Experimental Investigation of an Eddy-Current Bearing

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Summary

An AC-electromagnetic bearing based on eddy-current repulsion has been built and tested. The bearing was found to be inherently stable and able to provide support in five degrees of freedom, i.e. a short rotor was fully supported by a single bearing without any feedback control. However, with the current design configuration, the load carrying capacity and the stiffness and damping are lower than for the conventional DC-electromagnetic bearing and the power consumption is higher. Experimental confirmation of the inherent bearing stability and the support capabilities was reported in an earlier paper. The current paper reports on the experimental investigation of two additional capabilities, namely motoring and emergency shutdown without catcher bearings. In addition, quantitative experimental results are presented by which the goodness of each of the bearing capabilities can be judged. Based on these results, design modifications are proposed for improving the bearing capabilities.

Introduction

The magnetic bearing described in this paper is based on the so-called Electromagnetic River suspension for high speed vehicles which was proposed and demonstrated by Eastham & Laithwaite [1] in 1974. The Magnetic River was turned into a journal bearing by bending it into a circular shape (see Figure 1). The resulting Eddy-Current Bearing was designed and built on the basis of the Magnetic River behavior reported in the literature (see, for example, references quoted in [2] and [3]). No analytical work has yet been conducted. The objective was to determine whether the bearing would inherit the basic desirable characteristics of the Magnetic River such as inherent stability, support capability in five degrees of freedom, motoring capability, and emergency shutdown capability. This paper reports on the experimental findings to date. Preliminary results were reported in [4]. Additional background can be found in [5]. Work on other types of AC-electromagnetic bearings has been reported in [6] through [9].

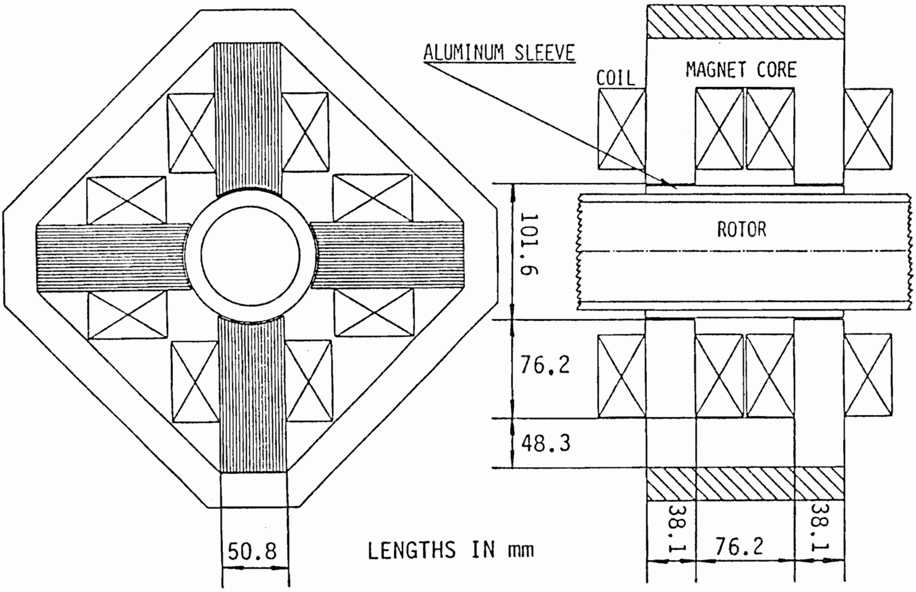

Figure 1 The Eddy-Current Bearing (Cross Section)

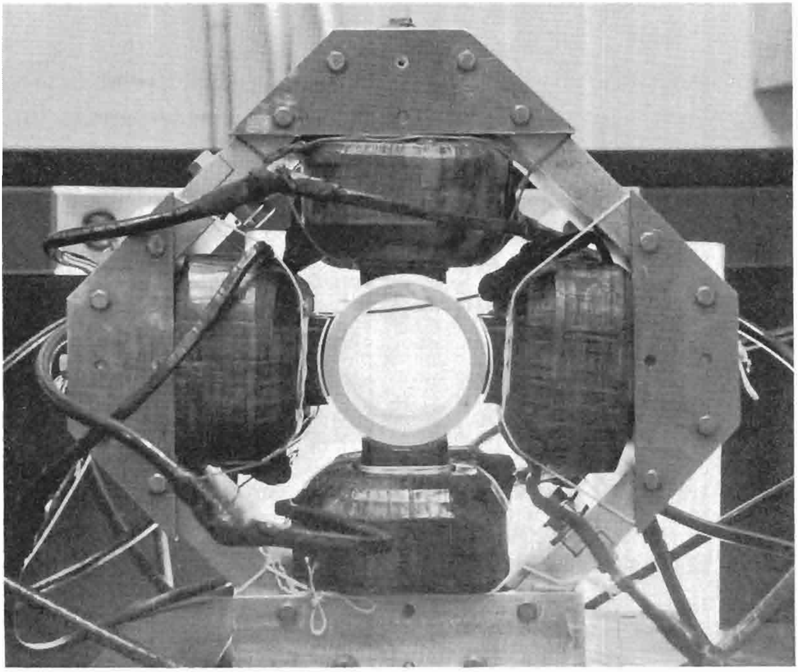

Figure 2 The Eddy-Current Bearing (Prototype)

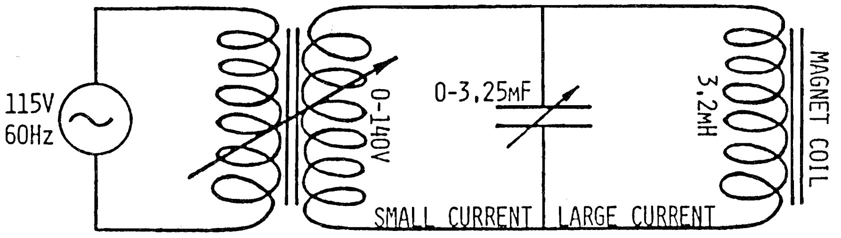

Figure 3 Electric Circuit for Each Magnet

The Experimental Apparatus

Four U-shaped electromagnets are spaced 90° apart in a star formation to form a 10.16 cm diameter bearing as shown in Figures 1 and 2. The magnets are mounted in a non-magnetic stainless steel housing. The magnet cores are made of grain-oriented 0.356 mm laminations with a saturation flux density of about 2 Tesla. The coils have 58 turns each. They are wound with two parallel flat copper wires with a total cross section of approximately 6.35 mm x 4.32 mm. The inductance of two coils mounted on one core was measured to be about 3.2 mH.

Each of the four magnets has an electric circuit as shown in Figure 3. Power is supplied from a 115V 60 Hz single phase outlet. The power is adjusted by means of the variable transformer. The variable capacitor is used to adjust the power factor (or tune the circuit) such that a large current will circulate between the capacitor and the coil while only enough current is drawn from the supply to cover the I^2R loss in the coils and in the rotor. The variable capacitor consists of a bank of oil-filled capacitors in parallel. Each capacitor bank has 13 100μF capacitors and 13 150μF capacitors connected such that the capacitance can be varied in steps of 100μF from zero to 3250μF. Fine tuning of the power factor is therefore not possible but the reactive power can be reduced sufficiently to permit experimentation with the available equipment. It was generally found that 11 to 13 capacitors needed to be switched in to minimize the supply current.

Five rotors made of construction aluminum were available for levitation. Three of these were 15.2 cm long with an inner diameter of 7.62 cm and outer diameters of 9.50 cm, 9.73 cm, and 9.91 cm respectively. They were used to study the effect of bearing clearance. A 15.2 cm long solid iron cylinder with 7.62 cm diameter was made to fit snugly inside the aluminum sleeves to provide extra weight. Two additional aluminum sleeves with lengths 12.7 cm and 17.8 cm were used to study the effect of sleeve length. A pure copper sleeve with length 15.2 cm and inner and outer diameters of 7.37 cm and 9.50 cm was also made to study the effect of improved conductivity. The masses of the three 15.2 cm aluminum sleeves were 1.038 kg, 1.176 kg, and 1.288 kg. The iron core mass was 4.883 kg and the copper sleeve mass was 3.859 kg.

Results

Levitation and Stability

All three 15.2 cm aluminum sleeves were successfully levitated as shown in Figure 2, confirming the inherent stability of the bearing and the five degree-of-freedom support capability. Contrary to expectations, slightly larger currents in all four magnets were required to achieve stable levitation of the large diameter sleeve than for the medium and small diameter sleeves (75A [82V] versus 60A [65V] in the bottom magnet). The larger current was not required to lift the sleeve but to provide sufficient support stiffness to prevent excitation of radial vibrations of the sleeve by the 60 Hz magnetic flux pulsations. Such excitation otherwise led to rattling of the sleeve against the pole faces.

With the iron cylinder inserted in the aluminum sleeves, there was insufficient power available to energize all four magnets for full levitation. With the bottom magnet excited only, the 6 kg sleeve/core combination could be lifted free of the bottom with 130A [128V] and 140A [133V] for the large and medium diameter sleeves respectively while the small diameter sleeve was unable to fully lift off at 160A [142V] which was the maximum power available. For comparison, 40A [44V] to the bottom magnet was required to lift each of the three sleeves without the iron core. Thus, a maximum lift capacity of 59N has been demonstrated so far.

Although the copper sleeve geometry is almost identical to the small diameter aluminum sleeve, it suffered axial instability and tried to exit the bearing when lifted. The long (17.8 cm) aluminum sleeve behaved similarly suggesting that the copper sleeve might be stabilized by reducing its length. The length of the copper sleeve was reduced to 13.8 cm which made it stable in the axial direction. However, pitching oscillations would very slowly build up and eventually the sleeve would start colliding with the pole faces. It is not known whether this was a true self excited instability or a subharmonic response to the 60 Hz nonlinear magnetic flux pulsations. In any case, it confirms that the inherent damping is very low.

Although the long (17.8 cm) aluminum sleeve suffered from axial instability, it had a significantly better radial support capability than the 15.2 cm sleeves. On the contrary, the short (12.7 cm) aluminum sleeve had less radial support capability than the 15.2 cm sleeves but considerably better thrust capability. This suggests, as expected, that it will be difficult to optimize the bearing with respect to all its capabilities simultaneously.

The magnetic support stiffnesses, with the three 15.2 cm aluminum sleeves levitated, were estimated by impacting the sleeves and counting vibration periods with a stopwatch. The average radial, axial and angular stiffnesses were found to be in the neighborhood of 80 N/m, 60 N/m, and 0.3 Nm/rad. The damping was again found to be very low, as evidenced by the long time taken for the vibrations to die out. These preliminary results showed, as expected, that the axial stiffness increased as the bearing clearance decreased. However, contrary to expectations, both the radial and the angular stiffnesses were found to increase with increasing clearance.

Motoring

The motoring capability was confirmed. With single phase current supply, the three 15.2 cm aluminum sleeves were levitated and would rotate in the bearing when the magnet currents were adjusted to position the sleeve eccentrically within the bearing clearance. They would stop rotating when brought back to the concentric position and would rotate in the opposite direction when brought to a diametrically opposite eccentric position. The larger the eccentricity, the higher the speed. The maximum speed recorded with single phase current was about 50 rpm. With 3-phase current, the rotational speed could be increased to about 750 rpm with the sleeves supported mechanically. It was not possible to fully levitate the sleeves with 3-phase current, apparently because the torque at zero speed would rotate the sleeves before metal contact could be broken, thus initiating a backward whirl instability.

Emergency Shutdown

It was predicted [5] that the rotor could be decelerated safely after a power failure by switching to battery operated DC-power. The operating principle would change to so-called electrodynamic levitation with the eddy-currents generated in the rotor by the high speed motion of the rotor surface past a 'row' of DC-magnets. Both levitation and braking forces would be generated. This is the principle used in levitation of high speed trains by superconducting magnets [10].

It has not yet been possible to fully demonstrate the electrodynamic levitation with the available equipment. The 9.50 cm diameter, 15.2 cm long aluminum sleeve was mounted on a 350 VA electric hand drill, inserted in the bearing, and accelerated to 1190 rpm. The top and side magnets were disconnected and the bottom magnet was connected to a large DC-power supply. A strong braking torque was developed as the DC-power was increased. At 8V, 250A, the braking torque almost stopped the drill but no appreciable lift force was detected. Apparently, the surface speed of the sleeve (6 m/s) was too low [11].

Efficiency

After less than five minutes of operation, the aluminum sleeves got too hot to be hand held whereas the magnets remained cool with only a modest temperature increase to be felt. Sleeve temperatures over 110°C were measured with corresponding magnet temperatures of about 35°C. The copper sleeve ran slightly cooler than the aluminum sleeves, attesting to its greater conductivity. An increase in supply current to one circuit would result in a similar current in the other circuits, indicating strong mutual inductance between the magnet coils.

Power Frequency

Finally, the effect of power supply frequency was studied using a 60 Hz magnet and a 400 Hz magnet. The 60 Hz magnet was identical to the bearing magnets except that the pole faces were flat. The 400 Hz magnet had identical geometry but was made of 0.1 mm laminations, and the number of turns was 15 per coil to achieve the same magnetic flux density as with the 60 Hz magnet but using a 150V, 400 Hz power supply. According to the analysis of [8], a frequency increase should result in a significant improvement of the lift capacity. This did not occur. The main effect was that thinner aluminum plates could be lifted with 400 Hz power supply, presumably because the eddy-current penetration depth decreases with increasing frequency.

Conclusions

The experiments have confirmed that the Eddy-Current Bearing retains the basic advantages and disadvantages of the Magnetic River suspension:

1. A single eddy-current bearing is sufficient to fully support a short rotor in all five degrees of freedom simultaneously.
2. The bearing provides inherently stable rotor support. No feedback control is needed.
3. The bearing will act as a motor and as a support simultaneously.
4. The lift capacity and the stiffness and damping achieved so far are well below those achieved by DC-electromagnetic bearings.
5. The efficiency of the bearing is low due to a high I^2R loss in the rotor. This is considered to be the most serious problem which must be overcome before the bearing finds practical application. The current thinking is to move the design closer to a conventional induction motor to gain motoring efficiency. The bearing could then be used in space-based applications such as flywheel energy storage systems where it could support the flywheel and also act as the motor/generator.

Acknowledgment

This work was supported by the TAMU Turbomachinery Research Consortium. Rig hardware was donated by IMC Corporation and by Magnetic Bearings, Inc.

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Stabilization of Rotor Motion