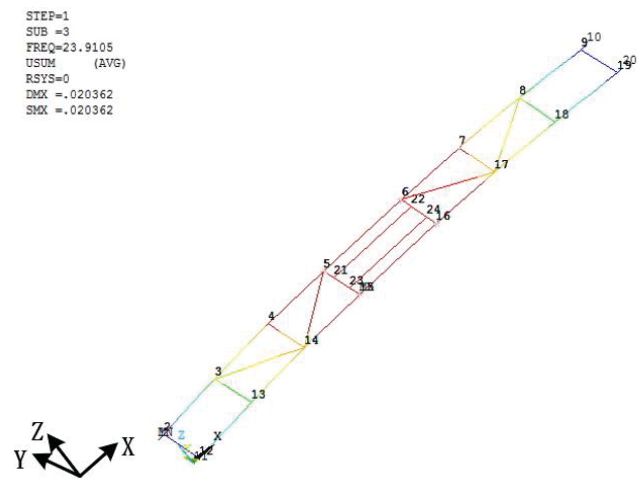
In this paper, the first 10 modes of the model are taken as the target mode. The first four modes of the finite element model of the fan bridge are listed in the paper, as shown in Figure 4. The first and fourth order shapes are bending vibrations in direction Z, the third order shape is bending vibration in direction Y, the second order shape is torsional vibration in direction X, and the fifth order shape is coupled vibrations. The natural frequencies of ten orders are shown in Table 1 . As can be seen from Table I, the natural frequency range of the fan bridge is 12.400-117.27 Hz .



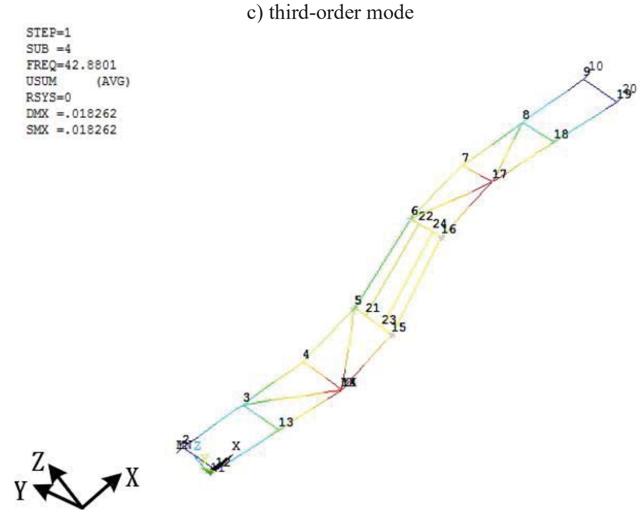
a) first-order mode



b) second-order mode



c) third-order mode



d) fourth-order mode

Figure. 4. The first 4th mode shape of the fan bridge

Table I. THE FIRST 10 NATURAL FREQUENCIES OF THE FAN BRIDGE

Order	1	2	3	4	5
Frequency (Hz)	12.400	12.889	23.911	42.880	44.395
Order	6	7	8	9	10
Frequency (Hz)	46.921	103.70	111.99	116.41	117.27

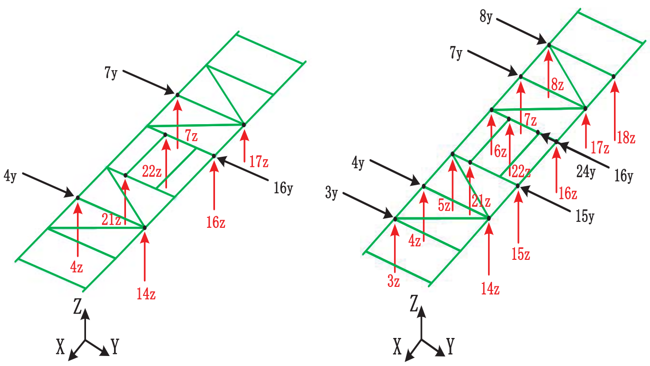
B. *Sensor optimization layout scheme*

In this paper, the effective independent method is used to optimize the sensor for health monitoring of the fan bridge. Table Ⅱ lists the results of the optimized arrangement of the sensor when the number of target sensors are 10 , 15 , 20 and 30 respectively . It can be seen from Table 2 that the arrangement direction of the sensor are the Y direction and the Z direction, and the X direction is not included, indicating that the modal information of the Y direction and the Z direction contributes more to the Fisher information matrix, and also reflects the tower's The main vibration is vibration in the Y direction and the Z direction. At the same time, the sensor position with a large number of target sensors contains the sensor position with a small number of target sensors.

Table II. SENSOR OPTIMAL PLACEMENT RESULTS UNDER DIFFERENT TARGET SENSOR NUMBERS

Node	Position			Node	Position		
	30	20	10		30	20	10
3y	●	●		4z	●	●	●
4y	●	●	●	5z	●	●	
7y	●	●	●	6z	●	●	
8y	●	●		7z	●	●	●
13y	●			8z	●	●	
14y	●			13z	●		
15y	●	●		14z	●	●	●
16y	●	●	●	15z	●	●	
17y	●			16z	●	●	●
18y	●			17z	●	●	●
21y	●			18z	●	●	
22y	●			21z	●	●	●
23y	●			22z	●	●	●
24y	●	●		23z	●		
3z	●	●		24z	●		

Figure 5 shows a comparison of sensor positions when the number of sensors are 10 and 20 . As can be seen from the figure, the position of the sensor is mainly in the middle of the fan bridge, and there are many sensors in the Z direction. At the same time, it can be seen that the sensor position exhibits a certain symmetry with the central axis of the bridge. In addition, it can be seen that the sensor position of 20 measuring points contains the sensor spot position of 10 measuring points, and as the number of target sensors gradually decreases, some closed points are eliminated.



a) 10 sensors b) 20 sensors

Figure. 5. Optimal placement results for different numbers of target sensors

IV. EFFECT EVALUATION

In Section 2.3 of this paper , the optimal placement of different numbers of target sensors is carried out. To evaluate the rationality of the optimal layout scheme, this paper evaluates the different optimization results by means of modal confidence criteria. The calculated MAC matrix is shown in Figure 6. In the figure, the horizontal axis is the modal order and the vertical axis is the MAC value. As can be seen from the figure, as the number of target sensors gradually decreases, the value of the off-diagonal elements of the MAC matrix gradually increases. When the number of sensors are 10 , 20, and 30 , the maximum values of the off-diagonal elements of the MAC matrix are 0.4198 , 0.1443, and 0.1413 and the average values of all non-diagonal MAC values are 0.0217 , 0.0088, 0.0053 and 0.3. According to the modal confidence criterion, when the number of target sensors is large, the maximum value of the non- diagonal elements of the MAC matrix is small, indicating the various modes acquired after the sensor is optimally arranged. The small linear correlation indicates that the modal information of the structure is good. When the number of sensors is small, the correlation between some modalities will be poor, which has certain influence on the acquisition of modal information.

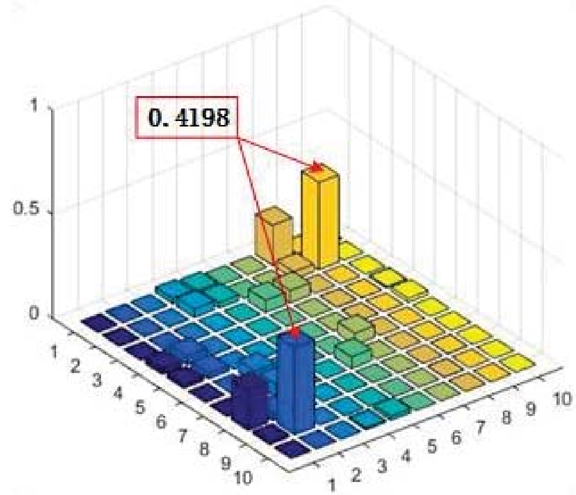


Figure. 6. MAC of 10 sensors

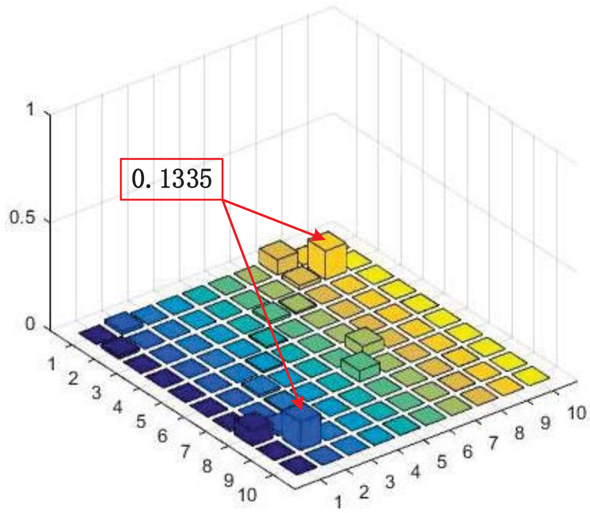


Figure. 7. MAC of 20 sensors

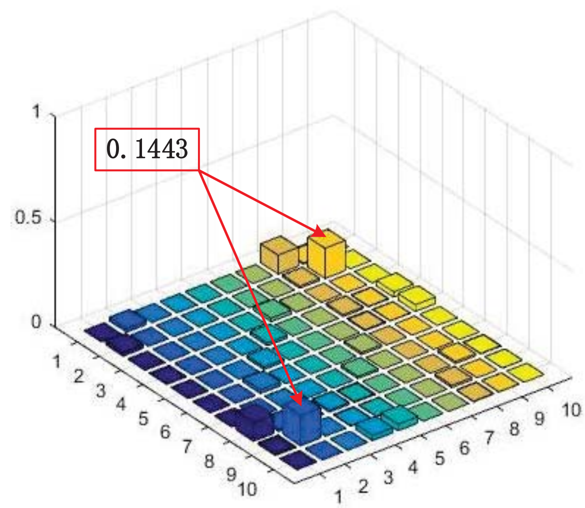


Figure. 8. MAC of 15 sensors

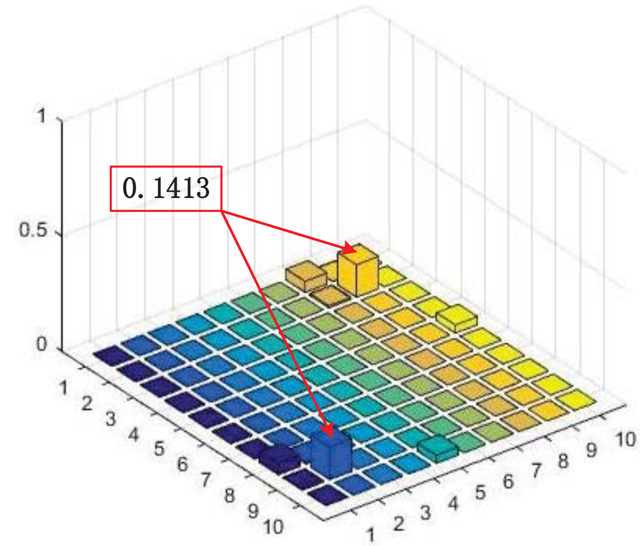


Figure. 9. MAC of 30 sensors

V. CONCLUSION

The finite element model of the fan bridge is established and the modal analysis is carried out. The first 10 modes of the bridge are obtained, and the first 10 natural frequencies of the bridge are obtained between 12.400-117.27Hz . And the vibration of the bridge is mainly the bending vibration in the Y and Z directions.

The effective independent method is used to optimize the sensor for the health monitoring of the fan bridge structure. When the number of target sensors goes to 10 , 20 and 30, the corresponding optimized sensor position and arrangement direction are obtained respectively. The position of the sensors are mainly in the middle of the fan bridge, and the sensors arranged in the Z direction are the most. At the same time, it can be seen that the sensor position exhibits a certain symmetry along the central axis of the bridge parallel to the Y direction.

By comparing the optimization results when the number of target sensors are different, it can be seen that the sensors position with a large number of target sensors contains a small number of target sensors. As the target number of sensors reduced, some points which are close to each other are gradually deleted.

ACKNOWLEDGMENT

The research was supported by the China National Key Research and Development Project(2017YFC0805905).

VI. REFERENCES

[1] Li Hongxing, Zhao ChunLian, and Shi XiaoHu, “Air cooling fan trays harmonic response calculation and analysis ,” Journal of Wuhan University (Engineering Science), 2008 (S1): 104-107 .

[2] Xue Fei and Ren Zhongyun, “Analysis of Harmonic Response of Fan Bridge Truss and Structural Desigen,” Journal of Wuhan University (Engineering Science) , 2010,43:77-80.

[3] Qi Zhiguang, and et al, “Vibration Characteristics Analysis and Contrast of Bridge Structures between Two ACC Fans,” Electric Power Construction , 2011(09): 6-10.

[4] Zhao Fei and Qu Tiejun, “Research on Vibrational Characteristics of Fan Bridge Truss Under Multiple Air Cooling Fans Working Condition,” North China University of Technology , 2012,1 (24): 68-71.

[5] Dou Ruijie, “Experimental study on vibration characteristics of air cooling fan system under working conditions,” North China University of Technology , 2010.

[6] Shao Yun, “Vibration Analysis of the Bridge Structures for the Direct Air Cooling System,” Applied Energy Technology , 2016(01): 4-7.

[7] Zhou Chao, Ma Zhiyong, Song Yuwang, Teng Wei, and Hu Liang,“Modal Analysis and Test Study of Air-cooled Island Bridge,”Equipment Management and Maintenance , 2016(S2):22-23.

[8] D. C. Kammer, “Sensor placement for on-orbit modal identification and correlation of large space structures,” Journal of Guidance Control & Dynamics, 1991, 14(2):251-259.

[9] G. Heo, M. L. Wang, and Satpathi D, “Optimal transducer placement for health monitoring of long span bridge,” Soil Dynamics & Earthquake Engineering, 1997, 16(7-8):495-502.

[10] Y. M. Fu, and L. Yu, “Optimal Sensor Placement Based on MAC and SPGA Algorithms,” Advanced Materials Research, 2012, 594-597:1118---1122.

[11] W. L. Poston, and Tolson R H, “Maximizing the determinant of the information matrix with the effective independence method,” Journal of Guidance, Control, and Dynamics, 1992, 15(6):1513-1514.

[12] Y. Chen, and L. U. Zixing, “ An interval effective independence method for optimal sensor placement based on non-probabilistic approach,” Science China(Technological Sciences), 2017(02):16-28.

[13] T. Kim, B. D. Youn, and H. Oh , “ Development of a stochastic effective independence (SEFI) method for optimal sensor placement under uncertainty,” Mechanical Systems & Signal Processing, 2018, 111:615-627.