Application and Research of the Active Magnetic Bearing in the Nuclear Power Plant of High Temperature Reactor *

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***Abstract* –The 10MW High Temperature Gas-cooled Test Reactor (HTR-10) constructed by the Institute of Nuclear and New Energy Technology (INET) of Tsinghua University in China, is the first modular high-temperature gas-cooled test reactor (HTR) in the world. When combined with the direct gas-turbine cycle, HTR achieves high inherent safety together with high efficiency. Besides, the possibility of water ingress in the core can be eliminated, the power unit design can be simplified and the construction capital and operational costs can be reduced. HTRs are thus considered as one of the most potential candidates for the new generation reactors in the 21st century. The direct gas-turbine cycle requires some kind of special designed bearings to support the shaft on which the gas compressors, turbine and generator are all installed in the primary loop. However, the design of the special bearings is a challenge task. Thanks to the rapid development of the Active Magnetic Bearing (AMB) in recent years, the contact-free and no-lubricating AMBs are regarded as the most competent option to support the turbomachine shafts in all the designed gas-turbine HTRs for their numerous advantages over conventional bearing technology. Two projects, HTR-10GT (HTR-10 Gas Turbine) and HTR-PM (HTR-Pebble-bed Module) initiated by INET, will consider incorporating the AMS technology in their power conversion systems. This paper focuses on the introduction of AMB applied to the power system of HTR, the design characteristics of the AMB system and the introduction of the related series of experiments to demonstrate the system functions and validate the control scheme to be used in the HTR-10GT and HTR-PM project.**

***Index Terms* – Active Magnetic Bearing, High Temperature Reactor (HTR), Nuclear Power Plant, Critical Speed, Modal Analysis**

I. INTRODUCTION

The 10MW high temperature gas-cooled test module reactor (HTR-10) with the core made of spherical fuel elements was designed and constructed by the Institute of Nuclear Energy Technology (INET) of Tsinghua University. It has the inherent safety features of the HTR-Module reactor: the reactor core can shut itself down via the negative temperature coefficients of reactivity even after accident-incurred introduction of any existing surplus reactivity, and the decay heat will be removed from the reactor core solely by means of physical processes[1-2].

As the major task in the first phase of the HTR-10 project emphasized the design, realization and validation of module pebble bed reactor, a steam-turbine of about 3 MW (electric power), instead of a gas-turbine, was used in the power conversion system. This reactor with steam-turbine reached its full power level in the early 2003[3-4].

Since 1990s, different research institutes and companies in the world have attempted to develop the design of and to build the reactor plant combining modular gas-cooled reactor with power conversion system implementing high-effective Brayton cycle based on the achievements in the technology of gas turbines, high-performance heat exchangers and electromagnetic bearings. The direct gas-turbine is advantageous in its simplification of the power unit design and a cut of construction cost and operational cost in addition to the high electric power production efficiency (up to 50%).

However, little practical experience has been obtained in the use of gas-turbine cycle in the nuclear power plant with high-temperature gas-cooled reactor despite that several prototype plants are conceptually designed around the world, such as the PBMR (South Africa), the GT-MHR (Russia, USA, etc.) and the GTHTR300 (Japan)[5-6].

In the closed Brayton cycle for the HTRs, the gas compressors, turbine and generator are all installed in the power conversion unit (PCU), whose shafts are supported by some kind of special designed bearings. The design of the bearings was a rather challenging task 20 years ago because the helium flow in the reactor primary circuit demands very clean environment while the conventional oil-lubricated bearings may result in oil leakage despite the adoption of complex oil-proof and gas seal means; moreover, the bearing maintenance in the PCU is also very difficult.

In order to experimentally validate the possibility of building high performance plants with direct closed gas-turbine cycle and the technology for future commercial applications, INET of Tsinghua University initiated the design of the PCU with direct gas-turbine cycle for the

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HTR-10 at the end of year 2000 in China. The HTR-10GT (HTR-10 Gas Turbine) project is supported by the State Science and Technology Committee as a national high technology research and development program. The turbine rotor, featuring large-size, vertical position, high-speed and flexibility, weighs about 1000 kg and rotates at 15000 r/min. Several critical speeds have been passed. It cannot be denied that it is both theoretically and practically a challenging project. The preliminary design of the AMB system has finished. At present, the optimal basic design is being performed by the INET.

At the same time, the 458MW commercial nuclear power plant (HTR-PM) designed by INET based on the HTR-10 technology decided to use the steam turbine for its technological maturity and reliability. AMB will be used to support the rotor of Helium blower fan of HTR-PM. The rotor weighs about 4700 kg and rotates at 3200 r/min.

Although the AMB technology has been successfully used and tested in turbine machinery in other heavy industrial fields, such as natural gas treatment with turboexpanders and storage (or production) with compressors, there is no application in the primary loop of gas-turbine HTRs. Many experiments and academic research about the AMB technology have been conducted by the INET of Tsinghua University for HTR-10GT and HTR-PM project. Several test rigs have been set up, including passing natural frequencies rig, the large AMB rig, the generator rotor rig for HTR-10GT, and test rig of Helium blower fan, etc.

This paper focuses on the design characteristics of the AMB system and the introduction of the related series of experiments to demonstrate the system functions and validate the control scheme, which will be used in the HTR-10GT and HTR-PM project. What follows is the introduction of the main characteristics of the AMB applied in power system of HTR.

II. STRUCTURE AND CHARACTERISTICS OF HTR-10GT

A. System Outline

The AMB system consists of elements inside the PCU and elements outside the PCU. The electromagnets and sensors are located in the PCU, while other AMB control system equipments are located beyond the PCU, such as controller facilities and power modules. Its structure along with the turbine rotor in the PCU is shown in Figure 1.

The generator rotor and turbine rotor are suspended by four radial and two axial electromagnetic bearings. Besides, there are auxiliary bearings to ensure rotor touch down when AMBs fail to work during operation and protect rotor when dynamic loads exceeding AMB load-carrying capacity. The length of the turbine rotor is about 3.5m and the weight is 1000kg. The normal rotor operation speed is 15000rpm (250Hz) at the turbine power level of 5.86MW and efficiency is 86%. The first and second bending critical speed (BCS) of the turbine rotor is 62Hz and 141Hz respectively.

B. System Components

1. Active Magnetic Bearing

The radial and axial magnetic bearings are located in the generator. The turbine parts are shown in Fig.2. In order to reduce the range of products, the magnetic bearings for generator rotor and turbine rotor are designed as the unified size according to the generator rotor load in operation condition. The radial gap of the radial bearing is 0.15mm considering the gap of 0.4mm between the compressor stator and blades in order to protect the compressor. The main parameters of the magnetic bearings are listed in Table I.

TABLE I.
MAIN PARAMETERS OF THE AMB

Parameter	Value
Radial active magnetic bearing	
Lifting capacity, N	3000
Interior / outer diameter of stator magnetic circuit, mm	150 / 300
Effective axial length, mm	100
Normal bias current, A	7.5
Mass, kg	118
Radial gap between bearing and rotor, mm	0.7
Radial gap between auxiliary bearing and rotor, mm	0.15
Axial active magnetic bearing	
Lifting capacity, N	20000
Interior / outer diameter of stator magnetic circuit, mm	170 / 364
Normal bias current, A	15
Mass, kg	180
Radial gap between bearing and rotor, mm	1.0
Radial gap between auxiliary bearing and rotor, mm	0.3

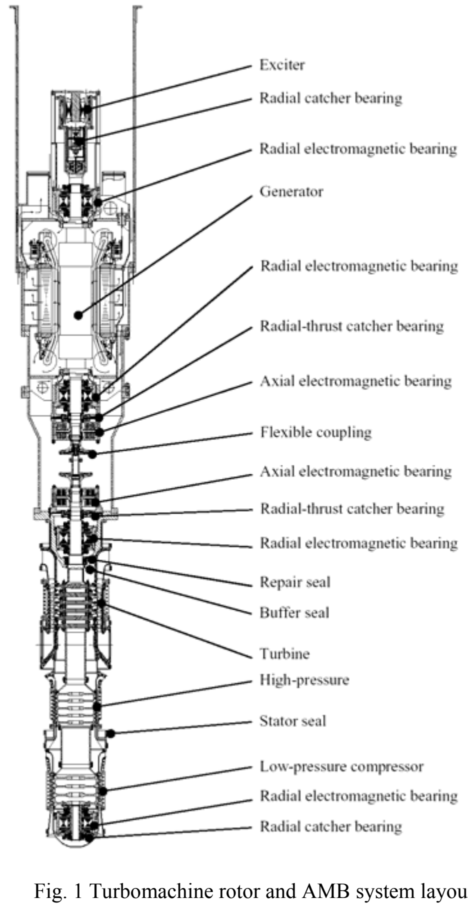


Fig. 1 Turbomachine rotor and AMB system layout

2. Position Sensor

The rotor displacements in radial and axial are monitored by the position sensors, which are of induction type. The sensor consists of sensitive elements located on the stator and an acting element located on the rotor in front of the sensitive elements. The sensitive element is an annular magnetic circuit with 24 poles, of which each 6 poles are grouped to detect the radial displacements in X and Y directions. In such a design, a kind of 2/3 redundancy working mode for sensor signals can be easily realized. The acting element is an extension made of the laminated ferromagnetic steel, which is fixed on turbine shaft. Windings around the stator perimeter are distributed in order to average and smooth the measure value. This kind of sensor has good sensitivity of no less than 10mV/μm and resolution of at least 1μm. Its cut-off frequency is so high enough (>5k Hz) that the phase lag at operation frequency can be neglected. The voltage signal after the sensor modulator can be transferred more than 200m without obvious attenuation.

3. Controller

The controllers, as well as all its peripheral equipment, including A/D, D/A, network card, etc., are of standard industry type, and are usually selected as high speed Digital Signal Processing (DSP) computer, which has good stability and excellent hard real-time interrupt processing capability. For example, the new DSP product of TI 6713 has powerful floating-point operation of 1350 MFLOPS and can be adopted as the ideal micro processor of the controller. The A/D converter has 10 channels with 500kS/s rate and 16bit precision, while the D/A converter has 5 channels with 1MS/s rate and 14bit precision. The controller shall have the following functions:

1）Receive information about displacement, rotation speed and angular position of the turbomachine rotor from the sensor converters;
2）Receive the control commands from the operation computer to change some parameters of the AMB control system;
3）Generate and release the current control signals in coil windings according to the specified algorithms and control commands;
4）Diagnose the states of the elements of the AMB system and transmit this information to the operator computer via networks;
5）Release signals about alarm and emergency protection.

4. Host Computer

The operating and monitoring computer (host) lies on the higher level of control channel, whose type is standard PXI industry computer and its operation system is universal MS Windows. The typical configuration of the host computer can select the NI with 2.3GHz Pentium 4 CPU. The communication between controller and host computer is based on industry network. The main functions of the host computer are listed as follows:

1）Establish and change the control algorithms or rules of the AMB;
2）Start up and stop the AMB control system;
3）Receive information about the states of AMB components and display this information by different graphical means on the monitor;
4）Diagnose controller state and make decision;
5）Log and print information about the state of the AMB control system components;
6）Send process information to the Instrument and Control (I&C) system of reactor plant.

5. Power amplifier

The power amplifier receives the control signal in analog voltage from the controller and keeps the current in the magnet winding according to this voltage signal. Generally speaking, power amplifier is a kind of controlled constant-current source to the inductive reactance. As the power of single amplifier unit is about 4.5kVA (300V, 15A), switch amplifier is the best type considering the loss and efficiency. In order to overcome the drawback of switch amplifier of sharp oscillation impulsion at stable operation state, special method is selected to realize a relative smoothly current, such as three-state voltage level, two H-bridge connecting in series, high switch frequency of 60k Hz and so on. The phase lag is less than 3° at 200 Hz to achieve good dynamic characteristics.

6. Others

There are some other auxiliary components, such as main power supply, UPS for backup power source, cables and penetrating connector. Due to space limitation, they are not introduced in detail in this paper.

III. SMALL FLEXIBLE ROTOR TEST RIG

As there is no application of the AMB to the PCU of nuclear power plant, especially for supporting a large vertical flexible rotor and passing two bending critical speeds in operation, it is imperative to carry out a series of experiments step by step for this project and the theoretical analysis as well.

A small test rig is established to test the control method of flexible rotor and accumulate experience of passing through critical speeds. If the experiment proves a success, a test rig with a mode-similar rotor to the actual one will be set up to find the way of controlling the actual rotor modes. Finally, the actual turbine rotor system along with the AMB system will be mounted in the PCU vessel of the HTR-10 reactor.

At present, the test rigs have been set up and a serial of experiments have been performed. The second BCS have been passed on the small flexible rotor test rig. What follows is the description of the experimental rig.

A. System Description

The objective of this experiment is to study the control arithmetic of how to pass the bending critical speed (BCS) so as to provide enough experience for the future turbine rotor control. The second BCS is designed as 700Hz, which is higher than that of the actual turbine rotor. The difficulty is deliberately increased considering the difference between small rotor in experiment and large rotor in the PCU. The structure and main parameters of the setup are shown in Figure 2 and in Table II respectively.

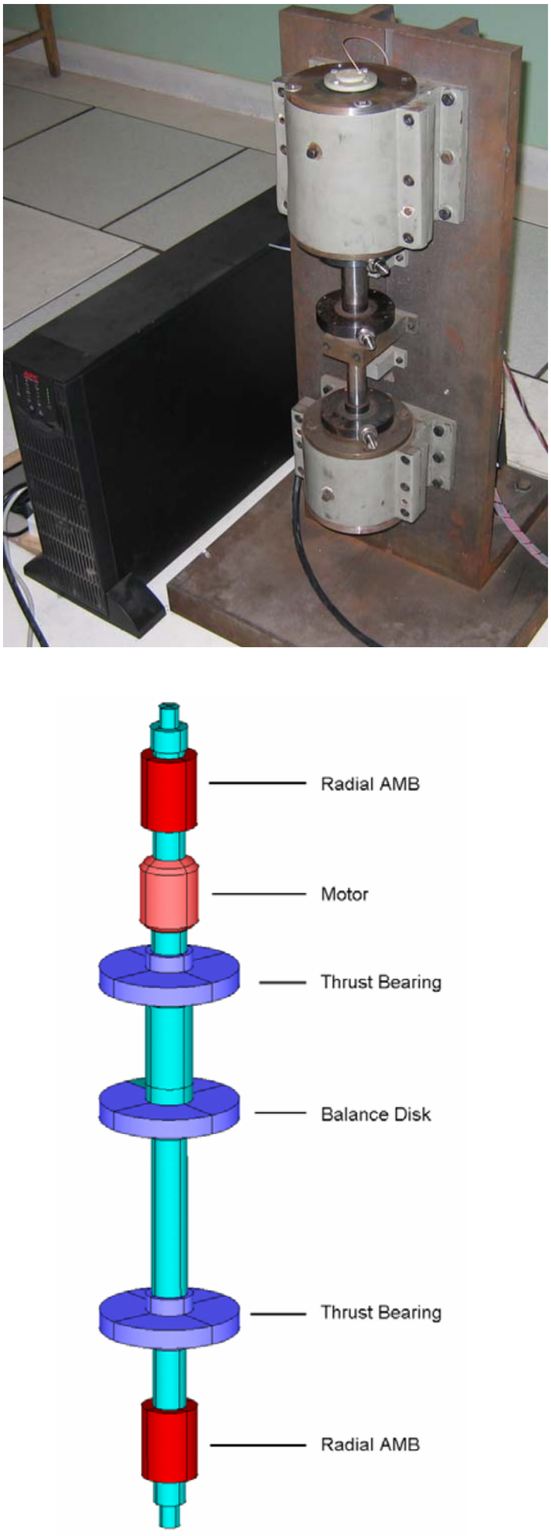


Fig. 2 The structure of the small test rig

TABLE II.
MAIN PARAMETERS OF THE SMALL SETUP

Rotor Mass	6.128kg
Rotor Length	613mm
Radial Moment of Inertia	0.148kg m^2
Polar Moment of Inertia	0.00379kg m^2
Air Gap	0.4mm
Coils	300n
Pole Area	320mm^2
Inductance	45.2mH

In order to quickly build the test rig, a PC controller is utilized to control the small experiment system on the famous free-charge real-time Linux system, and the sampling ratio is 10k Hz. Although the control system hardware is different from the one that will be used in the actual application, the control model and arithmetic are similar in terms of mathematics and control.

B. Modal Analysis

The finite element method is used to analyse the mode of the rotor. The magnetic bearings are simulated as four constant stiffness spring elements. The stiffness and damping of the magnetic bearing can be adjusted by changing the real constant property of the spring element. In the analysis, the stiffness is set to be 3×10^4N/m, which is obtained from the experiment and is much smaller than the traditional bearing, and the damping is set to be zero for the sake of simplifying the analysis.

Modal analysis of this rotor is processed. Table III gives the analytic data. Figure 3 gives the results of modal analysis.

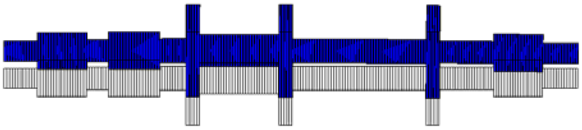
The result of the modal analysis shows the modal frequency and modal shape which are useful for the sensor distribution design of magnetic bearing. In this result, the gyroscopic effect is not included yet.

Because of the low bearing stiffness, there are two rigid critical frequencies reflecting only the relationship of the rotor's mass and the stiffness. The other two bending frequency are much more concerned about.

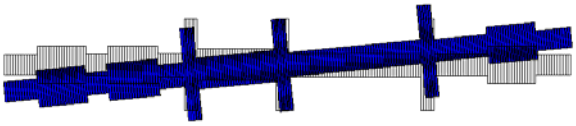
TABLE III.
THE ROTOR SYSTEM PARAMETERS

Density:	ρ= 7800kg/m^3	Radius of disc:	Rd = 50mm
Young's modulus:	E = 2.0×10^{11}N/m	Radius of axis:	Rs = 12mm
Poisson's coefficient	μ= 0.3	Radius of lamination:	Rl = 20mm

28Hz



45Hz



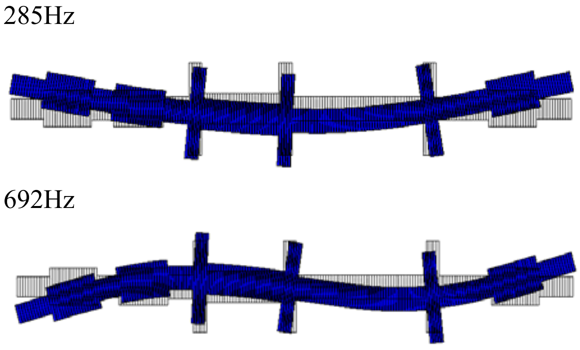


Fig. 3 Modal frequency and modal shape

C. Critical speed analysis

The basic differences between the dynamic behaviour of a non-rotating body and a rotating one are caused by gyroscopic properties. Typical natural vibrations of a spinning rotor manifest themselves as a "whirling" of the rotor axis, which whirls in the same sense as the rotor spin in a forward whirl or vice versa in a backward whirl. When the gyroscopic effect and the rotor whirling are considered into the modal and harmonic analysis, much more accurate resonant critical frequency result can be obtained, which is very necessary for the controller design. Figure 4 shows the eigenfrequency change as the rotor speed grows.

When taking gyroscopic effects into account, the critical speed result has not been well proved yet. But this result is similar to the result provided by transfer matrix method[7]. And this result shows no much change in the critical speed of this testing rotor when the running speed grows up.

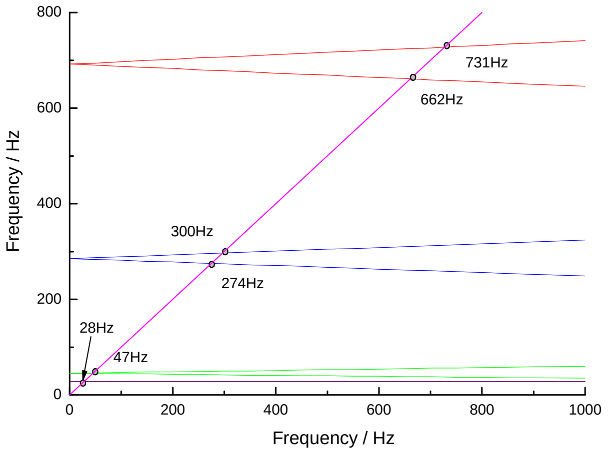


Fig. 4 Critical speed analysis with gyroscopic effect

D. Control System Design

The LQG method is introduced to design the controller based on state-space modern control theory. After a process of iteratively changing the weighting factors, a controller with input weighting matrix R and state weighting matrix Q is designed.

In the actual rotating experiments, it was found that at some special speeds, the rotor amplitude became too large due to the noise stimulating the nature bending modes of the rotor. In order to restrain the amplitude, some phase compensators are added into the above designed LQG controller at the first two bending frequency.

E. Measuring and Monitoring System

An online measuring and monitoring system is set up for this experiment in order to detect how the AMB system works in operation and make diagnosis whether the system behaves normally or not. Due to the distinct advantages of the VI (Virtual Instruments) technology and LabVIEW (National Instruments) platform, a graphic programming environment on VI as well as standard software on data acquisition and instruments control, are selected as a convenient tool and workbench to build the whole system. The main screen of this system is shown in Figure 5.

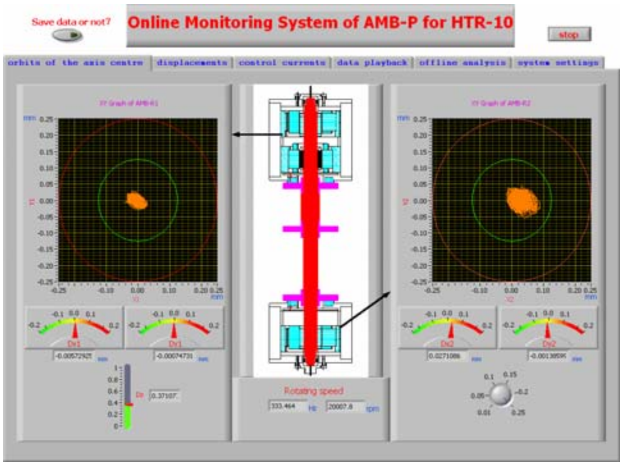


Fig. 5 Main screen of the measuring and monitoring rotor system

LabVIEW 7 Express, the latest version, has been selected as the system software platform. The PCI-6023E data acquisition board, a product also from National Instruments, has been selected as the system data acquisition hardware. According to the requirement and performance of the monitoring system, a personal computer with Windows 2000 system has been chosen to be the foundation and the data processor of the system. Through this system, the operation status can be obtained such as the orbit of the axis centre, the four radial displacement signals and their spectra during its passing the first bending speed.

F. Experiment

On the small test rig, the passing through BCS experiment was carried out elaborately. The LQG controller along with the phase compensators around the first two bending critical frequencies of 300Hz and 700Hz has perfect control performance. The rotor passed through the first BCS safely and smoothly and the amplitude was decreased obviously at the first BCS. Even so, the test rig can rotate at the first BCS for a long time without any abnormal phenomenon. Figure 6 shows the top (x1) and bottom (x2) axis loci and their frequency domain properties in passing through the first BCS.

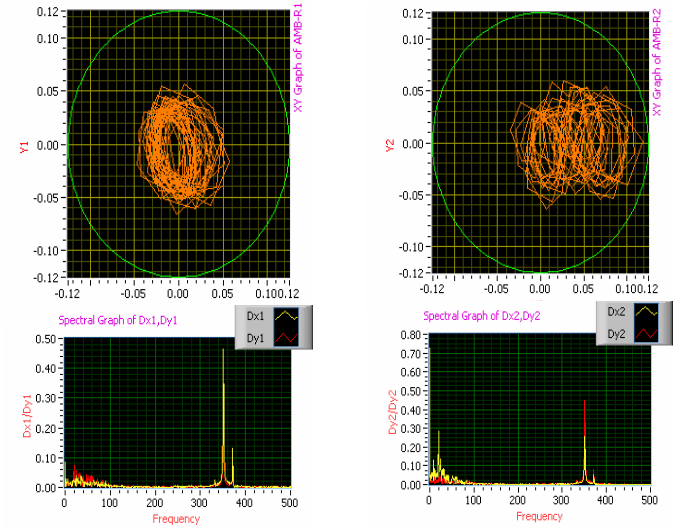


Fig .6 Top (x1) and Bottom (x2) axis loci and frequency properties over the first BCS

The successful passing through the second BCS verifies that the modeling and control design method is feasible and effective. Experiences are gained from this experiment, which will be certainly beneficiary for the future actual tuning process for the HTR-10GT AMB system.

IV. GENERATOR ROTOR TEST RIG

A test rig of HTR-10GT generator rotor is established to test the design method for large AMB and accumulate experience. A series of experiments are will be carried out step by step for this project and the theoretical analysis as well. The experimental results will demonstrate the system functions and validate the control scheme, which will be used in the HTR-10GT project.

Fig. 7 Critical speed analysis with gyroscopic effect

At present, the test rigs have been built. The structure is shown in Figure 7. The rotor's length is 3.5 m, its weight is about 3500 kg and the rotating speed is 3000 r/min.

V. AMB DESIGN OF HTR-PM

The HTR-10 reached its critical reaction at the end of year 2000, and was connected to the grid at the beginning of year 2003.

At present, the 458MW commercial nuclear power plant (HTR-PM) has already being designed by INET based on the HTR-10. The steam cycle will be applied to this project for its technological maturity and reliability.

AMB will be used to support the rotor of Helium blower fan of HTR-PM. The weight of the rotor is about 4700 kg and the rotating speed is 3200 r/min. The structure of the rotor is shown in Figure 8. The design parameters are listed in Table IV. The preliminary design has been finished. The next step focuses on building a test rig to carry out a series of experiments.

TABLE IV.
THE AMB PARAMETERS OF HTR-PM AMB

Parameters	Value
Maximum magnetic flux density of standard gas gap, T	1.5
Maximum axial force, kN	62.12
Radial force of single AMB, kN	18.74
Maximum excitation current, A	30
Temperature, ℃	<65.0
Speed, r/min	3,200

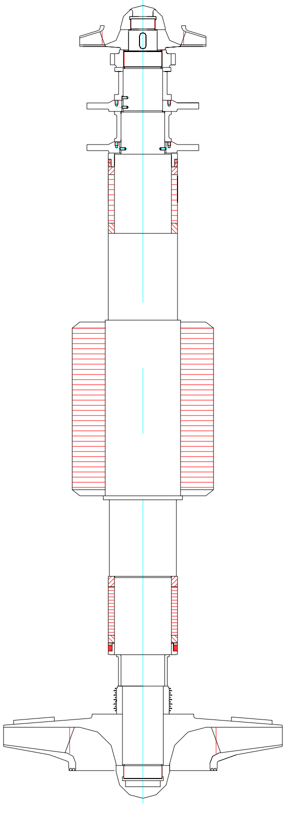


Fig. 8 Rotor structure of HTR-PM

VI. CONCLUSION

HTR-10GT is the first pebble-bed high temperature gas-cooled test reactor together with direct gas turbine designed and built by the INET in China. HTR-PM is a commercial nuclear power plant based on the HTR-10 technology. The AMB is the key system to support the rotor for the HTR-10GT and HTR-PM. The dynamic characteristics and related experiments of the AMB are introduced in this paper. The design methodology of the large AMB has been acquired and experiences of passing through the bending critical speed have gained through the experiments. The further design and experiments are being carried out continuously till the whole rotor system is installed in the HTR-10GT and HTR-PM.

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