DEVELOPMENT OF MAGNETIC BEARINGS FOR HIGH TEMPERATURE SUSPENSION [1]

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ABSTRACT
The application of active magnetic bearings (AMBs) for gas turbines and aircraft engines would open large potentials for novel design. In order to utilize the full advantages of active magnetic bearings, operation in gas turbine and aircraft engines requires that the magnetic bearing should work properly at high temperatures up to 550°C. This paper deals with the active magnetic bearing design for high temperatures, including the investigation on material evaluation, manufacturing process and high temperature displacement sensor development. Two test rigs have been built up to demonstrate the feasibility of using active magnetic bearings at high temperatures.

INTRODUCTION
High temperature active magnetic bearings (HT AMBs) offer the potential to replace conventional bearings and oil lubricated systems in gas turbines and aircraft engines. HT AMBs have the following advantages: [1]

- **Expected Potential for Significant Improvement in Performance of the Engines**

The current configuration of aero-engines has already reached a relatively advanced state of maturity and performance. Further significant improvements in performance can only be expected by introducing novel components which will lead to major changes in the design concepts. AMB technology offers this opportunity.

- **Reduced Weight**

Conventional oil-lubricated rolling element bearings have been used in aircraft engines for many years. They require an oil supply and scavenging system, as well as cooling systems. As AMBs don't need any lubricant, these systems can be eliminated, which results in a large decrement of the weight for the engines. About 10-15% of reduced weight is expected to be achieved for a large engine.

- **More Compact Design**

The working temperature of conventional oil lubricated bearings is limited to 150°C. Therefore, they have to be mounted remote from the hot part of the engine. Instead, AMBs working at high temperatures can be placed closer to the combustion chamber or turbine, which means a more compact design.

- **Increased Reliability and Safety**

In conventional aircraft engines, oil and oil mist are fire hazards. If the rolling element bearings can be replaced by AMBs, the removal of oil would significantly reduce the chances of fire due to spillage, fatigue failures or poor joints. Also the oil-lubricated bearings require labyrinth seals to stop oil migration, and the seals may cause instability of the rotor. The multiple redundant sensors and bearing coils can be integrated into AMBs, which means that any failure of a sensor or bearing coil is no longer critical. Furthermore, the feedback signals within the AMBs can be used to monitor the health of the engine during the flight. All of these would considerably increase the reliability and safety of the engines.

- **Good Rotordynamic Performance**

The maximum DN number of oil-lubricated bearing is only about 1.5 millions (mm-rev./min), it limits the

[1] The research is supported by EU BRITE project AMBIT (Active Magnetic Bearings in Aircraft Turbo-Machinery)
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shaft diameter especially for big fan engines and small high-speed turbines. The DN number of AMB could be as high as 4.5 millions which allows a large shaft diameter. The large shaft diameter and the repositioning of the bearings could greatly improve the rotordynamic performances at high speeds.

- **Increased Efficiency**

A large shaft diameter and high speed allows an increased transmission of torque and power.

- **Increased Efficiency**

With the ability of AMBs of working at high temperatures, the need for cooling air is reduced and the system may be able to run without any cooling system at all. In addition, the feedback controller of AMB could be adapted to minimize seal clearances. With less cooling air and the minimization of seal clearances the efficiency of the engines can be increased.

- **Increased Maintenance Intervals**

AMBs offer contact free support of the rotor system. The elimination of mechanical contact and lubrication system will significantly increase maintenance intervals.

- **State of the Art**

Some institutions in USA[2-5] and Japan[6] have been engaged in the high temperature active magnetic bearings development. Currently the investigation is still limited to the laboratory stage. The research presented in this paper is a part of the AMBIT project (Active Magnetic Bearings in Aircraft Turbo-Machinery) sponsored by European Community. The primary objective of the project is to explore the problems and benefits of using AMB in aero-engines.

- **Objectives**

The main objective of this paper is to give AMBs the ability to work at much higher temperatures than conventional bearings (up to 550°C for this project). An eddy-current displacement sensor is developed to measure the rotor displacement in which a new temperature compensation method is used to satisfy the special requirements at high temperatures. The sensitivity of the sensor decreases only about 7.4% at 550°C compared with that at room temperature. Two test rigs have been built to demonstrate the possibility of AMB working at high temperatures. One is a magnetic bearing system with one degree of freedom, in which the AMB and sensors have worked at 550°C for more than 100 hours and up to 710°C for 4 hours without any damages. The other test rig is a five degrees of freedom magnetic bearing system, which is a complete rotordynamic test facility and capable of speeds up to 20,000r/min and temperatures up to 550°C.

HT DISPLACEMENT SENSOR DEVELOPMENT

Contact free displacement measuring is a significant challenge for the application of high temperature AMBs such as in aircraft engines. So far inductance sensors[1,2], capacitance sensors[3], flux sensors[4] and sensorless method[5] have been successfully used in some high temperature magnetic bearing applications. No reports have been found about the application of eddy-current sensors in this field.

Temperature Compensation Technique

It is common that the resistance of the sensor coil increases at high temperatures, which is the main reason for a large decrement in the sensitivity of the sensor. For instance, the sensitivity of an eddy-current sensor decreases about 13.5% and 31.4% at 350°C and 550°C compared with that at room temperature, respectively. If the sensitivity of the sensor changes so large, it will result in a large decrement of the dynamic performance of the control system, and even serious instability problems.

A new method that uses eddy-current to compensate temperature effect has been applied to satisfy the special requirements at high temperatures up to 550°C[7]. The test results of the sensitivity at different temperatures are shown in Figure 1. As shown in the figure, the sensitivity of the sensor with temperature compensation only decreases 7.4% at 550°C compared with that at room temperature, and the sensor exhibits a good linearity over the whole measuring range. The temperature drift is only about 90mV (sensitivity=7.8mV/μm) from room temperature to 550°C. The maximum position disagreement over the whole temperature range is less than 12μm, which is very acceptable for normal AMB applications.

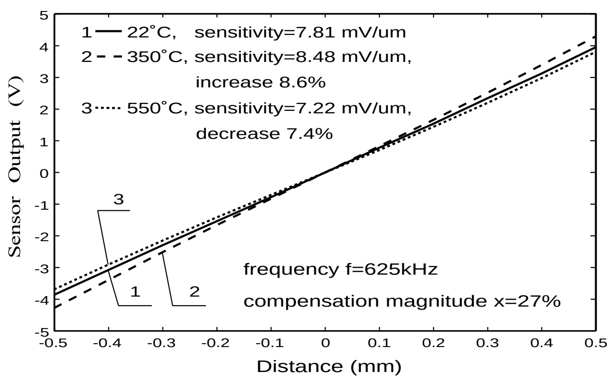

FIGURE 1: Sentivity of eddy-current displacement sensor with temperature compensation technique

Materials Used in the Sensor

Besides the performance variation at high temperatures, the materials and manufacturing process also limit the working temperature of normal commercial sensors. The high temperature displacement sensor developed by us is shown in Figure 2. The sensor coil is made of a silver wire with a very thin layer of ceramic coating, which can work up to 710°C without any damage. A kind of glass ceramic—Macor, which is machineable with ordinary metalworking tools, was used to make the sensor head. The continuous operating temperature of Macor can reach up to 800°C. The wire of a stranded Nickel Clad Copper with the insulation of a Nextel alumina-boria-silica fiber was used as high temperature lead wires.[7]

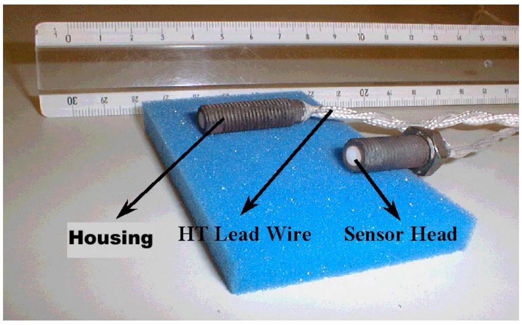

FIGURE 2: The high temperature displacement sensor

The sensors with above materials and the new manufacturing process show excellent temperature stability up to 550°C.

HIGH TEMPERATURE AMB TEST RIG

After the maximum benefits and limitations from using AMBs are clearly established, it is vital for the engine producers and users make an attempt to put it to full-scale designs. The main objective of this part is to provide answers to the feasibility and design problems of AMB working at high temperatures.

Materials for High Temperature AMBs

The conventional magnetic materials and insulated wires are not suitable for high temperature applications. The material selection is the crucial stage for high temperature AMB design. After the test and evaluation of several material combinations, the materials and their relevant manufacturing processes have been defined for the high temperature AMB application.

For the laminations of rotor and stator of high temperature AMBs, the cobalt-iron alloy AFK502R is selected because of its high magnetic saturation (about 2.4Tesla), high mechanical strength and high temperature limits (up to 850°C). Figure 3 gives the maximum flux density at different temperatures, it shows a good magnetic property and stability at high temperatures. The bearing coils were wound with a 27% Nickel Clad Copper wire with ceramic coating, which can work at least up to 710°C without any damage. A kind of machineable glass ceramic "MYKROY-1100" was used as the material of the coil former of HT-AMB, whose maximum continuous operating temperature is up to 600°C. The wire of a stranded Nickel Clad Copper with the insulation of a Nextel alumina-boria-silica fiber was used as the lead wires of the high temperature AMB actuator.

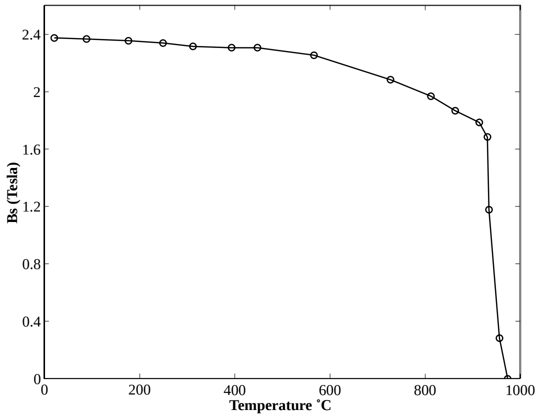

FIGURE 3: The maximum flux density of AFK502 at high temperatures

Besides the magnetic materials and insulated wires, other high temperature materials are also necessary for some components such as the rotor and AMB housing. HASTELLOY X alloy was selected as the material of the rotor and the housing of the high temperature AMBs. Some insulation paper and cloth such as "INSULPAPER-1200" and "SILIKAT-GEWEBE" were selected to protect the coil wound by ceramic wire. They can offer reliable electrical insulation at temperatures up to 1000°C.

One-degree-freedom HT-AMB rig

In order to test the magnetic materials and to find out optimal methods for the winding, curing, fixing, insulation and welding processes for making the AMB coils, a one-degree-of-freedom high-temperature AMB (1DF HT AMB) test rig has been built.

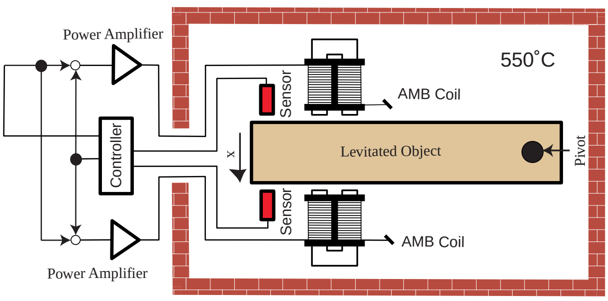

FIGURE 4: Principle of 1DF HT AMB rig

The principle of the 1DF HT AMB rig is shown in Figure 4, a photo is given in Figure 5. The AMB coils, high temperature displacement sensors and the levitated object made of high temperature material were put inside an oven. A simple controller and amplifier arrangement was used to control the levitation. It was put outside the oven and connected with the high temperature components using high temperature leading wires.

The objective of this 1DF HT AMB rig is to investigate the feasibility of levitation at high temperatures. After exploring different materials and several manufacturing processes, the magnetic levitation at 550°C was successfully implemented on this rig. The vital problems on material selection, insulation protection, heat treatment process of magnetic materials and other problems relevant to high temperature applications were found out through the experiment on this rig.

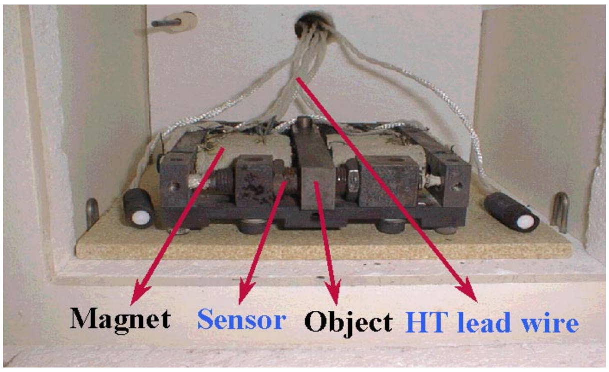

FIGURE 5: Photo of the 1DF HT AMB test rig

Five-Degrees-Of-Freedom HT-AMB Rig

Configuration of the rig

On the basis of successful experience of the 1DF HT AMB test rig, a five D.O.F high temperature magnetic bearing (5DF HT AMB) prototype with complete rotordynamic test facility has been developed. The sketch of the prototype is shown in Figure 6.

In the prototype, the rotor is supported by one high temperature (HT) radial AMB, one low temperature (LT) thrust AMB and another low temperature radial AMB. The high temperature AMB and sensors were put into a heating system where the temperature can be controlled.

The main technical data and specifications of the prototype are listed in Table 1. This complete rotordynamic prototype is capable of working at speeds up to 20,000r/min and temperatures up to 550°C.

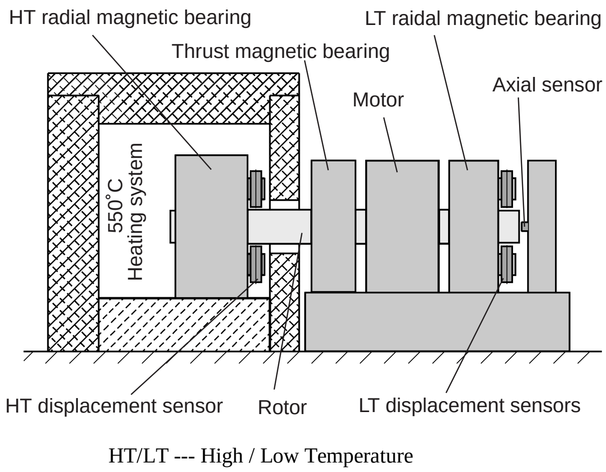

FIGURE 6: High temperature magnetic bearing system

TABLE 1: Technical data and specifications of the high temperature AMB rig

No.	Description	Value
1	Total length	465mm
2	Inner diameter of radial bearings	48mm
3	Outer diameter of radial bearings	HT AMB: 120mm LT AMB: 90mm
4	Air gap of radial bearings	0.4mm
5	Air gap of thrust bearing	0.5mm
6	Retainer bearing type	Ball bearings
7	Gap at retainer bearings	0.25mm
8	Power supply	220~240AC
9	Input power	300VA
10	Working temperature	HT AMB: 550°C LT AMB: 150°C
11	Maximum working speed	20,000rpm
12	Electronics	MECOS MBE8-50 Digital Controller & Amplifier
13	Control type	Current control
14	Sensors	Eddy current sensor with temp. compensation
15	Heating method	Controlled electrical heating

Actuator of HT-AMB

The high temperature magnetic bearing actuator is shown in Figure 7. The material for the fixing rings on the two sides of the actuator is HASTELLOY X, the magnetic lamination is made of high temperature magnetic material AFK 502R. The heating treatment has big influence on the magnetic properties of the material at high temperatures. In order to get the best magnetic material properties, a special heat treatment process has to be performed before precise manufacturing. The material property evaluation and heat treatment method was defined after discussion with the material supplier.

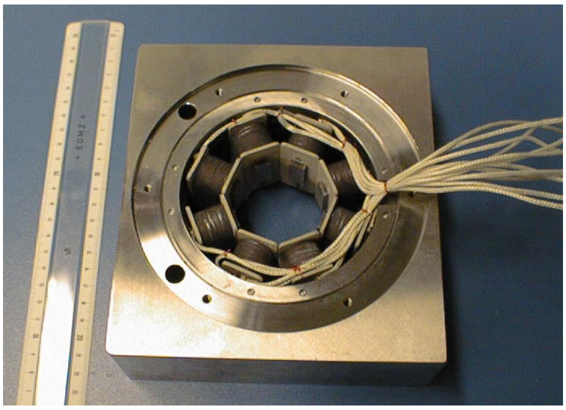

FIGURE 7: High temperature AMB actuator

For the insulated wires used in high temperature AMB coils, a curing process is required at temperature 750°C. Staying in such a high temperature for a long time has negative effects on the magnetic materials AFK502R. Therefore, different from conventional AMB applications, the high temperature insulated wires should be cured separately and should not be wound to the stator directly. To solve this problem, ceramic coil formers were used on the actuator as shown in Figure 7. By using the coil formers, it becomes very convenient to change a coil. Another advantage of this configuration is that they supply good electrical insulation between coils and bearing lamination. However, the formers occupy more space and they are disadvantageous to the heat dissipation, so the space optimization and thermal analysis have to be performed on the design stage.

The ceramic coating of high temperature insulated wire can be very easily damaged after working at high temperatures. In order to protect the insulation, soft thermal and electrical insulation paper INSULPAPIER 1000 is wrapped outside the coil, and then the insulation thread of SILIKAT GEWEBE is wound, finally a metal wire is wound as the most outside layer to fix the insulation paper and thread. With the above three measures, the ceramic coating is protected effectively.

From the experience of 1DF HT AMB system, the welding connection at high temperature part is not reliable, so the coil is wound without weld connection. The finished coil needs to be put into an oven for the curing process.

Figure 8 shows the assembled bearing stator in the support block and the heating system. The lead wires that connect the high temperature AMB coils with amplifiers are protected by an insulation tube (Nextel alumina-boria-silica fiber).

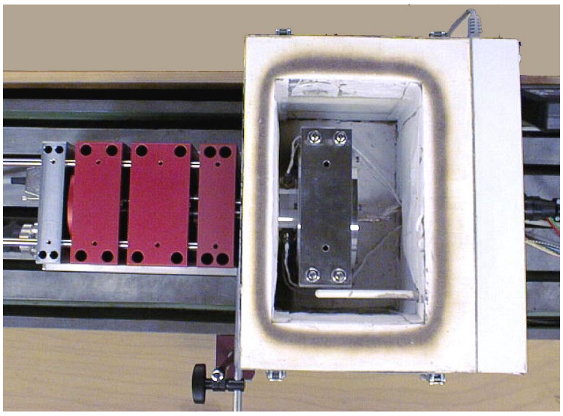

FIGURE 8: High temperature AMB test rig

Thermal and rotordynamic analysis

The maximum working temperature of conventional low temperature AMBs is only 150°C~180°C. In order to know the temperature on the low temperature parts, a thermal analysis of the rotor was performed with ANSYS. Without forced convection, the temperature on the thrust bearing's disk is about 210~250°C. The conventional low temperature thrust bearing can not work properly at such high temperature. Therefore, the cooling compressed air was led to the rotor before the thrust bearing, so the temperature on it decreases to 120~140°C, at which the low temperature thrust bearing can work properly without any problems.

To find the right positions of sensors, the rotordynamic analysis was performed using FEM modeling. The first two critical speeds are 38000rpm and 85520rpm. The rotor was designed as a rigid rotor that works below the first critical speed in order to avoid the complicated control problems.

Prototype of the HT AMB test rig

Figure 9 gives the photo of the whole test stand. The high temperature radial AMB is put into an oven with controlled heating. The prototype uses MECOS MBE8-50 electronic system which includes 5 channels of digital controllers and amplifiers. Through the interface program, the status of AMBs can be monitored, and the controller can be programmed on the control computer. The whole system has been tested, the high temperature AMB and its sensors work properly at the temperature range from room temperature to 550°C.

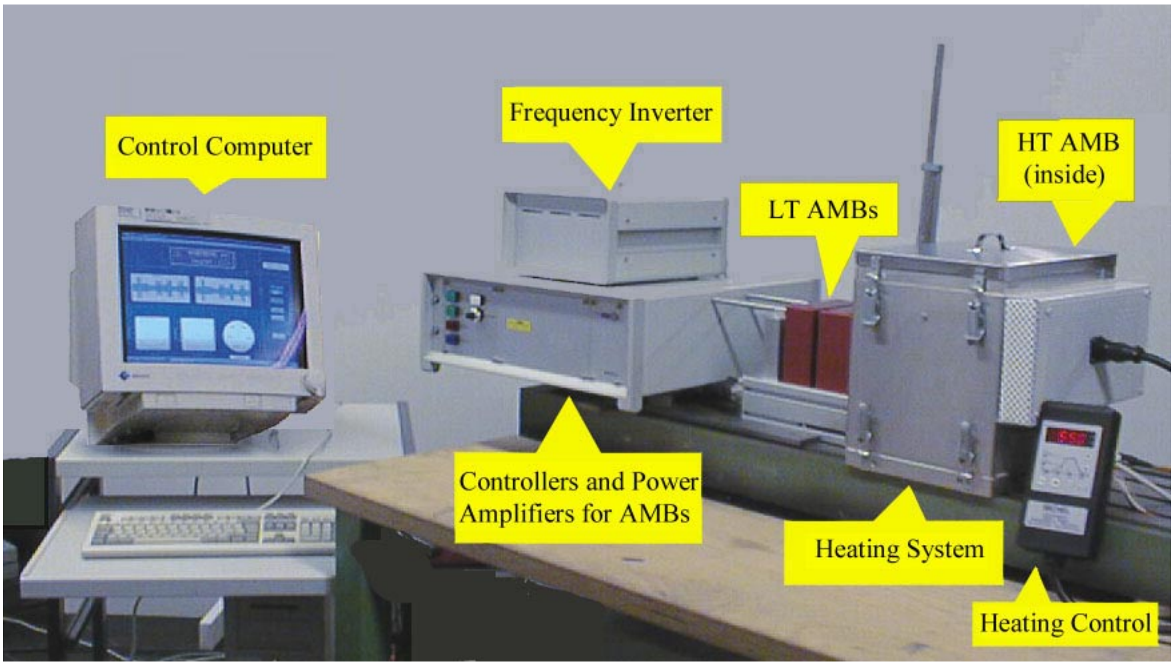

FIGURE 9: HT AMB demonstrator test rig

OUTLOOK OF THE FUTURE WORK

Various tests such as a load capacity test, endurance test of coils, temperature increases inside the coils, force-current-displacement relationship and dynamic performance of AMBs at high temperatures will be performed. Any temperature related control problems will also be investigated.

CONCLUSIONS

The eddy current displacement sensor with temperature compensation was developed. The sensor has good stability and performance at high temperatures, and it has been successfully used at the high temperature AMB systems. High temperature suspension has been successfully implemented on two HT AMB test rigs which are capable of working at temperatures up to 550°C. The investigation on design concept, material test and evaluation, manufacturing process and insulation protecting technology are expected to be helpful for the future HT AMB development for gas turbine applications.

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