Study on the dynamic characteristics of the horizontally encrypted column network spring vibration isolated turbine-generator foundation

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Abstract. To investigate the dynamic characteristics of the horizontally encrypted column network spring vibration isolated turbine-generator foundation, according to similarity theory, a 10:1 scale model of the horizontally encrypted column network spring vibration isolated turbine-generator foundation, including two condensers, was tested on site, and the dynamic characteristics of the model are analyzed by excitation method, and the natural frequencies, mode shapes and damping ratio of the integral structure are acquired. This study shows that the first two mode shapes of the turbine-generator foundation are translation and torsion, the high mode shape is accompanied by column-end swing and local distortion; the condenser is more stable in the integral structure; the natural frequency of this foundation is higher than the dual-row column spring vibration isolated turbine-generator foundation, and it is significantly lower than rigid foundation, and the mode shape distribution is different from them.

1. Introduction

Turbine generator is the main power equipment in power plants, its foundation design usually takes into account the dynamic characteristics. With the development of Chinese industrial system, the total installed capacity of turbine generator units has been significantly improved. To meet the needs of production equipment, to ensure that production equipment is in a good working environment, to improve the dynamic characteristics of the turbine-generator foundation, the design of the turbine generator foundation is mainly optimized in two aspects: on the one hand, spring vibration isolation technology has been widely used in the large-scale turbine-generator foundation, and it is gradually maturing\cite{1, 2}; on the other hand, special foundation form such as combined foundation and horizontally encrypted column network foundation\cite{3} are generated. In addition, the vibration performance of non-structural components and the influence of such components on the main structure are not well understood and need to be studied in depth.

In recent years, spring vibration isolated turbine-generator foundations have been studied by a number of scholars. In Reference 4, the acceleration signal is received by input force signal, displacement data is calculated and vibration isolation efficiency is calculated by using displacement difference. In reference \cite{5}, the 8:1 test model of the spring vibration isolation foundation of the turbine generator in power plant is established, using the excitation method, the dynamic characteristics such as the natural frequencies, mode shapes and damping ratio and the transmissibility of the spring vibration isolation element are obtained, and compared with the rigid foundation, the vertical natural frequency
of the spring vibration isolated turbine-generator foundation is significantly lower than that of the rigid foundation. In reference [6], the 10:1 model of the spring isolation foundation of turbo-generator is established, and the dynamic characteristic test and forced vibration test are carried out. It is proved that the spring isolation foundation is the most friendly to the half-speed turbine with the operating frequency of 25Hz.

This paper relies on a large practical project with the installed capacity of 1300MW, the turbine area used the horizontal encryption form of the column network, generator area used the form of double column, and the upper plate of the foundation is connected with the lower frame by the spring isolators.

Through building a 10:1 model of spring vibration isolated turbine-generator foundation to study its dynamic characteristics and the vibration performance of the condenser in the overall structure by using MIMO excitation method.

2. Spring Vibration Isolated Turbine-generator Foundation

This test model of the horizontally encrypted column network spring vibration isolated turbine-generator foundation has been built by several concreting in the structural laboratory. The total weight of the model is approximately 25400 kg (of which the soleplate weighs 9282.233 kg, the top plate weighs 6216.276 kg and the condensers weigh 2100 kg). According to the similar theory of the model test, the dimension similarity constant was selected to be 10, the constants of the elastic modulus and the material density were selected to be 1, and the other constants of the physical quantities were calculated by the dimensional analysis method. See Table 1 for the specific values. According to the similar mass ratio and the height of the center of mass to simulate the condenser component, the simulated structure includes the main structure, pier and strip foundation. Each pier is arranged with a spring isolator, and each strip foundation is arranged with three spring isolators.

Materials used in this model is the same as the prototype structure, in which the roof is used C35 and the rest members are used C45. The test block is cured under the same conditions, and the strength of the standard cube after 28 days is measured. The elastic modulus of the concrete material is calculated as $3.15 \times 10^{10}$N/m². Reinforcement ratio of column and beam section meet the similar theory, selected $12, 14, 16$ HRB400 steel bar, stirrup choose from $\phi 6, \phi 8$ diameter HPB300 reinforced. Condenser choose $12$ HRB400 steel bar distribution reinforcement, to prevent cracking.

Table 1. Similarity ratio of scale model

| Physical quantity | Coefficients | Physical quantity | Coefficients |
|-------------------|--------------|-------------------|--------------|
| Dynamic coefficient | 1            | Acceleration      | 1/10         |
| Elastic modulus   | 1            | Frequency         | 1/10         |
| Stiffness         | 10           | Deformation       | 10           |
| Mass              | 1000         | Time              | 10           |

Note: Similarity ration = Prototype/Model

According to the code[7], the influence of turbine equipment will be considered in the form of added mass, and the counterweight will be carried out according to the actual equipment quality 1000:1. The
key points will be designed according to the bearing pedestal of the equipment unit, so as to ensure that the position of the clump weight corresponds to the actual position of the equipment and the load type is consistent. In this paper, the turbine area of the test model adopts four rows of columns, which is different from the foundation of the double-row column. See Figure.1 for the structural diagram, and see Figure.2 for the solid structure of the test model.

3. Dynamic characteristic test
This experiment uses random signal as the input signal, by the dynamic signal generator output random vibration signal, through the power amplifier to enlarge this signal, and then transmitted to the shocker to generate an exciting force, the vibration force through the force sensor acting on the vibration point of the structure under test. The force sensor sends the excitation signal to the signal collector through the charge amplifier, and at the same time tests the acceleration signal of each measuring point with the acceleration sensor, and then sends the acceleration signal through the amplifier to the data acquisition instrument, using the modal analysis software (LMS) to analyze and process the excitation force and acceleration signal.

Experiments are carried out using spatial excitation method, because the selection of the excitation point cannot in principle be a vibration node, and ensure that the vibration energy is all on the structure, not biased to one side, so the final choice of B21 point (X-way), B03 point (Y-way) and B1 Point 2 (Z-way) is the excitation point. This test set a total of 181 measuring points, including 32 measuring points of the top plate, 11 measuring points of the bearing, the condenser and its support 40 measuring points, frame beams, plates, columns 98 measuring points, as shown in Figure 3.

4. Analysis of test results
Figure 4 shows some typical modes of vibration, model 1 shows the longitudinal translation of the overall structure. In model 9, the overall structure shows vertical translation except the high-pressure cylinder area of the top platform plate, the condenser shows vertical translation, but the vibration amplitude of coagulator 2# is significantly larger than 1#. In model 10, the platform sways vertically around the horizontal center axis, the condenser 1# is vertical translation, and the condenser 2# is twisted horizontally, the vibration status is inconsistent. In model 11, the top plate presents the 1st-order bending, the vibration amplitude is larger at the high-pressure cylinder area, the lower frame presents the 1st-order longitudinal bending, with the condensers moving vertically and in the opposite direction. In
model 15, the top plate is swinging vertically around the longitudinal center axis, the lower frame structure is curved composite vibration, the high-pressure cylinder area frame vibration amplitude is large, and the condenser vibration is not obvious. In model 17, the top plate is folded vertically versus, the lower frame structure is curved composite vibration, the intermediate frame is twisted horizontally, the condensers vibrate vertically with the same direction. In model 18, the frame presents the 1st-order bending longitudinally, condensers vibrate slightly vertically with the opposite directions. In model 24, the top plate presents the 2nd-order bending, the frame of high-pressure cylinder presents the 2nd-order horizontal bending, condensers vibrate vertically, and the direction of condenser 1# is different from the bending direction of the top plate.

In summary, the first two modes of vibration of the turbine-generator foundation are overall translation and torsion, while the high modes of vibration are more composite vibration with column-end swing or local twist. The condenser vibration is mainly longitudinal translation, and changes its own vibration direction and vibration amplitude with the vibration of the main structure.

Figure 4. The typical vibration modes shapes of the whole foundation

5. Structural form
Because this test model adopts the horizontal encryption form of the column network, distinguished with the double-column frame (in Figure 5), as the horizontal stiffness increases, the horizontal translation and torsion vibration in the experiment are not obvious. According to the test results, the natural frequency of the horizontally encrypted column network spring vibration isolated foundation with the increased stiffness is basically higher than that of the dual-row column spring isolated foundation.

Figure 5. Schematic diagram of two foundations

Based on the test results, the dynamic characteristics of the horizontally encrypted column network spring vibration isolated foundation and the double column foundation and the rigid foundation of the contrast bar network are analyzed, and the specific test data are found in Table 3. The structure form of the model in literature[8] is similar to that of this paper, considering the condenser model, and added
mass of the turbine equipment, and the structure form of the model in literature\[5-6\] is the double column spring vibration isolated foundation, considering the condenser and equipment in the form of added mass, the above four sets of tests are tested using LMS system software, the test method is similar, in other words, this analysis is feasible, and the data measured in literature\[9\] are derived from rigid foundation. The dynamic characteristics of different frame form can be seen more clearly in Figure 6.

### Table 2. Comparison of dynamic characteristics

| Mode shape | Horizontally encrypted column spring vibration isolated foundation | Double column spring vibration isolated foundation | Rigid foundation |
|------------|---------------------------------------------------------------|-------------------------------------------------|------------------|
| Date in this test | Data in REF \[8\] | Data in REF \[5\] | Data in REF \[6\] | Data in REF \[9\] |
| 1 | 1.35 | — | 0.96 | 2.37 |
| 2 | 0.69 | 0.88 | 0.68 | 1.01 | 2.48 |
| 3 | 1.18 | 3.08 | 0.90 | 1.25 | 2.84 |
| 4 | 3.27 | 2.77 | 3.07 | 6.62 |
| 5 | 3.46 | 3.12 | 3.12 | 7.04 |
| 6 | 3.66 | 3.44 | 2.93 | 8.12 |
| 7 | 4.81 | 2.57 | 3.42 | 12.32 |
| 8 | 5.19 | 3.31 | 4.46 | 12.84 |
| 9 | 7.4 | 3.74 | 5.48 | 13.04 |

Note: - indicates that there is no such mode shape

As shown in Table 2, Figure 6, the longitudinal translational frequency of the top platform is basically within 1Hz on the horizontally encrypted column network spring vibration isolated foundation. The vertical translation frequency of the horizontally encrypted column network spring vibration isolated foundation and the double column spring vibration isolated foundation are around 3Hz. The vibration frequency of the vertical 1st-order bending of the top plate of the horizontally encrypted column network spring vibration isolated foundation is 3.5HZ-4Hz, and the vertical frequency of the 2nd-order bending is more than 7Hz, which is slightly higher than that of the double-row column spring isolated foundation.

The vertical swing mode around the longitudinal center axis of the horizontally encrypted column network spring vibration isolated foundation is obviously hysteresis compared with that of the double column spring vibration isolated foundation, and the frequency of this mode is above 4.7Hz. Since the vertical transmission appeared, the natural frequency of the horizontally encrypted column network spring vibration isolated foundation is generally higher than that of the double column spring vibration
isolated foundation, and the maximum difference of the 2nd-order bending frequency of the top plate is greater than 4Hz.

To sum up, the natural frequency of the horizontally encrypted column network spring vibration isolated foundation was slightly improved compared with the natural frequency of double column spring isolated foundation, and there are differences in the mode distribution. Compared with the rigid foundation, using the horizontal encryption, the increase of foundation stiffness increases the natural frequency, but the spring isolation support makes its vertical frequency significantly reduced, avoiding the main working frequency of the equipment, thereby improving the working environment of the equipment.

6. Conclusion

Through the study of the dynamic characteristics of the horizontally encrypted column network spring vibration isolated turbine-generator foundation model, the following conclusions can be obtained:

- The vertical frequency of this foundation is 3.266Hz, which proves that the foundation natural frequency is effectively reduced by using vibration isolating spring, which can meet the foundation design requirements and ensure that the equipment is in a good working environment.
- The low mode shape of this foundation is mainly the overall vibration, such as translation, torsion, bending, etc., the high mode shape is accompanied by the column end swing, distortion and other local vibration, the horizontal translation of overall structure is missing, the horizontal torsion is not obvious, the condenser is mainly vertical translation, and with the mode shape of the main structure changes its vibration direction and amplitude.
- The form of the horizontally encrypted column network makes stiffness increased in some areas, and the natural frequency is generally higher than that of the double column spring vibration isolated foundation, which is always lower than the rigid foundation.
- Due to a lack of controlled trials, the impact of the condenser on the main structure is not known, and it needs the subsequent numerical simulation to analysis.

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