

## DESIGN AND EXPERIMENTS OF THE ACTIVE MAGNETIC BEARING SYSTEM FOR THE HTR-10

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**ABSTRACT:** The 10MW high temperature gas-cooled test modular reactor coupled with direct gas-turbine cycle (HTR-10GT) is designed by the Institute of Nuclear Energy Technology (INET) of Tsinghua University in China, in order to experimentally validate the possibility of creating high performance plants with direct closed gas-turbine cycle and the technology for future commercial applications. The vertical turbomachine shaft of the HTR-10GT is designed to be supported by active magnetic bearings (AMB). First, the reliability and safety, as well as the design requirements and design bases are discussed in this paper. Next, the AMB system is described in detail and the preliminary rotor dynamic analysis is presented. Then two experiments are introduced: one is a small flexible rotor test rig from which the modeling and control method of passing through the bending critical speed are studied; the other is a full size magnetic bearing test rig to research the characteristics of the AMB which will be helpful in the future actual AMB system for the HTR-10GT. If the state-of-the-art concept of AMBs is realized in this project finally, it can be predicted that the application of the AMBs in the design of the HTRs coupled with direct gas-turbine will become largely conventional in the future.

**KEY WORDS:** High temperature gas-cooled test reactor, direct gas turbine cycle, active magnetic bearing, control system design, bending critical speed

### 0. INTRODUCTION

The modular High Temperature gas-cooled Reactor (HTR) combined with direct gas-turbine cycle (closed Brayton cycle) can bring high inherent safety together with high efficiency (Barnert, 1995). Besides these, the direct gas-turbine can also remove any possibility of water ingress in the core, simplify the power unit design and reduce capital building and operational costs. So the HTRs are considered one of the most potential candidate for the new generation reactors in the 21st century, and several prototype plants are conceptually designed around the world (Ohashi, 2000; Lecomte, 2001; Koster, 2003), such as the PBMR (South Africa), the GT-MHR (Russia, USA, etc.) and the GTHTR300 (Japan).

In the closed Brayton cycle for the HTRs, the gas compressors, turbine and generator are all installed in the primary loop, whose shafts are supported by some kind of special designed bearings. The design of the bearings is a very difficult problem 20 years ago because the helium flow in the reactor primary circuit must keep very clean, and the conventional oil-lubricated bearings may result oil leakage despite adopting complex oil-proof and gas seal means, and the bearing maintenance in the PCU is also very difficult. Fortunately, with the rapid development of the Active Magnetic Bearing (AMB) in

the recent years (Gray, 1990; Schweitzer, 1994), the contact-free and no-lubricating AMBs are considered as the most competent means to support the turbomachine shafts in all the designed gas-turbine HTRs, due to their numerous advantages over conventional bearing technology.

In order to experimentally validate the possibility of creating high performance plants with direct closed gas-turbine cycle and the technology for future commercial applications, the Institute of Nuclear Energy Technology (INET) of Tsinghua University started the design of the power conversion unit (PCU) with direct gas-turbine cycle for the 10 MW high temperature gas-cooled test modular reactor (HTR-10) at the end of year 2000 in China (Zhang and Yu, 2002). This so-called HTR-10GT project is supported by the State Science and Technology Committee as a national high technology research and development program. The preliminary design of the PCU system was finished by the mutual efforts of the INET and the OKBM (Russia) at the beginning of year 2003 (Shi, et al, 2003), just when the HTR-10 reached its full power level. At present, the optimal basic design is being performed by the INET.

This paper focuses on the design characteristics of the AMB control system for the HTR-10GT and 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 project.

## **1. GENERAL SYSTEM REQUIREMENTS**

Although the AMB technology has been successfully used and tested in turbine machinery of other heavy industrial fields (Horst, et al., 2000), such as natural gas treatment with turboexpanders and storage (or production) with compressors, there is not an application instance in the primary loop of gas-turbine HTRs. In the design of the AMB control system, the following design basis, requirements and functions shall be considered.

### **1.1. Design Bases**

Besides the common industry standards, e.g., API 617, IEC and ISO900X, the design development of the AMB system shall take into account the following main nuclear power plant standards, regulations and rules of safety regulatory documentation in China:

- (1) Rules for Nuclear Safety for NPPs
- (2) Rules for Design of Electrical Equipment
- (3) Electrical Equipment Testing Code
- (4) Instrumentation and Automatic Means for Nuclear Plants Technical Requirements
- (5) Requirements to Quality Assurance Program for NPPs
- (6) Codes for NPPs Seismic Design
- (7) Irradiation Testing Code
- (8) Special Conditions for Delivery of Equipment, Instrumentation, Materials and Products for Nuclear Power Installations

### **1.2. General Requirements**

The AMB control system should meet the following design requirements:

- (1) To take up radial and axial loads and provide stabilized supporting of the turbomachine rotor in operation
- (2) To ensure the turbomachine rotor stable working in all operation cases (including passing the critical speeds)
- (3) To reliably operate for a long time in gas fluid under conditions of high speeds, temperatures and radiation at minimum loss of friction and power consumption
- (4) To ensure reliable control over electromagnetic bearing operation in all normal, abnormal operation modes and during design-basis accidents

### 1.3. Main System Functions

The AMB control system should have the following main functions:

- (1) Control function: provide safe and reliable control in all operation modes and ensure the required lifting capacity to effectively prevent the interrupt of operation in single failure of equipments;
- (2) Diagnosis function: has the capability to detailed analyze, record and diagnose the states of the elements of AMB control system in all operation modes;
- (3) Communication function: exchange information between the AMB system and the instrument and control (I&C) system of reactor plant

## 2. SYSTEM STRUCTURE AND CHARACTERISTICS

### 2.1. Working Principle

The typical AMB system diagram is illustrated in Fig.1. Besides the controller, the general control system also includes the sensor, A/D and D/A conversion and power amplifier.

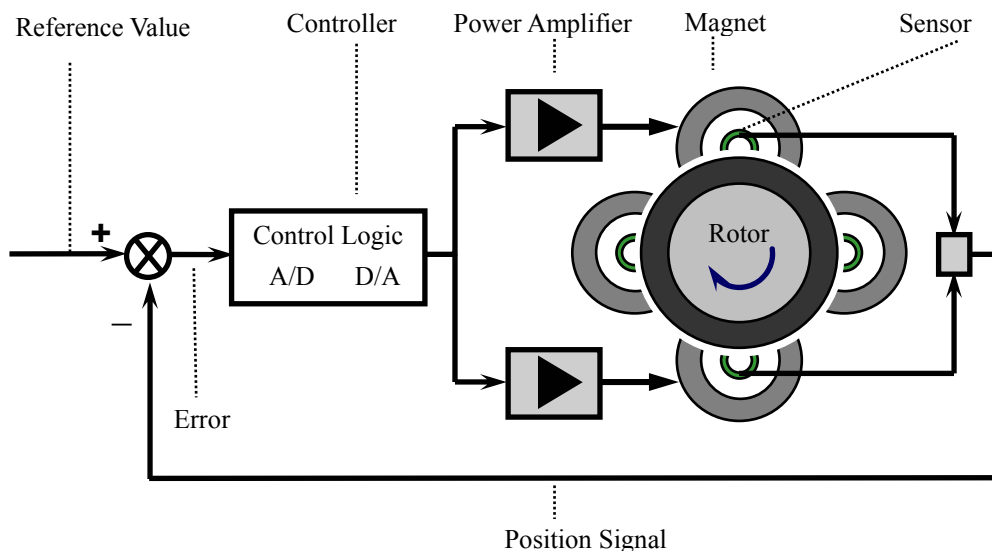


FIGURE 1. Typical AMB system working principle diagram

The rotor's displacement along one of the axes is detected by the position sensors and converted into signals of standard voltage. Then compared with the setting value, the error signal enters the controller. After A/D conversion, the controller processes this digital signal according to a given regulating rule

(control arithmetic) and generates a signal of current setting. After D/A conversion, this current signal enters the power amplifier, whose function is to maintain the current value in the electric magnet winding at the current level set by the controller. Therefore, if the rotor leaves its center position, the control system will change the electromagnet current in order to change its attraction force and, respectively, draws the rotor back to its balance position.

## 2.2. System Outline

The AMB system is divided into 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, including controller facilities and power modules. Its structure along with the turbomachine rotor in the PCU is shown in Fig.2.

The generator rotor and turbocompressor rotor are connected by a flexible coupling to form a single rotor system in vertical layout, which are suspended by four radial and two axial electromagnetic bearings. Besides, there are catcher 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 total length of the rotor is about 7m and the weight is 1500kg. The normal rotor operation speed is 15000rpm (250Hz) at the turbine power level of 5.86MW and efficiency is 86%.

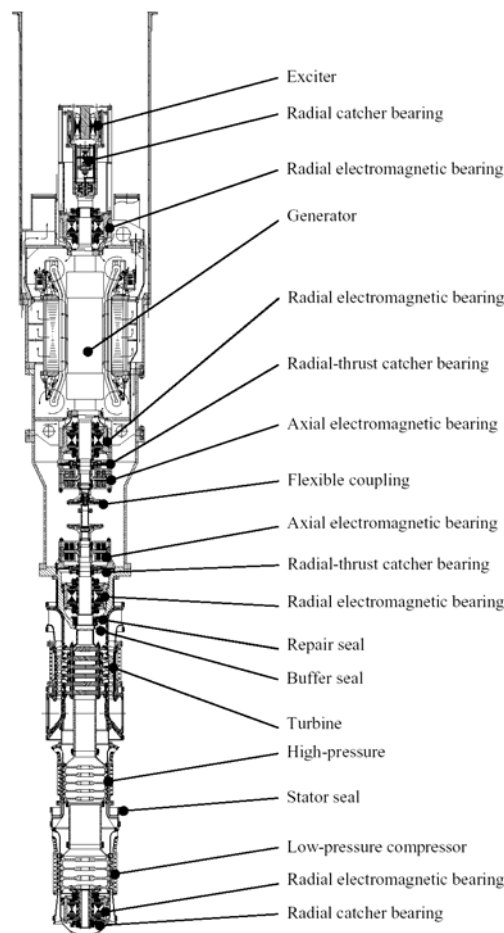


FIGURE 2. Turbomachine rotor and AMB system layout.

## 2.3. System Components

### 2.3.1. Magnetic Bearing

The radial and axial magnetic bearings are located in the generator and turbocompressor parts shown in Fig.2. In order to reduce the range of products, magnetic bearings for generator rotor and turbocompressor rotor are designed as the unified size according to the generator rotor load in operation condition. The radial bearing radial gap 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 1.

TABLE 1. Main parameters of the magnetic bearings

Parameter	Value
Radial electromagnetic 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 catcher bearing and rotor, mm	0.15
Axial electromagnetic 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 catcher bearing and rotor, mm	0.3

### 2.3.2. 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 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 turbomachine 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/ $\mu$ m and resolution of at least 1 $\mu$ m. Its cut-off frequency is enough so high (>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.

### 2.3.3. Controller

The controllers, as well as all its peripheral equipment, including A/D, D/A, network card, etc., is standard industry type, 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.

#### **2.3.4. Host Computer**

The operating and monitoring computer (host) lies on the high level 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 in the 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.

#### **2.3.5. 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 losses and efficiency. In order to reduce 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  $3^\circ$  at 200 Hz to achieve good dynamic characteristics.

### 2.3.6. 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 don't be introduced detailed in this paper.

## 2.4 Rotor Dynamics

Rotor dynamics is the basis for control arithmetic design and is also important for the operation of the whole turbomachine. The analysis tools is used the famous Finite Element (FE) software Marc. The boundary parameters are: density of  $7800\text{kg/m}^3$ , Pos rate of 0.3, supporting stiffness of  $5 \times 10^6 \text{ N/m}$  and Young's modulus of  $2 \times 10^{11} \text{ Pa}$ . The preliminary rotor dynamic analyses for the generator rotor and turbocompressor rotor are illustrated respectively in Fig.3 and Fig.4. The results indicate that it needs to pass four nature frequencies (including two elastics) from the startup to the normal operation speed 250Hz.

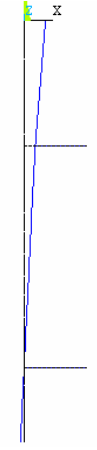
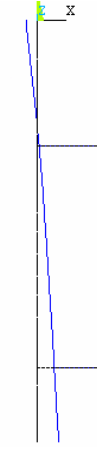

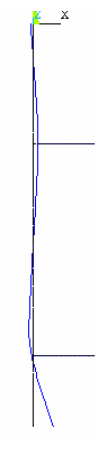
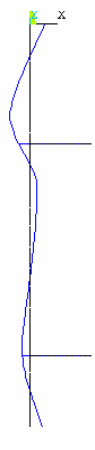
Order	1	2	3	4	5
Mode					
Frequency (Hz)	13.35	19.31	58.65	129.6	327.1

FIGURE 3. Rotor dynamic analysis for the generator rotor

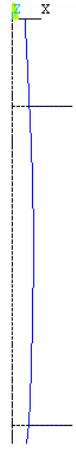

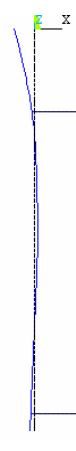

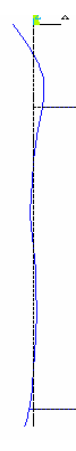
Order	1	2	3	4	5
Mode					
Frequency (Hz)	14.77	25.96	61.87	141.6	345.2

FIGURE 4. Rotor dynamic analysis for the turbocompressor rotor

### 3. EXPERIMENTS

#### 3.1. Experiment Program

As we know that there is no application for the AMB used in the PCU of nuclear power plant, especially for supporting a large vertical flexible rotor and passing two bending critical speeds in operation, serials of experiments step by step are necessary for this project, as well as the theoretical analysis.

First, a small test rig is established to test the control method for flexible rotor and accumulate experience for passing through critical speeds. Then a full size of magnetic bearing with a rigid rotor is constructed to verify the large magnetic bearing design and its characteristics. After the above two experiments are successful, a test rig with a mode-similar rotor to the actual one will set up to find the way of controlling the actual rotor modes. Then a full scale test (1:1) will be performed outside the reactor to validate all the designed properties of the AMB system. Finally, the actual turbomachine rotor system along with the AMB system will be mounted in the PCU vessel of the HTR-10 reactor.

At present, we have already built the former two test rigs and performed a serial of experiments. On the small flexible rotor test rig, we have succeeded passing through the first bending critical speed (BCS). And on the test rig of full size of magnetic bearing, we realized stable suspending and now are preparing the property experiment study. In the follows, these two experimental rigs will be described briefly.

#### 3.2. Small Flexible Rotor Test rig

##### 3.2.1. System Description

The emphasis of this experiment is to study the control arithmetic of how to pass the bending critical speed (BCS) and to provide enough experience for the future turbomachine rotor control. The first BCS is designed as 300Hz, which is higher than that of the actual turbomachine rotor. It is deliberate to increase some difficulty 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 Fig.5 and in Table 2 respectively.

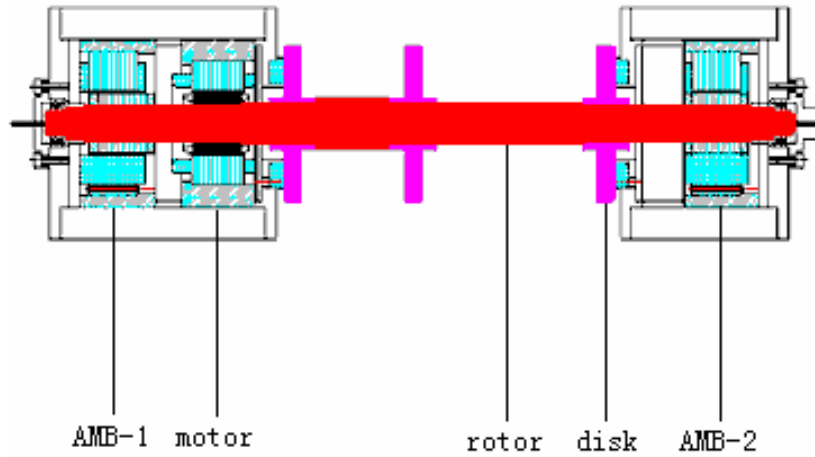


FIGURE 5. The structure of the small setup

TABLE 2. Main parameters of the small setup

Rotor Mass	6.128kg
Rotor Length	613mm
Radial Moment of Inertia	0.148kg m <sup>2</sup>
Polar Moment of Inertia	0.00379kg m <sup>2</sup>
Air Gap	0.4mm
Coils	300n
Pole Area	320mm <sup>2</sup>
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 from the view point of mathematical and control.

### 3.2.2. Model Analysis

The system mathematic model is established by using a method named SDM (Subsection Discrete Method). After splitting the flexible rotor and reduce the order of the model with modal reduction method, a more comfortable model for control is got in space-state form. Fig.6 shows the first six eigen-shapes of the rotor system. From left to right, the four vertical lines respectively represent the lactations of top sensor, top bearing, bottom bearing and bottom sensor.

From Fig.6, it illustrates that the designed system has good observability and controllability for passing through the fist two BCSs.

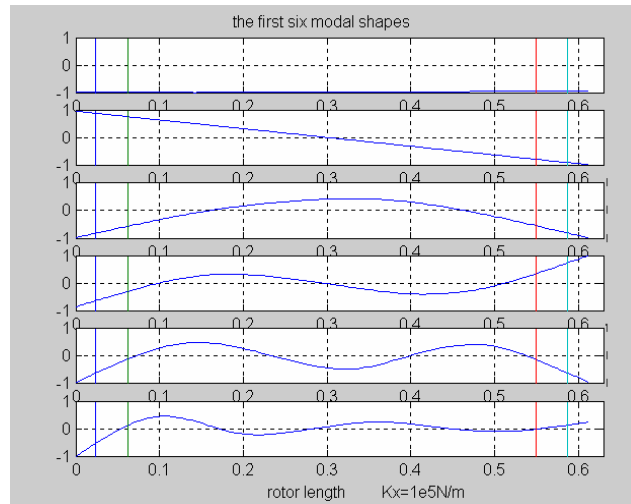


FIGURE 6. Eigen-shapes of the rotor system

### 3.2.3. Control Design

Here a 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. When given  $3 \times 10^4 \text{N/m}$  supported stiffness, the two rigid eigen-frequencies and two lower bending eigen-frequencies are 21.3, 32.3, 303.5 and 706.4 Hz respectively, which are coincident in both theory calculation and actual experiment measurement.

In the actual rotating experiments, it was found that at some special speeds, the rotor amplitude became too large because of 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.

### 3.2.4. Measuring and Monitoring System

An online measuring and monitoring system is built 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 Fig.7.

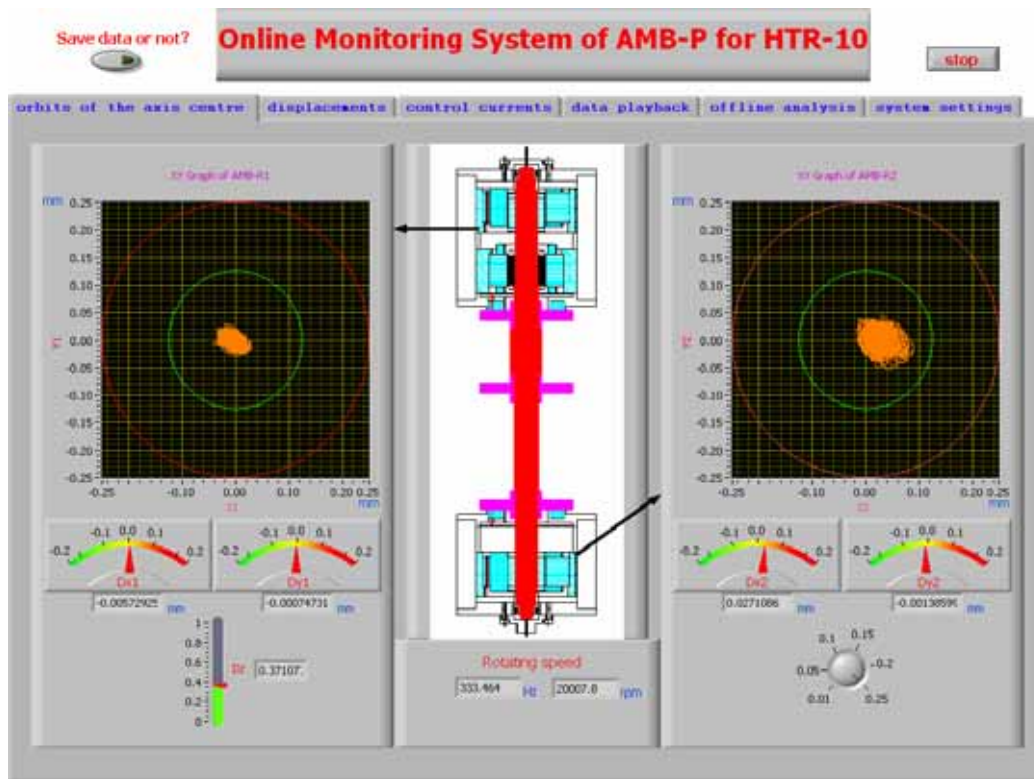


FIGURE 7. Main screen of the measuring and monitoring rotor system

LabVIEW 7 Express, the latest version, has been chosen 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, we can easily and clearly know the operation status including the orbit of the axis centre, the four radial displacement signals and their spectra during its passing the first bending speed.

### 3.2.5. 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. Fig.8 shows the top (x1) and bottom (x2) axis loci and their frequency domain properties in passing through the first BCS.

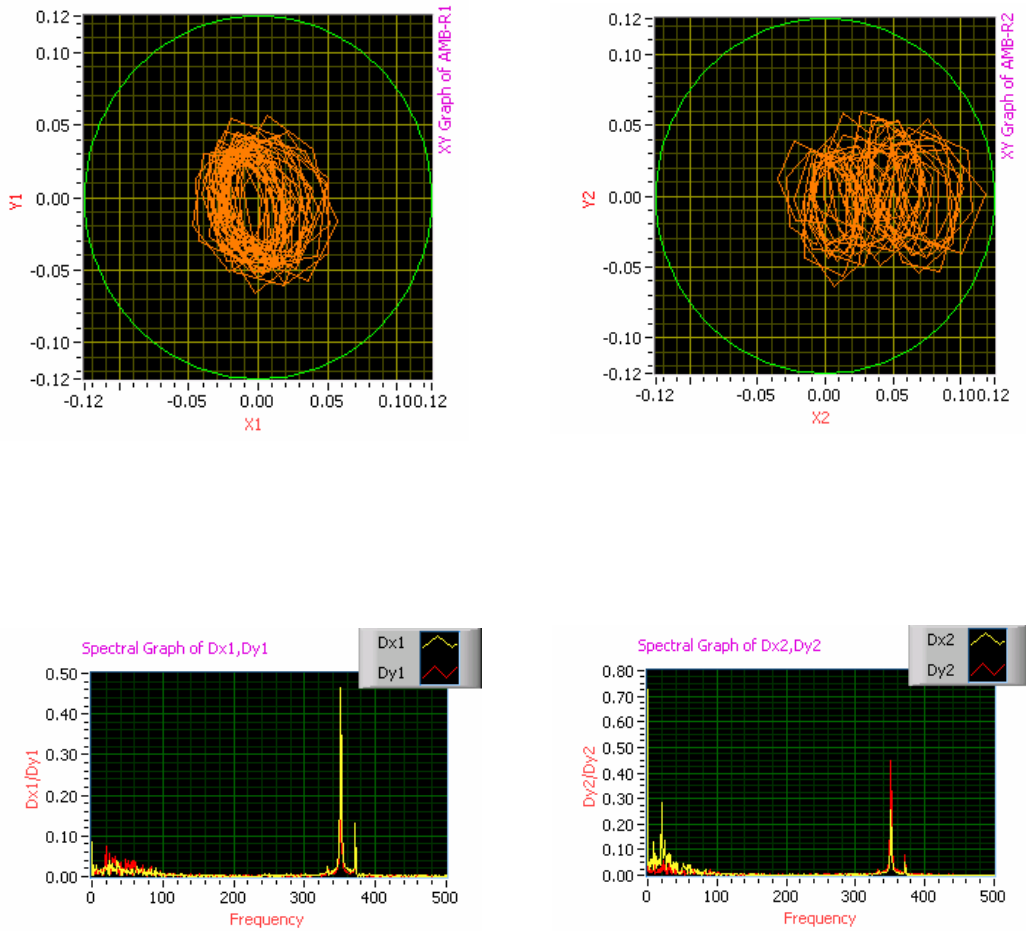


FIGURE 8. Top (x1) and Bottom (x2) axis loci and frequency properties over the first BCS

After passing through the first BCS, the amplitude of the axis loci decreases gradually because of the automatically centering effect. This phenomenon agrees well with the rotor dynamic analysis. Now, the rotating speed approaches 500Hz and the next step is focus on passing through the second BCS of 700Hz.

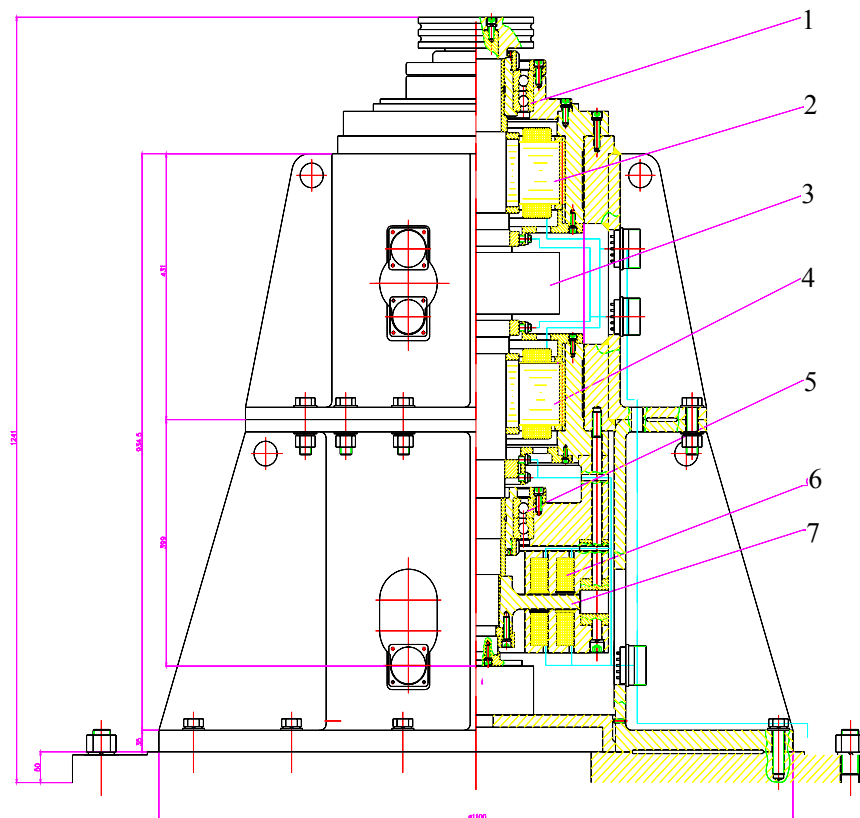
The successful passing through the first BCS verifies that the modeling and control design method is feasible and effective. We also have obtained a lot of experiences in this experiment, which will be certainly useful in the future actual tuning process for the HTR-10GT AMB system.

### 3.3. Full Size Magnetic Bearing Test Rig

#### 3.3.1 System Introduction

This experiment aims to study the actual full size AMB’s characteristics and verify the design process because of our lacking of large AMB design experience. We also want to test the performance the prototype of the power amplifiers and improve them in the next design phase. In order to simplify the other difficulties, a rigid rotor is designed to make our attention to the magnetic bearing itself. The structure layout of this test rig is shown in Fig.9.

A standard industrial control computer with a Pentium 4 CPU of 2GHz is selected as the main controller. The power amplifier is a kind of two H-bridge connecting in serial type with a switching frequency of 60k Hz and total power of 45k VA.



- 1 – upper catcher bearing; 2 – upper radial AMB; 3 – power winding;  
 4 – lower radial AMB; 5 – lower catcher bearing; 6 – axial AMB; 7 – thrust disk

*FIGURE 9. System structure layout of the full size magnetic bearing test rig*

### 3.3.2. Radial Rearing

The radial bearing consists of a stator part and a rotor part, whose structure is illustrated in Fig.9. The stator includes stator casing, magnetic circuit and coils of power winding. These coils form 16 radial oriented electromagnets. Magnetic system of radial bearing is divided into four sectors which ensure rotor positioning in two mutually perpendicular directions (along X and Y axes). Each sector consists of four electromagnets. Rotor part of radial bearing represents cylindrical magnetic circuit made of electric steel sheets and fixed on rotor shaft. The main parameters of the radial bearing are listed in Table 3.

*TABLE 3. Main structure parameters of the radial magnetic bearing*

Parameter	Value
Outer diameter of the stator magnetic circuit, mm	300
Diameter of the stator magnetic circuit bore, mm	150
Axial length of the stator magnetic circuit, mm	100
Number of magnet poles	16
Effective magnetic circuit area, mm <sup>2</sup>	1500
Shaft diameter, mm	105
Number of turns on the pole	100
The wire cross-section square, mm <sup>2</sup>	1.227
Inductance of single coil winding, mH	30

### 3.3.3. Axial Bearing

The axial EMB also consists of a stator and a rotor part, shown in Fig9. The stator includes two annular electromagnets with their pole horns directed towards each other which provide tension force directed along the rotor axis. Each electromagnet represents annular magnetic circuit with concentrically located slots where power windings are put. Each electromagnet has two windings consisting of two identical cylindrical coils located one on another. This double-coil structure can provide a kind of redundancy in case of one single coil failure, because in the vertical layout the whole weight of the rotor is supported by the axial bearing and the safety issue is more serious than the radial bearings.

The rotor part of bearing located between electromagnets represents thrust disk fixed on rotor shaft. To provide accurate alignment of the thrust disk relative to the rotor axis a seating on the conic surface through intermediate sleeve is used. The unit of rotor axial position sensors and radial-axial catcher bearing are installed in the lower part. The main parameters are illustrated in Table 4.

TABLE 4. Main structure parameters of the axial magnetic bearing

0.1.1 Parameter	0.1.2 Value
Outer/interior diameter of the outer pole, mm	364/342
Outer/interior diameter of the middle pole, mm	282/252
Outer/interior diameter of the interior pole, mm	192/170
Effective magnetic circuit area, mm <sup>2</sup>	12600
Disk thickness, mm	23
Number of turns in the coil	300
Wire cross-section area, mm <sup>2</sup>	5.385
Inductance of single coil winding, mH	15

### 3.3.4. Control Design

Due to the rotor is rigid, a decentralized control method in all five-degree are adopted. In each degree of control channel, a single-degree AMB mathematical model is established. Then a PID controller is designed by the help of Matlab software based on the model. The integration saturation effect and anti-noise in high frequency are also considered in the controller design.

### 3.3.5. Experiment

At present, the static suspending experiment is being processing. Because of the exist of the relative large switching power amplifier, electric motor and frequency converter, the sensor's signals are influenced by the above electro magnetic noise. So a filter circuit is designed to improve the signal-to-noise performance. The suspending experiment at small bias working current is almost completed. We succeed in realizing all five-degree suspension of the full size large AMB system, which is the basis of the further characteristic experiment. Next, we will increase the bias current and prepare the experiment of measuring the properties of the AMB, including the stiffness, force-current coefficient, force-displacement coefficient, maximum bearing force and so on.

## 4. 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. The AMB is the key important system to support the turbomachine rotor in the PCU. The design characteristics and related experiments of the AMB are introduced in this paper. From the experiment results, we have mastered the method and achieved some experience of passing through the bending critical speed, and we have also preliminarily designed and realized a full size AMB suspension. The further design and experiments are being carried out continuously till the whole PCU system installed in the HTR-10 reactor around the year of

2006.

Generally speaking, if the state-of-the-art AMBs are successfully used in the HTR-10GT and bring the concept to realization, it can be predicted that the application of the AMBs in the design of the HTRs coupled with direct gas-turbine will become largely conventional in the future. The experience obtained from other industrial applications that magnetic bearings can increase availability and reduce O&M costs will also be validated in the HTRs.

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