N89-22913

EXPERIMENTAL VERIFICATION OF AN EDDY-CURRENT BEARING[1]

Jorgen L. Nikolajsen
Department of Mechanical Engineering
Texas A&M University
College Station, Texas 77843, U.S.A.

A new type of electromagnetic bearing has been built and tested. It consists of fixed AC-electromagnets in a star formation surrounding a conducting rotor. The bearing works by repulsion due to eddy-currents induced in the rotor. A single bearing is able to fully support a short rotor. The rotor support is inherently stable in all five degrees of freedom. No feedback control is needed. The bearing is also able to accelerate the rotor up to speed and decelerate the rotor back to standstill. This paper describes the bearing design and the experimentation to verify its capabilities.

INTRODUCTION

The Eddy-Current Bearing described here 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].

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

---

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

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 which can be switched in and out of the circuit independently. Each capacitor bank consists of 13 100μF capacitors and 13 150μF capacitors which are connected such that the capacitance can be varied in steps of 100 μF from zero to 3,250μF. Fine-tuning of the power factor is therefore not possible but the reactive power can be reduced sufficiently to permit the 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. Also, a pure copper sleeve with length 15.2 cm and inner and outer diameters of 7.37 cm and 9.50 cm was 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

All three 15.2 cm aluminum sleeves were successfully levitated as shown in Fig. 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 levitate the large diameter sleeve than 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 6kg 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 current available. For comparison, 40A [44V] to the bottom magnet was required to lift each of the three sleeves without the iron core.

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 could possibly be stabilized by reducing its length. The short (12.7 cm) aluminum sleeve had the largest thrust capability of all the sleeves but inferior radial support capability. This suggests, as expected, that it probably will not be possible to optimize the bearing with respect to all its capabilities simultaneously.

The motoring capability was also confirmed. With single phase current supply, the three 15.2 cm levitated sleeves 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 strong torque at zero speed would rotate the sleeves before metal contact could be broken, thus initiating a backward whirl instability.

After a few minutes of operation, the aluminum sleeves got too hot to be hand held whereas the magnets remained cool with only a slight temperature increase to be felt. Also, the copper sleeve did not get as hot as 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.

The magnetic support stiffnesses, with the three 15.2 cm 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 also very low, as evidenced by the long time taken for any vibrations to die out.

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 low. Additional damping can be supplied by a simple eddy-current damper and design optimizations may improve the stiffness and the lift capacity but it is unlikely that they will ever exceed those of DC-type magnetic 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, thereby further reducing the load carrying capacity but gaining 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.

REFERENCES

1. Eastham, J.F. and Laithwaite, E.R. "Linear Induction Motors as Electromagnetic Rivers", Proc. IEE, Vol. 121, No. 10, pp. 1099-1108, 1974.
2. Jayawant, B.V. "Electromagnetic Levitation and Suspension Techniques," Edward Arnold, London, 1981.
3. Jayawant, B.V. "Electromagnetic suspension and Levitation," IEE Proc., Vol. 129, Pt. A, No. 8, pp. 549-581, 1982.
4. Nikolajsen, J.L. "An AC-Electromagnetic Bearing for Flywheel Energy Storage in Space," To be published in NASA CP, Magnetic

Suspension Workshop, NASA Langley, Feb. 1988.

5. Nikolajsen, J.L. "A Magnetic Bearing Based on Eddy-Current Repulsion," NASA Conference Publication 2443, Rotordyn. Instab. Prob. in Hi-Perform. Turbomach. pp. 460-465, 1986.

6. Bolton, H. "An Electromagnetic Bearing," IEE CP 120, Linear Electr. Machines, London, pp. 45-50, 1974.

7. Iskierka, S. "Influence of Irregularities of Exciting Current Density Distribution on Induction Bearing Work," Acta Technica Csav, No. 5, pp. 572-582, 1984.

8. Iskierka, S. "Analysis of an Induction Bearing by the Finite Element Method," Archiv fur Electrotechnik, Vol. 67, pp. 375-380, 1984.

9. Connor, K.A. and Tichy, J.A. "Analysis of an Eddy-Current Journal Bearing," ASME Pap. 87-Trib-10, 7pp., 1987.

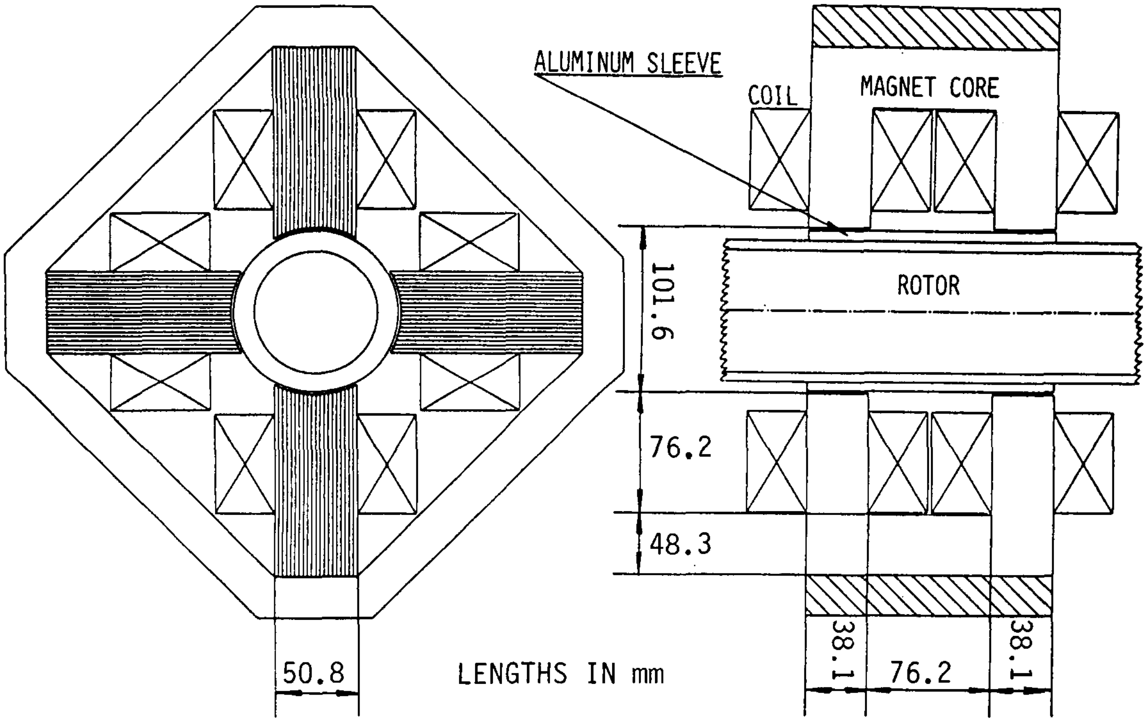

Figure 1 The Eddy-Current Bearing (Schematic)

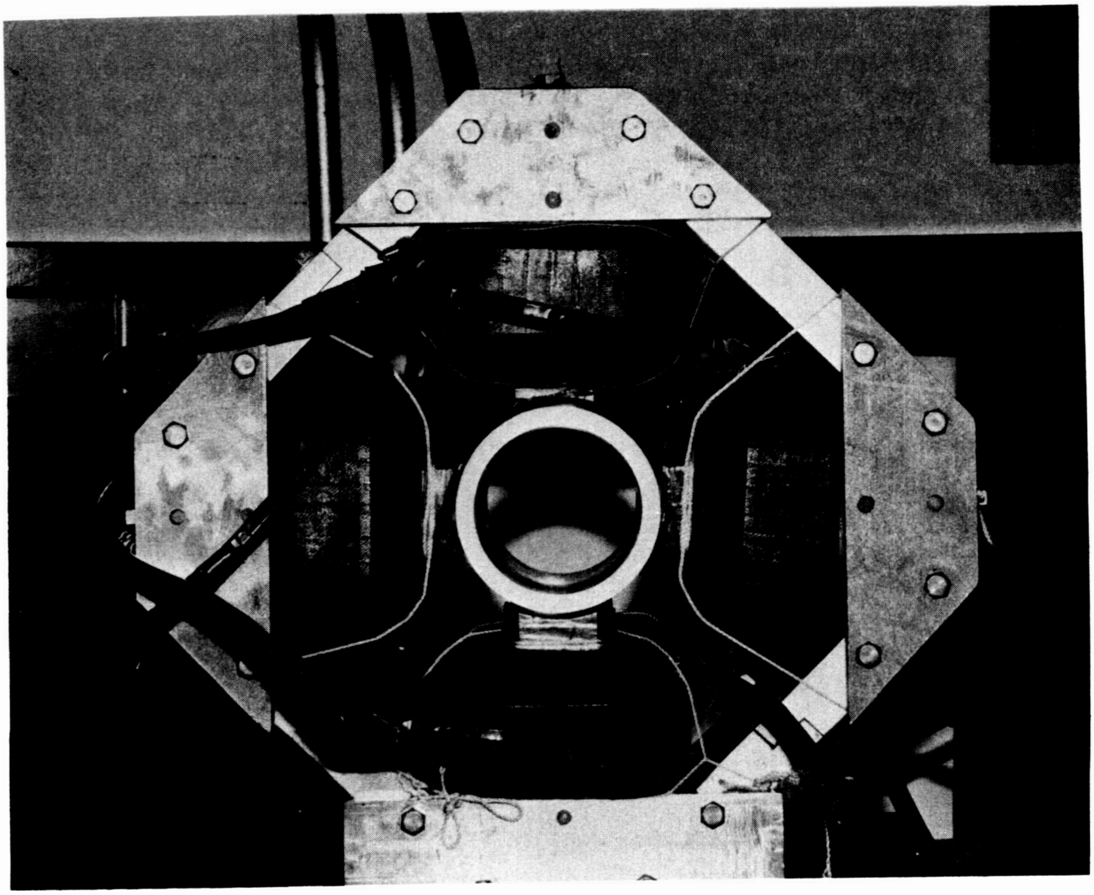

Figure 2 The Eddy-Current Bearing Prototype

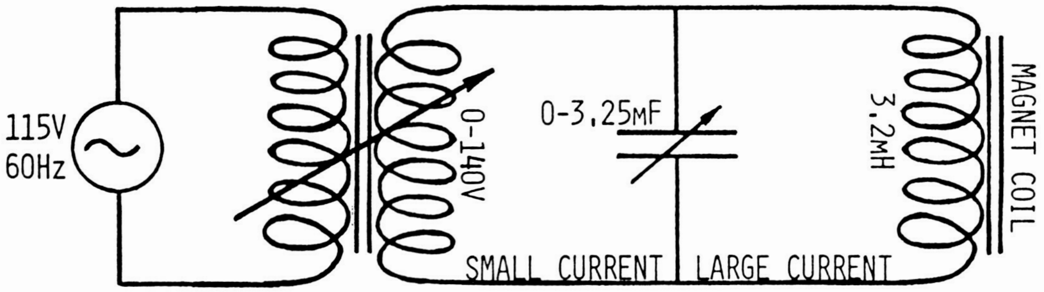

Figure 3 Electric Circuit for Each Magnet