MINIATURE ACTIVE MAGNETIC BEARING FOR VERY HIGH ROTATIONAL SPEEDS

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ABSTRACT

For certain special applications, very high rotational speeds may be necessary (Beams, 1937). As a feasibility study, a small experimental system, with a rotor of 5 mm diameter and 38.8 mm in length, was built to operate at 1'600'000 r.p.m.. The bearing system and the inductance drive are presented.

INTRODUCTION

There is certain interest in using miniature turbo-generators as a mobile power source, p. e. for autonomous robots. The high density and fast refuelling of chemically bound energy such as in fuel features advantages over rechargeable batteries. Because of their simplicity and lower noise emission levels, gas turbines are better suited for driving a generator than piston engines. Research on gas turbines as micro-electromechanical systems is been performed at the Gas Turbine Laboratory at MIT. Here, gas lubricated bearings are being studied.

For application in an autonomous robot, the power output of the turbo-generator is required to be in the 100 W range, which asks for a very small gas turbine. Due to the thermo- and aerodynamic laws governing power conversion in gas turbines, the circumferencial velocities of both the compressor and the turbine of the machine must be held at high levels. Hence, for a small turbo-generator providing 100 W, one expects rotational speeds between 1 and 2 million r.p.m..

The objective of this project is to investigate the suitability of magnetic bearings for these and similar applications. A magnetic bearing system for a test rotor which would allow rotational speeds well above one million rounds per minute (r.p.m.) was designed and built. Together with the bearing system, a suitable electric drive was created.

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ROTOR

The rotor has to be designed to withstand the mechanical stress at the desired rotational speed. Since reluctance force bearings are used, the rotor is fabricated from ferromagnetic steel, limiting the circumferencial velocity to about 500 m/s. This leads to a small cylindrical rotor with a diameter of 5 mm and 38.8 mm in length.

To keep the frequencies of bending modes high, the rotor needs to be as rigid as possible. Therefore, the rotor is solid and no lamination is used. The frequencies of the first four bending modes were calculated to be at 14 kHz, 37 kHz, 67 kHz and 102 kHz. At one million r.p.m., the rotational frequency is 16.67 kHz. Hence, one has to accelerate the rotor across the first mode.

MAGNETIC BEARING

A five axis fully active magnetic bearing system is used to stabilise the rotor. Its components are described below:

MAGNETS

Radial Bearings: Because the rotor is not laminated, a homopolar configuration is used to minimise eddy current and hysteresis losses. The axis of the rotor is chosen to lie vertically, which reduces variations of the magnetic field around the rotor to a minimum, as the weight of the rotor does not act in the radial direction. The radial bearing magnets are displaced slightly from the nodes of the rotor's bending modes to allow active damping of the latter.

Axial Bearings: Due to the small area at the ends of the rotor, pot magnets are used as depicted in Figure 1. Because the rotor is suspended vertically, the axial bearing only has to support its weight and no dynamic forces.

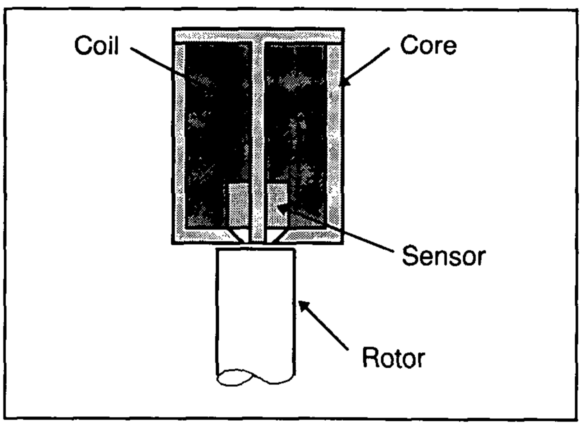

Figure 1: Axial bearing magnet with sensor

SENSORS

Eddy current sensors are placed at both ends of the rotor for radial offset measurement. Placing the sensors at this location yields the strongest signal when the rotor performs bending oscillations, thus facilitating the damping of these modes. The rotor was coated with a 50 μm thick layer of Copper at the sensor locations to improve signal quality.

Because of the very limited space available, the axial eddy current sensors were originally positioned on the core together with the bearing magnets, as can be seen in Figure 1. Strong coupling between the magnet and sensor windings made this design difficult to handle, though. Thus, the push-pull configuration of two bearing magnets with two sensors was abandoned. The lower magnet was disconnected and the upper sensor replaced by a dummy coil, operating the axial bearing single-sidedly.

As evaluation electronics, the ECS6 sensor card manufactured by MECOS TRAXLER AG in Switzerland was used.

CONTROLLER

To control this small system with its high rotational frequencies, a fast controller and minimum delay in sensor electronics and power amplifier is important. For this reason, both the PD controller and the amplifier are implemented as analogue circuits.

Considering the radial bearing controller, two operation modes were implemented: de-centralised operation (four stand-alone controllers) on one hand and control of tilt and translational displacements on the other. In the de-centralised mode, there is a controller for displacements in the x-direction and one for the y-direction for each radial bearing, with z coinciding with the rotor's axis. This is the well-known configuration used for most magnetic bearings.

By coupling the controllers of the upper and lower bearings of a single plane (for instance, the xz-plane) as shown in Figure 2, translational/tilt operation is established. The rotor is

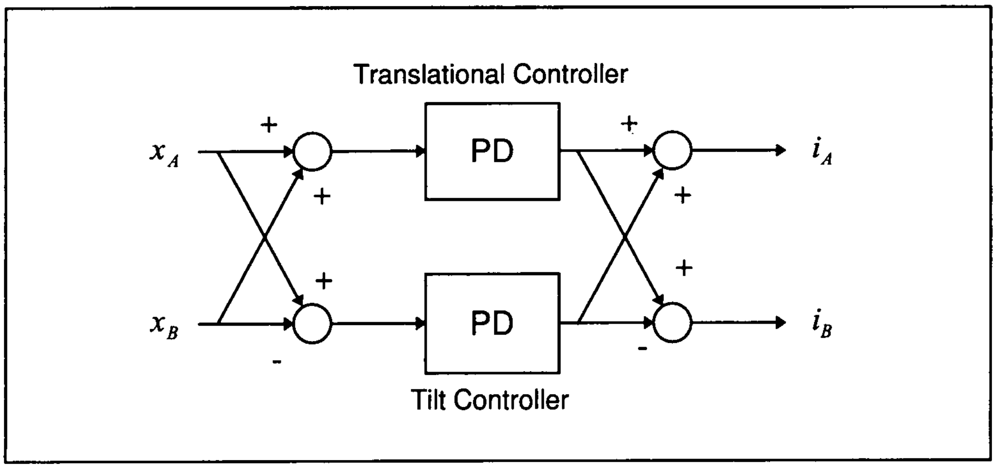

Figure 2: Translational and tilt displacement control in the xz-plane

stabilised using the sum, respectively the difference of the displacement signals x_A and x_B. The indices A and B stand for the upper and the lower bearing, while i_A and i_B designate their corresponding control currents. Naturally, the same is done for the *yz*-plane. This configuration can optionally be chosen instead of the de-centralised one mentioned above to investigate its performance in controlling gyroscopic effects of the rotor.

The axial bearing controller is of the simple PD structure. As stated earlier, it is operated single-sidedly with a magnet suspending the rotor from the top and a sensor coil on the bottom.

INDUCTANCE MACHINE

The design of the motor is critical. The rotating magnetic field in the stator reaches frequencies well above 17 kHz. Losses in laminated silicon iron are too high at these levels. Sintered iron would be applicable but its permeability is low. Hence, ferrite based on MnZn is used for the stator core. The rotor itself is coated with 0.1 mm of copper to achieve strong eddy currents in order to form an inductance motor.

The machine features a stator with two pole pairs (see Figure 3). Two opposing coils each are connected in series. An external function generator combined with an amplifier induces an AC current in the coils, with a 90° phase shift between the two pole pairs. Using a higher number of pole pairs would result in improved efficiency and power density. This design was chosen for its ease of manufacturing, though. The main goal for this motor was seen more in functionality than in high efficiency, as it will only be used for experiments.

Alternatively, a synchronous motor with permanent magnets on the rotor would perform with much higher efficiency and power density. The low mechanical strength of permanent magnets prevents their use at the high rotational speeds intended.

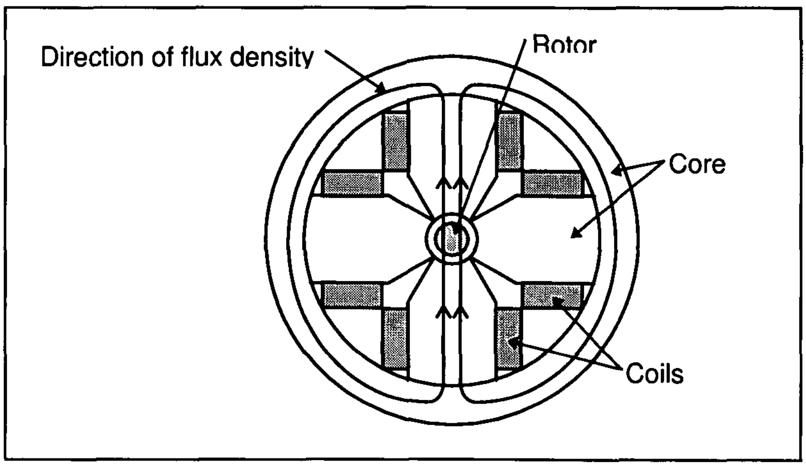

Figure 3: Inductance motor with two pole pairs.

HOUSING

A heavy aluminium housing is used for safety reasons in case of fatal failure. The housing is completely closed and sealed since the rotor runs in a vacuum. This is done to reduce friction losses and disturbance of the rotor due to turbulence. Investigations under atmospheric pressure are intended as well.

CONCLUSIONS

For a cylindrical rotor with only 5 mm in diameter, the axial bearings pose a challenge in design and operation. Because integrating the sensors into the magnets results in strong coupling between the two, it might be suitable to implement self-sensing bearings. The force which can be applied by the axial bearing is small. This will have to be taken to account when, for instance, designing a turbo-generator: usually, the rotor of a gas turbine enacts considerable axial thrust onto the bearings.

The components of such a miniature magnetic bearing system can be manufactured using classical machining methods. For the production of large numbers, one might want to consider the use of micromachining technology.

OUTLOOK

The bearing system and motor presented will be used to study the stabilisation of fast-spinning rotors with magnetic bearings. Different configurations for the motor will need to be investigated, as this is not a well-known subject.

REFERENCES

Beams, J.W.: High Rotational Speeds. *J. Appl. Phys.*, 8 (1937), 795-806

Closs, M.F.: *Magnetic Bearing for a High-Speed Rotor.* Master Thesis, International Centre for Magnetic Bearings, ETH Zurich, 1997