Proceedings of the HTR 2014
Weihai, China, October 27-31, 2014
Paper HTR2014-21327

Finite Element Analysis of the Rotor System of a Magnetically Suspended Compound Molecule Pump

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Abstract –*A novel magnetically suspended compound molecule pump has been designed, which has been supported by the active magnetic bearings (AMBs) system with 5 degrees of freedom. According to the characteristics of the high speed and AMBs, the rotor system of the magnetically suspended compound molecule pump has been analyzed by the finite element method. Modal analysis has been performed for the rotor, thus modal frequencies and corresponding modal shapes have been obtained. For the high rotating speed the blades usually have tended to be destroyed as the results of the centrifugal deformation and vibration. So several static parameters have been analyzed, such as stress distributions and deformations. Simulation results provide a theoretical foundation for the design of the magnetically suspended compound molecule pump's controllers. The reliability and safety of the structure have been verified completely. Furthermore, this paper is of great significance for the pumps' future developments.*

I. INTRODUCTION

As a novel low-carbon, high efficiency, high compression ratio vacuum equipment, the magnetically suspended compound molecule pump has been widely used in the semiconductor industry, space simulation, energy and other fields[1, 2], which has been supported by the AMBs system. The AMBs system has many advantages such as no contact, no lubrication, low vibration and high speed. So it has been widely used in turbo machinery, flywheel energy storage, nuclear power and other fields[3, 4]. For example the AMBs system has been used in the 10 MW high-temperature gas-cooled reactor (HTR-10GT) program[5]. Because of the complex working principle and involving many areas, the magnetically suspended compound molecule pump is not easy to be manufactured. Now, only a few companies can provide such commercial products, such as Leyblod, Varian, Osaka, KYKY, etc.

The rotor system of the magnetically suspended compound molecule pump has some main characteristics such as the AMBs system, high speed, variable support stiffness and thin blades. In order to realize stable operation, the rigid critical speed of the rotor system must be surpassed. The thin blade structure can produce deformation. Rotor deformation and rotor vibration or resonance is the main causes of failure of the mechanical structure, which is the focus of the study.

In this paper, the rotor system of the magnetically suspended compound molecule pump is analyzed by the finite element method. The modal analysis and rotor statics analysis is performed. Modal frequencies and corresponding modal shapes have been obtained. And stress distributions and deformations have also been obtained at high speeds, as well as the safety and reliability are evaluated. Simulation results provide a theoretical foundation for the design of the magnetically suspended compound molecule pump's controller.

II. STRUCTURAL DESIGN OF THE MAGNETICALLY SUSPENDED COMPOUND MOLECULE PUMP

The magnetically suspended compound molecule pump with turbine blade and multi-spiral groove is shown in Fig. 1. Its mechanical structure contains turbine blades, multi-spiral groove and the AMBs system[6, 7]. In order to avoid the mechanical collision caused by the rotor deformation and mechanical vibration or resonance, the structural design focuses on the following clearances: the radial blade clearance between rotor blades and pad rings, the blade clearance between the rotor and the stator blades, the multi-spiral groove clearance between the rotor and the inner-outer stator.

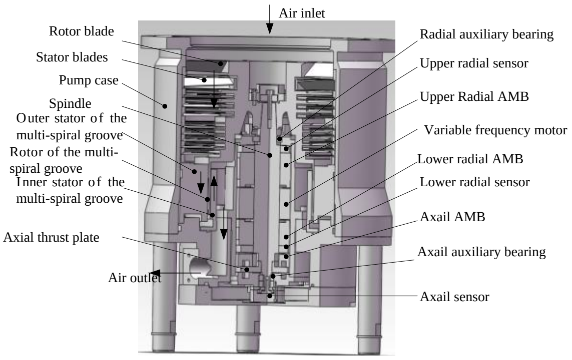

Fig. 1: Structural diagram of the magnetically suspended compound molecule pump with turbine blade and multi-spiral groove

III. MODEL OF ROTOR SYSTEM

The rotor has rotational symmetry structures and is supported by the AMBs system. The AMBs system provides the support stiffness and damping for the rotor system, and it is composed of two radial magnetic bearings and an axial magnetic bearing. In order to meet the design requirements, the support stiffness of two radial magnetic bearings is 5 N/μ m, and the support stiffness of the axial magnetic bearing is 10 N/μ m. The support damping of the AMBs system is ignored in this paper. The support of the radial magnetic bearing is the equivalent of the four spring loads. As shown in Fig. 2, the four springs are uniformly distributed on the circumferential surface of the rotor. Through them the degrees of freedom for the rotor *x* and *y* direction are constrained. Each stiffness of the equivalent springs is for half of the support stiffness of the magnetic bearing system. As shown in Fig. 2, like the radial magnetic bearing, the support of the axial magnetic bearing is the equivalent of an axial spring load. The degree of freedom for the rotor *z* direction is constrained. The equivalent spring's stiffness is equal to the support stiffness of axial magnetic bearing.

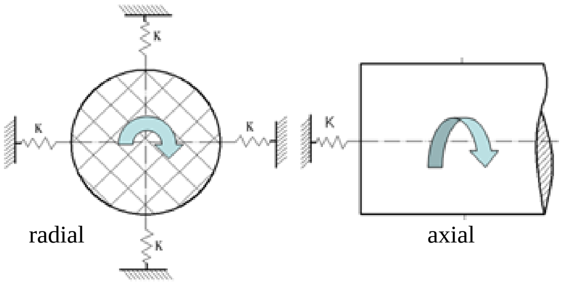

Fig. 2: Spring equivalent of AMBs

The geometry solid model of the rotor is created firstly. Because of this complex structure, the model is created in Solidworks, and then it is imported into ANSYS. Considering the accuracy of the later calculation, the model is meshed by the sweep method, therefore the model needs to be cut by the faces before meshing, and this work can be carried out in Solidworks or ANSYS. AMBs are replaced by the equivalent spring elements, which are created by using the corresponding node in the location of AMBs.

After loading and meshing, the model of the rotor system is shown in Fig. 3. It contains 90717 nodes and 37942 elements. The modal analysis and rotor statics analysis will be carried out based on it.

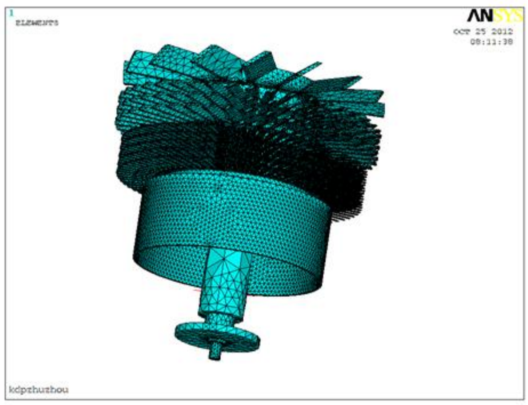

Fig. 3: Finite element model of the rotor system

IV. MODAL ANALYSIS

The rotor system of the magnetically suspended compound molecule pump is supported by the AMBs system. The support stiffness of the rotor system is adjustable. In order to realize stable running, the rigid critical speed of the rotor must be surpassed. With the rotating speed increasing, the rotor vibration or resonance is the main causes of the failure of the mechanical structure. So modal frequencies and modal shapes of the rotor have to be studied[8, 9].

Through the simulation, the first six order modal frequencies of the rotor system are shown in Table 1. They include the first three order rigid modal frequencies and the first three order flexible modal frequencies. And the modal shapes corresponding to the modal frequencies are shown in Fig. 4 as well.

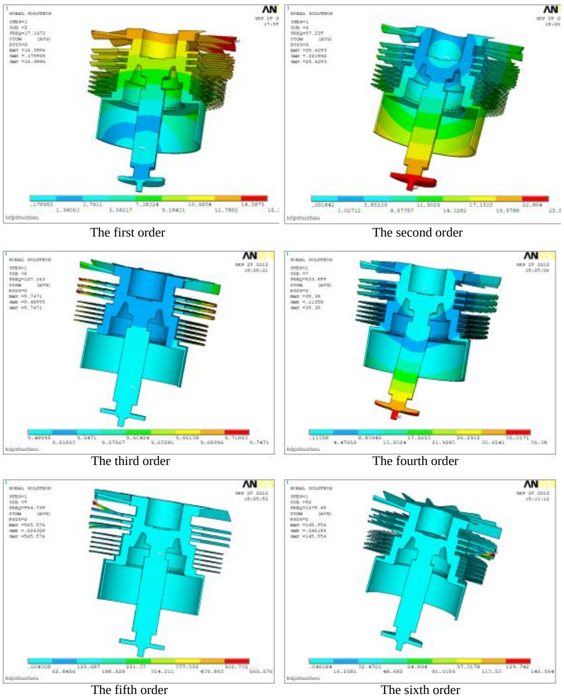

Fig. 4: Modal shapes of the rotor system

Table 1: Modal frequencies of the rotor system

Order	First	Second	Third	fourth	fifth	sixth
Freq(Hz)	17	57	107	533	954	963

The diagram of the first four order modal shapes of the rotor system is shown as Fig. 5.

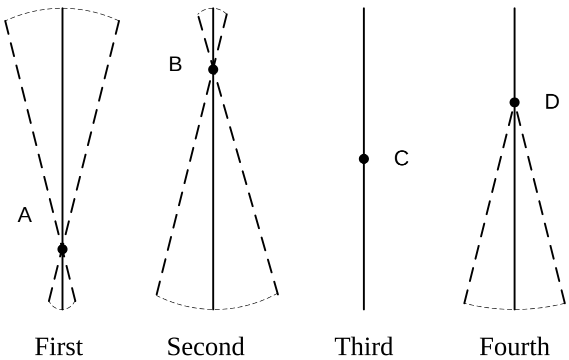

Fig. 5: Diagram of the modal shapes

As shown in Table 1, Fig. 4 and Fig. 5, the first-order rigid modal frequency is 17 Hz. With A point as the fixed-point rotation from Fig. 5, which is at the lower end of the rotor, the rotor linearly swings along the *x* axis or *y* axis direction. The second-order rigid modal frequency is 57 Hz. Like with the first-order rigid modal shape, the rotor swings side to side. And the only two differences are, right there, and there versus here and here. The fixed-point rotation is now at the upper end of the rotor, which is B point shown in Fig. 5. The third-order rigid modal frequency is 107 Hz. At the moment the rotor runs up and down along the *z* axis direction. So this modal is often called axial rigid modal.

The fourth-order modal frequency is 533 Hz. This modal belongs to the flexible modal. So it is also called the first-order flexible modal. D point is the connection between the blades of the rotor and the spindle of rotor from Fig. 5. With D point as the fixed-point rotation, the spindle of the rotor linearly swings along the *x* axis or *y* axis direction. But the blades of the rotor are almost fixed. In theory the thin stiffness of the connection between the blades and the spindle of rotor finally caused this modal. So it is often called the flexible wheel-hub modal in the project.

The modals of the rotor are the vibrations of the blades from the beginning of the fifth-order modal. The modal shapes are also the elongation and torsional deformation of the blades which belong to intrinsic properties of the blades. And the modal frequency spacing is small. These higher-order flexible modals depend on the structure and shape of the blades. When the blades have been designed, these corresponding modal frequencies must be much greater than the operating speed of the rotor in order to avoid resonances.

The operating speed of the magnetically suspended compound molecule pump is set to 250 Hz. So the critical speed and vibration problems of the rotor need to be studied because of the high operating speed. As shown in Table 1, the rigid critical speed of the rotor needs to be surpassed in order to realize stable operation. So the vibration of the rotor at the rigid critical speed can be the focus of the research in the process of the controller design. Then the operating speed is much less than the first-order flexible modal frequency from Table 1, so only the vibration caused by the flexible modal need to be analyzed. Simulation results provide a theoretical foundation for the control strategy of the magnetically suspended compound molecule pump.

V. ROTOR STATICS ANALYSIS

Centrifugal inertial force of the rotor can be generated at the high rotating speed. The thin blades and traction wheel could be deformed or fractured under the together function of centrifugal inertial force and gravity. Its existence can also result in the collision of the rotor-stator structure. So it is necessary to carry out the rotor statics analysis to verify the reliability and safety of the rotor structure, if only for the purpose of avoiding them.

The rotor statics analysis has been performed by the finite element method. The stress distribution and deformation of the rotor can be obtained at the rotating speed of 250 Hz. Under the together function of centrifugal inertial force and gravity, the deformations of the rotor are shown in Fig. 6 and Fig. 7, and the stress distribution is shown in Fig. 8

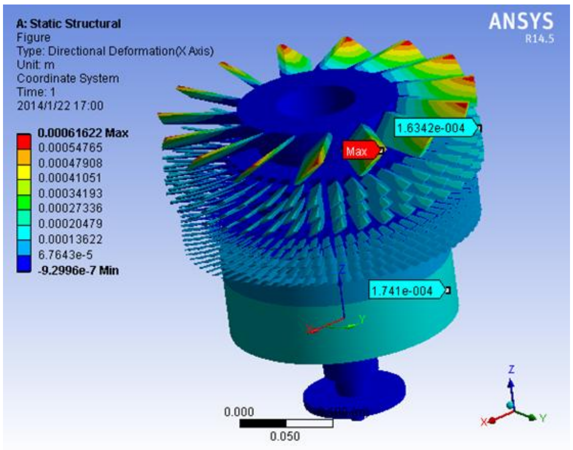

Fig. 6: Radial deformation cloud images of the rotor at the speed of 250 Hz

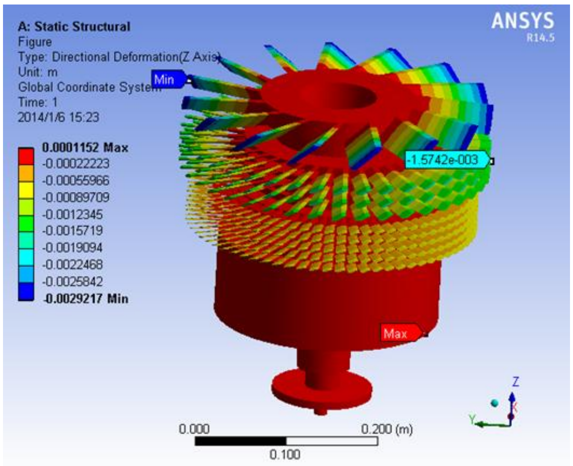

Fig. 7: Axial deformation cloud images of the rotor at the speed of 250 Hz

As shown in Fig. 6 and Fig. 7, the thin blades and traction wheel generate the certain deformations at the rotating speed of 250 Hz, which is composed of elongation along the radial direction and bobbing along the axial direction. As shown in Fig. 6, the maximum radial deformation occurs at the end of the first stage rotor blade. This deformation is 0.62 mm, less than the radial blade clearance of 2.5 mm. The radial deformations of the other blade are also less than their corresponding radial blade clearances in the same way. At the same time the deformation at the end of the traction wheel is 0.17 mm, also less than the multi-spiral groove clearance of 1.25 mm. As shown in Fig. 7, the maximum axial deformation occurs at the end of the first stage rotor blade. This deformation is 2.92 mm, less than the blade clearance of 3.5 mm. And the deformation at the end of the second stage rotor blade is 1.57 mm, less than the blade clearance of 2.5 mm. And the axial deformations of the other blades are also less than their corresponding blade clearances in the same way. Finally simulation results show that the radial and axial deformations of the rotor cannot be cause a collision.

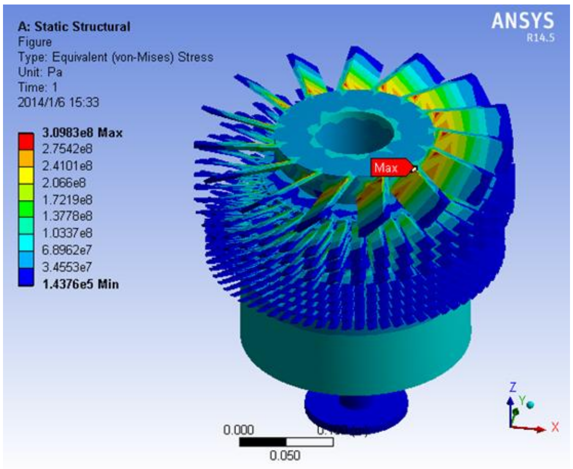

Fig. 8: Stress distribution cloud image of the rotor at the speed of 250 Hz

As shown in Fig. 8, the maximum stress is concentrated at the root of the rotor blade. And the value of it is 310 Mpa, much less than the material yield strength of the 490 Mpa. The safety of the rotor has been verified through the strength analysis.

VI. CONCLUSION

In this paper, the magnetically suspended compound molecule pump has been designed. And the finite element model of the rotor system supported by the AMBs system has been established. Modal analysis and rotor statics analysis have been carried out based on it. Modal frequencies and corresponding modal shapes have been obtained. And the stress distributions and the deformations also have been obtained at the rotating speed of 250Hz as well. Simulation results show that the operating speed is higher than the rigid critical speed, but much less than the first-order flexible modal frequency. It provides a theoretical foundation for the control strategy. Simulation results also show that centrifugal deformation and stress concentration of the rotor are existent at the operating speed. Centrifugal deformations are mainly concentrated at the end of the thin blades and traction wheel, less than design clearances of the structure. The maximum stress is concentrated at the root of the rotor blade, much less than the material yield strength. In theory, the reliability and safety of the structure have been verified completely.

VII. ACKNOWLEDGMENT

Thanks go to Lei Zhao for his constant encouragement and guidance. This paper is financially supported by the National Natural Science Foundation of China (No. 51275261) and National S&T Major Project (No. ZX069).

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