Technical Design of Active Magnetic Bearings for the Helium Turbomachine of HTR-10GT

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Abstract: The high temperature gas-cooled reactor (HTGR) coupled with gas turbine cycle is considered as one of the leading candidates for future nuclear power plants. The gas turbine cycle will also play an important role in the six GIV nuclear reactor systems as energy conversion system. The 10MW high temperature gas-cooled test reactor coupled with gas-turbine circle (HTR-10GT) has been carried out by the Institute of Nuclear and New Energy Technology (INET) of Tsinghua University in China since year 2002. In the power convention unit (PCU) of the HTR-10GT, the contact-free and no-lubricating active magnetic bearings (AMB) are adopted to support the vertical high-speed helium turbomachine shaft, because of their numerous advantages over the conventional oil mechanical bearings under the special reactor operating conditions. Based on the previous studie, the final engineering design of helium turbomachine and the AMBs for the HTR-10GT have been finished recently. This paper firstly introduces the design principle and technical futures of the AMBs. Then the main structure, as well as the key dimensions and parameters of the different helium turbomachine and AMB components are illustrated in detail. Further more, the load capacity of AMB and the rotor dynamics of helium turbomachine draft are analysized.

Keywords: Active Magnetic Bearings, Helium Turbomachine, HTR-10GT, Load Capacity

Introduction

The 10MW high temperature gas-cooled reactor (HTR-10) is one of the Chinese National High Technology Projects, which is designed by Institute of Nuclear Energy Technology, Tsinghua University. HTR-10 reached its first criticality in 2000, and begun its full power operation in 2003 [1]. Based on the success of the HTR-10, a helium turbomachine generator system coupled with HTR-10 denoted by HTR-10GT was launched to demonstrate the feasibility of the HTGR gas turbine technology [2].

The 10MW high temperature gas-cooled test reactor coupled with gas turbine circle (HTR-10GT) is considered as one of the most important development fields of the future HTR technology due to its simple system, high efficiency and potential economical competitiveness [3]. In the power convention unit (PCU) of the HTR-10GT, the contact-free and no-lubricating active magnetic bearings (AMB) are exclusively adopted to support the vertical high-speed helium turbomachine shaft [4], because of their numerous advantages over the conventional oil mechanical bearings under the special reactor operating conditions [5]. However, at present, no experience on helium turbomachine with AMB equipment running in the HTR system of helium environment, especially for the large flexible PCU rotors, has been performed actually. Therefore, the design and experiment of high performance helium turbomachine with AMB as well as high reliability and safety are very important for the HTR engineering applications.

The performances of AMB affect the layout of gas turbine system related with safety and economics of the nuclear power plant. Based on the previous studies and small tests of the AMBs [6], the final engineering design of the AMBs for the HTR-10GT helium turbomachine rotor has been finished by the INET recently. In this paper, the design principle and technical futures of the AMBs will be briefly introduced. Then the main structure, as well as the key dimensions and electrical parameters of the different helium turbomachine and AMB components will be illustrated in detail. Besides, the rotor dynamic analysis will be conducted to provide the mathematic model for the unbalance attenuation with high performance control system design in order to smoothly pass the first two bending critical speeds before reaching the rated speed, which is deemed as the most challenge for the large vertical flexible AMB suspending rotors in the HTR-10GT project.

PCU Structure Layout

The helium turbomachine composed of turbine, low pressure compressors (LPC) and high pressure compressors (HPC) is the most important component of power conversion system in HTR-10GT since it provides driving force for helium flow as circulator and drives the shaft rotating to generate power by compression and expansion process. Therefore, its performance is directly related to the overall system effectiveness and economy.

The turbine and compressor rotor, with a length of 3.5 m and a weight of 540 kg, is designed to be running at a rated rotation speed of 15,000r/min. The layout of the AMB units for the turbine and compressor is illustrated in Fig.1. As for the generator rotor, its length and weight are about 4.6 m and 3500 kg respectively, and its rotation speed is 3000 r/min. Each rotor has two radial AMBs and one axial AMB to perform the suspension function under different operating load conditions. Besides, there are catcher bearings to ensure rotor safely touch-down when AMBs fail to work or the dynamic loads exceeding the designed AMB capacity during operations.

The AMB system is divided into elements inside the PCU and elements outside the PCU. The electromagnets and sensors, as well as high-temperature cables, are located in the PCU, while the AMB control system equipments are located in the operating room, including the controller facilities, power modules and online monitoring system.

In the design of AMB system, a serial of challenges must be overcome in order to ensure the reliability and stability during the reactor start up, power change and shutdown for the future engineering application, such as high speed to exceed two natural bending frequencies, high temperature environment (about 350 °C), high load-carrying capacity, and so on.

The following sections will focus on the discussion of the design and test of the helium turbomachine AMBs, which is the one of the biggest challenges in the HTR-10GT project.

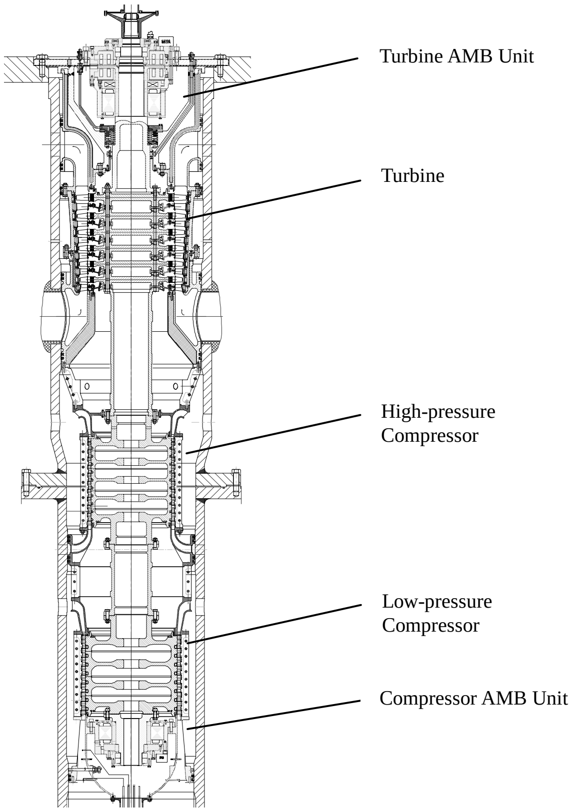


Fig. 1: Layout of the helium turbomachine unit.

Technical Design Characteristic

General System Requirements: Besides the common industry standards, e.g., API 617, IEC and ISO900X, the development of the AMB system shall also take into account the following design requirements:

(1)Take up radial and axial loads as well as providing stabilized supporting of the helium turbomachine rotor in operations.

(2)Ensure the rotor stable working in all operation cases (including passing natural bending critical speeds).

(3)Reliably operate for a long time in gas atmosphere under conditions of high speeds, temperatures and radiation at minimum loss of friction and power consumption.

(4)Ensure reliable control over AMB system in all normal, abnormal operation modes and during design-basis accidents.

Turbine AMB Unit: Turbine is a turbomachine which can convert the thermal energy of working medium to mechanical energy. Considering the requirement of HTR-10GT, the aerodynamic design and structure design of turbine were finished. The configuration of turbine is illustrated in Fig.2. The turbine of HTR-10GT was designed to have 6 stages with equal inner diameter. Some aerodynamic design results are shown in Fig.3.

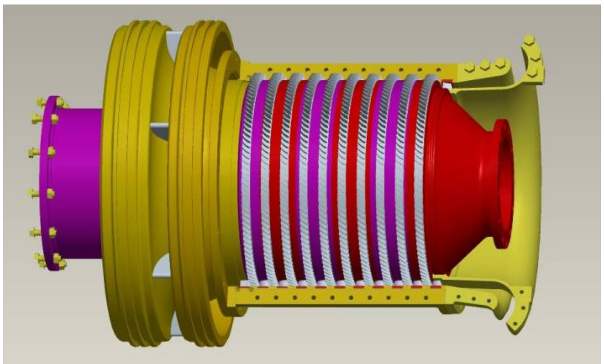


Fig.2 The Configuration of Turbine

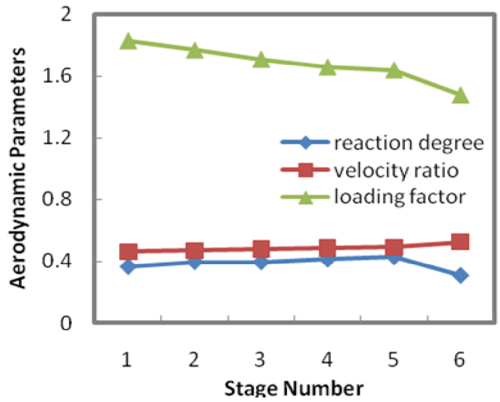


Fig.3 The reaction degree, velocity ratio, loading factor for turbine

The turbine AMB unit is located at the top of the turbine rotor, which can perform the suspension functions in axial and radial directions. The main elements of the turbine AMB unit include the radial and axial AMBs, position sensors, speed sensors, catcher bearings, and so on, shown in Fig.4. The main parameters of the magnetic bearings are listed in Table 1.

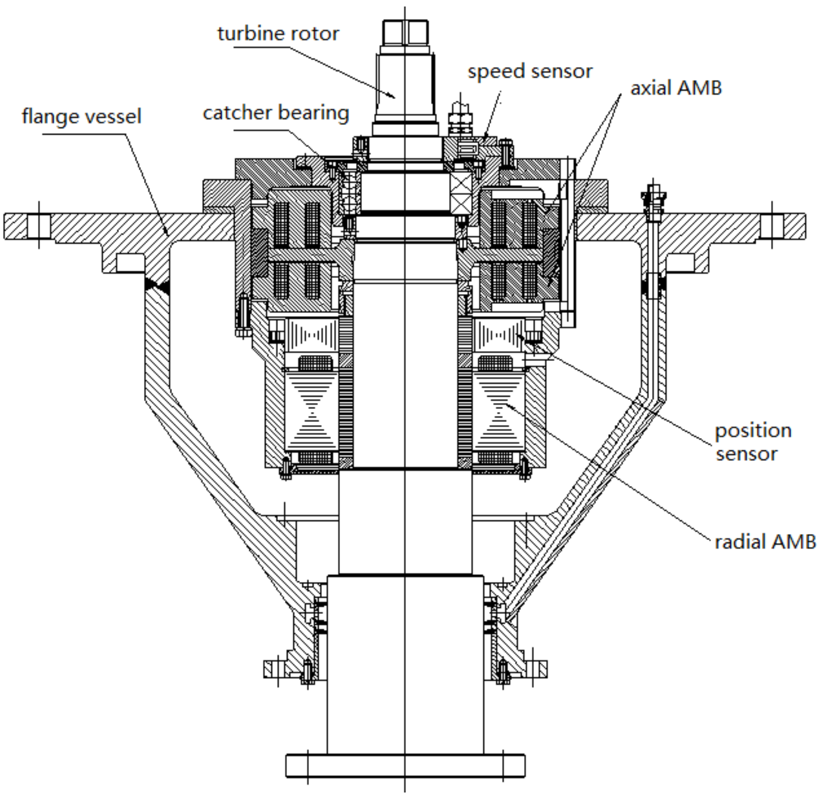


Fig. 4: Structure of the turbine AMB unit.

The axial AMB consists of a stator and a thrust disk, which is situated at the upper part of the turbine rotor. The stator includes two annular electromagnets with their pole horns directed towards each other and provide tension force directed along the rotor axis. Each electromagnet represents annular magnetic circuit with concentrically located slots where power windings are put. In the vertical layout the whole weight of the rotor is supported by the axial AMB, so the designed lifting capacity is 9800 N and the axial gap is 0.7mm. The rotor part of the axial AMB located between electromagnets represents thrust disk fixed on the rotor.

Table 1: Main parameters of the AMBs

Parameter	Value
Radial electromagnetic bearing	
Designed lifting capacity, [N]	1960
Interior / outer diameter of stator magnetic circuit [mm]	150 / 270
Effective axial length, [mm]	90
Maximum current, [A]	30
Diameter of the rotor, [mm]	118
Number of coil turns for one pole	30
Radial gap between bearing and rotor,[mm]	0.6
Radial gap between catcher bearing and rotor,[mm]	0.15
Axial electromagnetic bearing	
Designed lifting capacity, [N]	9800
Interior / outer diameter of stator magnetic circuit, [mm]	168 /308
Maximum current, [A]	30
Number of oil turns	80
Radial gap between bearing and rotor, [mm]	0.7
Radial gap between catcher bearing and rotor,[mm]	0.3

The radial AMB, adopted a kind of 16 poles structure with a designed capacity of 1960 N, consists of a stator part and a rotor part. The stator includes the stator casing, magnetic circuit and coils of power winding. These coils form 16 radial oriented electromagnets. The magnetic system of radial bearing is divided into 4 sectors which ensure rotor positioning in two mutually perpendicular directions (along X and Y axes). Each sector consists of 4 electromagnets. The rotor part of radial AMB represents cylindrical magnetic circuit made of electric steel sheets and fixed on the rotor shaft.

The radial gap for the radial catcher bearing is designed as 0.15 mm considering the gap of 0.4 mm between the compressor stator and blades in order to protect the compressor, while the radial gap of the radial AMB is set as 0.6 mm.

The position sensors are of induction type, which has good sensitivity of no less than 10mV/μm and resolution of at least 1μm. 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.

Compressor AMB Unit: According to the requirement of HTR-10GT, the aerodynamic design and structure design of turbine were finished. The configuration of compressor is illustrated in Fig.5.

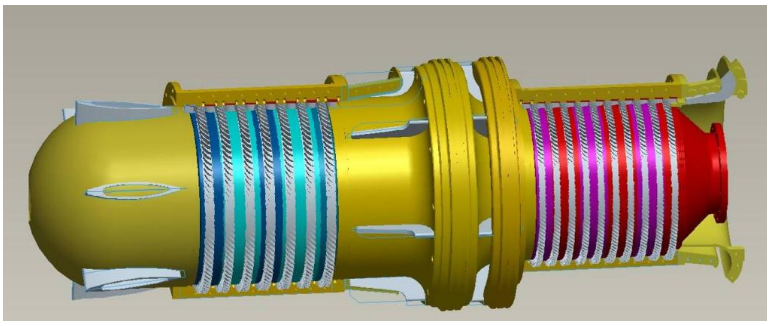
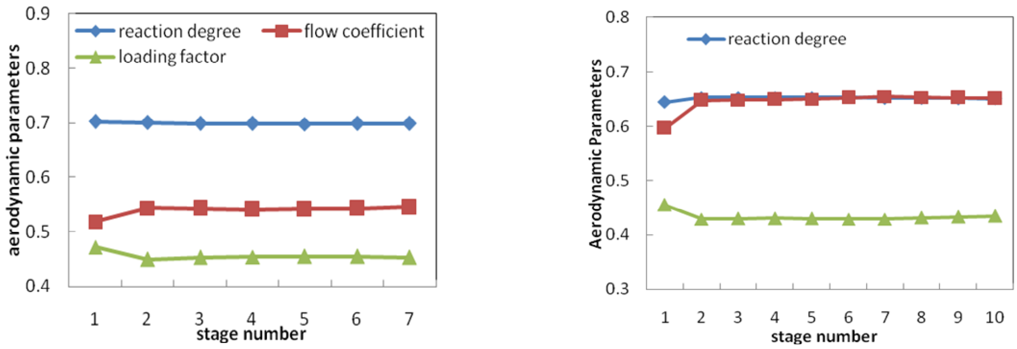


Fig.5 The Configuration of Comprssor

The low pressure compressors and high pressure compressors had 7 stages and 10 stages respectively, with equal inner diameter and modeling-designed. Some design results are shown in Fig.6.



LPC HPC

Fig.6 The reaction degree, flow coefficient, loading factor of different stage for compressors

The compressor AMB unit is settled at the bottom of the compressor rotor, which can provide the radial supporting. Therefore, compared with the turbine unit, its structure is less completive, only consisting of the radial AMB, position sensors and catcher bearings, shown in Fig.7.

The interior and outer diameters of the compressor AMB stator are designed as 180 mm and 300 mm respectively due to the space considerations, which are larger than the turbine ones. However, the other designed parameters, such as the radial lifting capacity, the gaps, the pole structure as well as the catcher bearings and sensors are identical to the turbine ones.

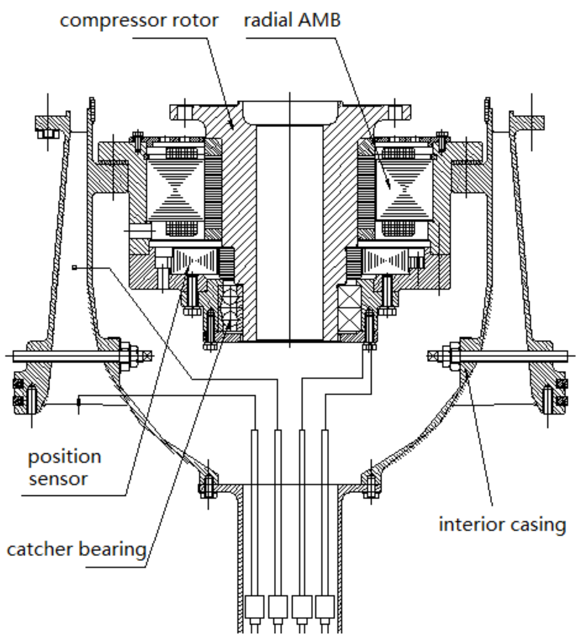


Fig. 7: Structure of the compressor AMB unit.

Other Components: The AMB controller, 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. The new dual-core product of TI OMAP-L138 integrates one 300MHz 320C674x DSP core with a powerful floating-point operation of 1800 MFLOPS and one 300MHz ARM926 MPU core, which can be adopted as the ideal micro processor of the AMB 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 operating and monitoring computers (host) lies on the high level control channel, whose type is standard PXI industry computer and its operation system is universal MS Windows. The new typical configuration of the host computer can select the Intel CPU of Core 2 Duo T7500 with two cores of 2.2GHz. The communication between controller and host computer is based on industry network.

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 9 kVA (300V, 30A), switch amplifier is the best type considering the losses and efficiency.

There are some other auxiliary components, such as the main power supply, UPS for backup power source, cables and penetrating connectors. Due to space limitation, they won't be introduced detailed in this paper.

Electromagnetic properties

The electromagnetic analysis for the AMBs was carried out by the help of the Finite Element Method Magnetics (FEMM) software, which is a suite of programs for solving low-frequency electromagnetic problems on two-dimensional axisymmetric and planar domains.
The electromagnetic forces of the axial and radial AMBs according to the currents at the normal gaps are shown in Fig. 8. It can be seen that the maximum lifting capacity of the axial AMB is about 18000 N with a margin of 80% more than the designed value of 9800 N. As for the radial AMB, the maximum electromagnetic force is approx. 4500 N, which is more than 120 % of the designed value of 1960 N. Therefore, there are enough capacities for the AMBs to deal with different load variations during the system operation.

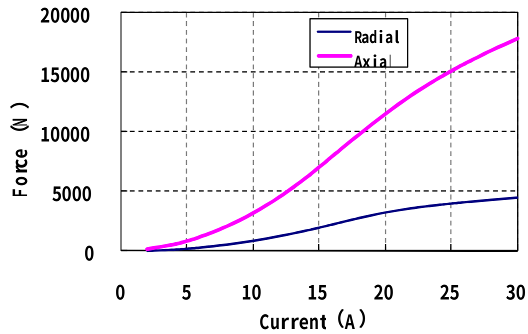


Fig. 8: Load capacity of AMBs at normal gap

Rotor dynamics

The rotor dynamics calculation result shows that the designed turbine and compressors rotor would exceed two bending frequency before reaching the rated speed of 250 Hz. Fig.9 shows the corresponding modal shapes, and Table 2 lists the natural frequencies.

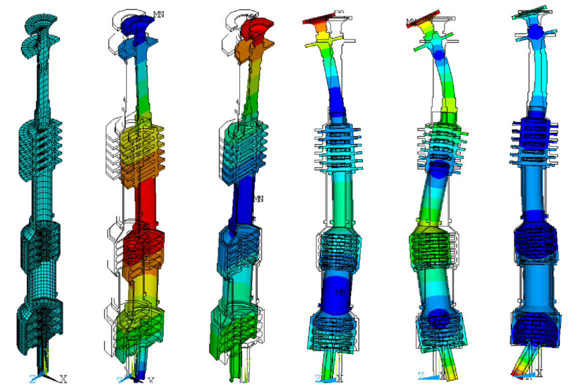


Fig. 9: Modal shapes of the turbine rotor

Table 2: Natural frequencies of turbine rotor (Hz)

Natural frequency	Value
Parallel frequency	17
Tilting frequency	32
1st bending frequency	70
2nd bending frequency	191
3rd bending frequency	302

Conclusions

HTR-10GT is a pebble-bed high temperature gas-cooled test reactor together with direct gas turbine designed and built by the INET in China. Active magnetic bearings are considered as one of the key systems to support the helium turbomachine rotor in the PCU. The technical design characteristics of the HTR-10GT helium turbomachine and its AMBs are discussed detailed in this paper. Then the main structure, as well as the key dimensions and parameters of different helium turbomachine and AMB components are illustrated in detail. Further more, the load capacity of AMB and the rotor dynamics of helium turbomachine draft are analysized.

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