Study of Active Magnetic bearing for Helium Circulator in HTR-10

Sun Zhuo，Shi Zhengang，Xu Yang，Zhao Lei
Institute of Nuclear and New Energy Technology, Tsinghua University，Beijing, China

ABSTRACT

Helium circulator is a key equipment in the 10MW high temperature gas-cooled reactor (HTR-10). It is installed in pressure shell and the driving motor of circulator operates at 0.1MPa, 65℃ helium condition. Under that condition it is difficult to lubricate and maintenance the bearings. So the active magnetic bearings (AMBs) used in helium circulator are studied. The AMBs are controlled by a 32-bits digital signal processor (DSP) and a switching-type power amplifier. The experimental results of long-term operating, cold condition operating and high temperature operating with full load prove that the AMBs meet the requirements of HTR-10 very well. The helium circulator will be the first AMBs equipment servicing in nuclear reactor in China.

INTRODUCTION

The 10MW high temperature gas-cooled reactor of Tsinghua University (HTR-10) is a new generation of reactor with good inherent security feature. HTR-10 takes the entire ceramic covered granule as the fuel element, the graphite as moderator and the reactor core structural material, and the helium as the cooling agent. The main helium circulator is installed in primary circulate, as the power supply to drive the helium flowing in the reactor internal recycling. The thermal energy of reactor core is carried out by helium to heat up the evaporator, and then the steam drives steam turbine generating set to generate electricity.

The helium circulator impeller works in 3.0MPa, 250 ℃ helium environment, and the driving motor of impeller works in 0.1MPa, 65 ℃ helium environment. Because it’s forbidden to use volatile lubricant, and it is difficult to maintenance the bearings after the helium circulator is installed in the primary circulate of reactor, lubrication of circulator bearings is an important cause to reduce the safety and the service life of high temperature gas-cooled reactor. In HTR-10 the grease lubricated ball bearings meets the requirements of helium circulator because HTR-10 is an experimental reactor and the design service life is short. But in future, new type bearings have to be adopted in helium circulator to guarantee the long service life of the commercial high temperature gas-cooled reactor nuclear power plant.

The active magnetic bearings (AMBs) are one kind of non-contact type bearings, the shaft is suspended in the magnetic field of AMBs and the movement of shaft is controlled accurately by AMBs. Because there is no mechanical wear, AMBs don’t need lubricant and maintenance. Moreover AMBs has long service life for the same reason. So AMBs are suitable for high temperature gas-cooled reactor.

In order to accumulate experiences for application of AMBs in the future commercial high temperature gas-cooled reactor nuclear power plant, the ball bearings of the helium circulator will be replaced by AMBs in the HTR-10 second-stage project.

STRUTURE OF THE HELIUM CIRCULATOR

The outline dimensions of the new helium circulator with AMBs are similar to original circulator, only bearing areas were redesigned, convenient for replacing between two circulators. Structure of the new helium circulator with AMBs is shown in fig.1.

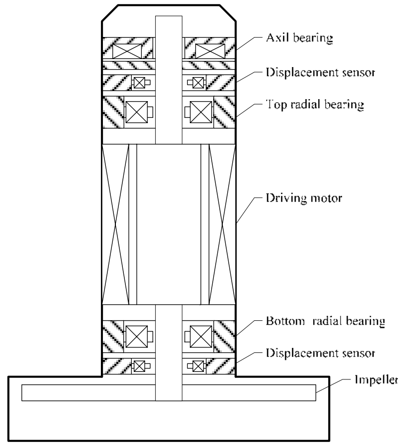


Fig.1 Schematic of the helium circulator structure

The helium circulator is the vertical structure, and the impeller is installed in bottom. The rotor of asynchronous motor is installed in the middle of shaft and the stator is installed on the shell of circulator. The total mass of shaft and the impeller is about 400kg. A labyrinth and a thermal insulation layer are settled between the impeller and the motor, preventing the high temperature gas around the impeller damaging the AMBs. Fig.1 is a schematic drawing of the helium circulator, so the labyrinth and the thermal insulation layer are not shown.

The AMBs are composed of mechanical structure part and the electrical control part. The mechanical structure part mainly includes the stator, the rotor of AMBs and the auxiliary bearings. The electrical control part mainly includes displacement sensors, controller and the amplifier.

As revolving, the shaft of helium circulator is suspended by AMBs. Only when the helium circulator stops rotating and the power supply of AMBs is switched off, the shaft of helium circulator falls on the auxiliary bearings. The auxiliary bearings are ceramic ball bearings. When AMBs are working normally, the auxiliary bearings keep static and have no load, therefore the auxiliary bearings have no lubricant.

The AMBs are divided into three components. From top to bottom in turn they are axial bearing, the top radial bearing and the bottom radial bearing. An axial bearing control the axial degree of freedom, the top radial bearing control the upper shaft two radial degrees of freedom, and the bottom radial bearing control the lower shaft two degrees radial of freedom, so the shaft is suspended 5 degrees of freedom.

The displacement sensors of AMBs are divided into two groups and are separately installed beside the top and bottom radial bearings. The top group of sensors measure radial and axial displacement, and bottom group of sensors measure the radial displacement of the lower extremity shaft. Sensors are inductive type differential displacement transmitters, having the merits of high sensitivity and strong anti-interference ability.

THE CONTROLLER OF AMBS

From the values of shaft displacements, the controller of AMBs calculates the coil current values which keep the shaft suspending and controls the power amplifier to output correct coil currents. So the movement of shaft is controlled by controlling the coil currents. The controller is a digital control system which is mainly composed by 3 parts: sensor excitation sources, demodulating circuits and the digital signal processor (DSP) circuits. The sensors are inductive type differential displacement transmitters, basic principle is shown in fig.2.

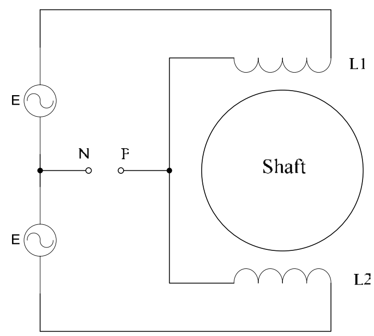


Fig.2 Principle of inductive type differential displacement sensor

In fig.2, E represents the excitation sources and L1, L2 are sensor's coils. The coils are inductors in fact, and the shaft is the iron core of inductor. Therefore the movement of shaft up-and-down between the two coils shown in fig.2 just likes the iron core moving up-and-down in the two inductors, so one inductance value of L1 and L2 increase and the other decrease, the voltage between points P and N varies consequently.

The voltage between points P and N is denoted by U_{PN}, then the varying of U_{PN} corresponds to the varying of shaft displacement. The voltage peak-to-peak value and the frequency of E are constant, therefore the frequency of U_{PN} is constant, but the voltage peak-to-peak value of U_{PN} varies along with the displacement of shaft. Thus the displacement signals output by sensors are amplitude modulation (AM) signals, and the displacement of shaft can be measured by demodulating the AM signals. The expression of U_{PN} is:

$$U_{PN} = \frac{L1 - L2}{L1 + L2} E \qquad (1)$$

When the shaft moves in a certain distance, the inductance value (L1+L2) keep constant approximately, therefore only the difference inductance value (L1-L2) determines U_{PN}. So the sensor shown in fig.2 is a differential displacement sensor.

The function of demodulating circuits is to demodulate U_{PN} to obtain the displacement signal.

DSP circuits are composed of DSP processor, A/D converter, memory, D/A converter, power management circuit and other periphery circuit. The DSP processor is TI Corporation's TMS320VC33, which is one kind of 32-bits floating point digital signal processor and its operating speed may achieve 150MFLOPS. The program may be written in C programming language for the high speed of DSP, convenient for realizing and debugging AMBs' algorithm.

THE POWER AMPLIFIER OF AMBS

The coil current values are calculated by DSP and then amplified by power amplifier. So the function of power amplifier is generating coil currents to control the displacement of shaft according to the computing results of DSP.

Efficiency, output current ripple and response speed are main performance index of a power amplifier. The linear power amplifier has the merits of quick response speed, small current ripple, but its efficiency is very low. So linear power amplifier is suitable for low output power situation. The switching type power amplifier has bigger output current ripple, but the efficiency may exceed 90%, so switching type power amplifier is suitable for high output power situation.

The power amplifier of helium circulator AMBs outputs 15A maximum current. Thus switch type is the only choice. In order to increase response speed, the power amplifier uses unipolarity bridge type main circuit, and uses direct current feedback control method. The main circuit structure of power amplifier is shown in fig.3.

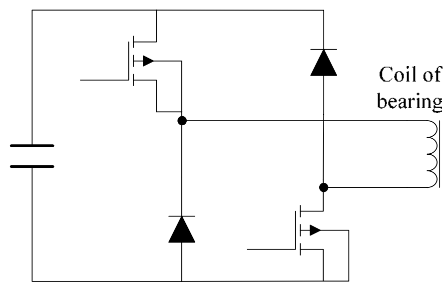


Fig.3 Main circuit structure of power amplifier

CONTROL OF AMBS

When the rotor of circulator is suspended, the magnetic force produced by some direction AMBs' coil is the function of displacement in this direction and the current in coil. Around the operating point the magnetic force could be linearized as [3,4]:

$$f(x,i) = k_s x + k_i i \qquad (2)$$

where, x is displacement; i is the current in coil; k_s is force-displacement coefficient; k_i is force-current coefficient.

Taking the current as control object, the mathematical model of single freedom degree controller is:

$$i(x) = -\frac{(k+k_s)x + d\dot{x}}{k_i} = K_p x + K_d \dot{x} \qquad (3)$$

where, k is the stiffness; d is the damping; $\dot{x} = \frac{dx}{dt}$ is the derivative of displacement; $K_p = -\frac{k+k_s}{k_i}$ is the proportional coefficient; $K_d = -\frac{d}{k_i}$ is differential coefficient.

Eq.(3) shows that the linearized controller of AMBs is a proportion - differential (PD) controller. In order to eliminate the steady-state error, an integral component is added to the controller, so the linearized model of AMBs is a PID controller.

In eq.(3) , k_s 、 k_i are determined by structure parameters such as magnetic pole area, turn number, gas length which were settled already in the design stage. The parameters of the PID controller should be calculated according to the stiffness, damping, and response speed of helium circulator.

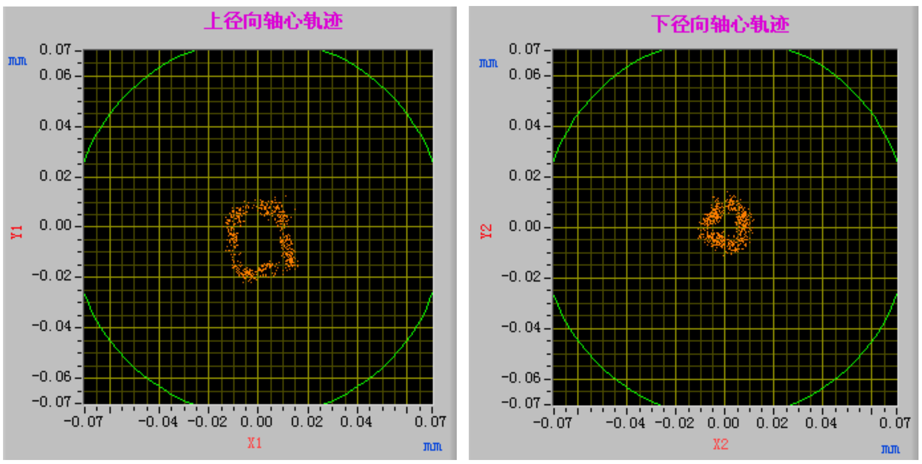
EXPERIMENTAL RESULTS

There is no precedent for AMBs applied in nuclear power plants of China, so the performance of AMBs has to be confirmed by a series of experiments before the helium circulator is installed in HTR-10. Main experiments include long-term operation experiment, insulation test, cold condition operation experiment and high temperature state experiment.

The insulation test is to check the insulation of the sensor coils, bearing coils and cables of AMBs. The helium circulator works in the helium environment, so the insulation test has to be operated in same helium environment.

After the insulation test, the long-term operation experiment was done for helium circulator. The circulator was installed in air environment to rotate 15 days at highest rotational speed continuously. The AMBs were stable and has not appeared any breakdown.

The cold condition experiment was done in the air, and the temperature around the circulator impeller was maintained below 60℃ by a water cooler when the helium circulator worked with full load. The cold condition experiment is to analyze the performance of AMBs under full load condition. In the experiment, the impeller of helium circulator was installed in a simulation closed circuit, and the driving motor, the AMBs are outside. Adjusting the wind resistance of the circuit, the load of helium circulator can be adjusted. When the helium circulator rotational speed achieved the rated highest rotational speed 5,100 rpm, the circulator power achieved the rated maximum power 160kW. The trace of shaft is shown in fig.4.



(a) Trace of upside shaft (b) trace of downside shaft

Fig.4 Trace of shaft

From fig.4 it is shown that the biggest displacement of shaft is no more than 0.02mm when helium circulator operating at highest rotational speed and full load condition. The distance between the auxiliary bearings and surface of the shaft is 0.15mm, therefore the shaft and the auxiliary bearings have not contacted, the shaft is at the suspended state.

The simulation circuit of high temperature state experiment is same to the cold condition experiment's. Reducing the water flow of the cooler, the simulation circuit is heated up to 250 ℃ by the impeller of helium circulator. The AMBs and the driving motor of helium circulator are outside the simulation circuit and their temperature is room temperature. Adjusting the wind resistance of simulation circuit, the helium circulator power achieved the rated maximum power 160kW when the rotational speed achieved the rated highest rotational speed 5,100 rpm. The Trace of shaft is same to Fig.4 in high temperature state experiment.

CONCLUSION

There is no precedent for AMBs applied in nuclear power plants of China, so the performance of AMBs has to be confirmed by cold condition experiment, high temperature state experiment, long-term operation inspection experiment and other experiments before the helium circulator is installed in HTR-10. The experimental results prove that the active magnetic bearings developed by institute of nuclear and new energy technology, Tsinghua university (INET) meet the requirements of HTR-10 very well. The helium circulator of HTR-10 will be the first AMBs equipment servicing in nuclear power plant in China.

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