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PRELIMINARY EXPERIMENTS ON AN EDDY CURRENTS BEARING

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ABSTRACT

The present paper concerns a preliminary investigation on the forces produced by eddy currents for magnetic rotating bearing applications. These forces may be conveniently used to achieve stable contactless levitation without active control or superconducting materials, so that passive magnetic bearings operating at ambient temperature can be realised.

The bearing configuration utilised here is such that no eddy losses occur in nominal condition.

In this paper, details of force measurements of a type of rotating bearing configuration are presented. These, to the best of our knowledge, are not found in previous publications.

INTRODUCTION

Passive magnetic bearings (PMB) are based on inherently stable magnetic or dynamical phenomena so that they do not need either an active control or cryogenic systems to attain contactless levitation. However their dynamical performances may be inferior to these of active magnetic bearings (AMB) or superconductor magnetic bearings [1, 2, 3].

As it is known, static stable levitation (i.e. without rotation) is impossible to achieve without electronic control, superconductors or diamagnetic materials [4], however, a stable levitation is achievable with electrodynamic effects (eddy currents) [5-8]. Repulsive forces produced by eddy currents were proposed for magnetic levitation systems since late ‘60 [6-14] and, in the last thirty years many researchers studied the electrodynamic technique in combination with superconductors and/or active control for high-speed transportation systems [1, 10].

The goal of this research is to develop a reliable design technique for eddy current bearings based on permanent magnets. The PMB could be very compact, simpler, less subject to failure, and, potentially, lower in cost than conventional magnetic bearings.

The main disadvantage is that the stability is only achieved in a limited range of operating speeds and it is impossible at rotor standstill without using an auxiliary system.

PMB should be suitable for many applications where a high accuracy of the journal is not required and/or when the required stiffness values are not very high (spindle machines, flywheels, for example).

The present paper reports on the experimental results about the determination of eddy current forces produced in a rotational system. Rotor-dynamics effects are not discussed in this contribution.

EDDY CURRENTS

The modern formulation of the Lenz’s law (first enunciated in 1834) says that currents induced in a conductor by a time-varying magnetic field produce a field that opposes the change in the flux.

Although the original wording was less accurate, it was intended to describe induced currents forces. From this point of view, it is simpler to explain some elementary and well-known phenomena concerning forces produced by eddy currents, as the Thomson jumping ring and Arago disk.

In 1992 Saslow [4] reports a very interesting analysis of this fact. A new formulation is proposed and demonstrated: "A conductor, when subject to a time-varying magnetic field, feels a force due to induced currents, in that direction where the dissipation rate (or rate of entropy production) due to the induced currents is least" (see the cited paper for the complete demonstration).

This version of Lenz's law is just a generalisation of original Lenz's formulation, but is more useful than the ordinary expression because it emphasises motion and forces.

Using Saslow's formulation, induced currents tend to accelerate a conductor in the direction that most effectively decreases the rate of Joule heating, so even high velocity effects for magnetic levitation are covered.

Actually the basic principles for magnetic levitation by eddy currents, residing in Maxwell's theory, can be more conveniently appreciated in this approach.

Maxwell's receding images construction

With a technique of virtual charges, receding with a characteristic velocity, it can be possible to model the magnetic effect produced by currents induced in a conductor. This method called Maxwell's receding images construction permits to express directly forces produced by relative motion of a conductor and a magnetic field source.

The analytical demonstration of this method (not reported here) derives from the simple case of a magnetic monopole suddenly arising at the height h above a thin conducting sheet. The magnetic field due to the induced currents will appear to arise from a specular monopole at distance h below the sheet moving vertically from the sheet at the so-called recession velocity v_0 resuming conductor's electrical properties. It can be calculated that $v_0=2/\mu_0\sigma d$, where μ_0 is the vacuum magnetic permeability, σ the electrical conductivity and d the sheet's thickness.

At first there is no change in magnetic flux within the conductor, then eddy currents decay (the image moves away from sheet) and the initially shielded magnetic field penetrates. In case of a superconductor sheet ($\sigma\rightarrow\infty$), the image does not recede and induced magnetic flux completely expels magnetic field from conductor.

More complicated cases can be modelled by superposition of suddenly appearing monopoles generating trains of virtual magnets. By using this technique it is possible to analyse the forces produced by eddy currents on a monopole moving at constant velocity v parallel to the sheet. In this case, the global effect can be calculated as the sum of a term depending from currents induced and a term generated by flux-expelling image. The first term is prevailing at low velocity, instead the second one is more important for magnetic levitation and occurs at high velocity.

Lift and drag force

As seen before, for high frequency self-inductance effects dominate electrical resistance and the magnetic flux is repelled. For simplified cases, some general results were derived in [11] and it is possible estimate two components of force produced by image magnets. The first component F_D, called drag force, is opposing to motion, while the second one F_L is called lift force because tends to repel moving magnet from sheet.

If distribution of eddy currents can be considered constant along the sheet's thickness (thin sheet hypotheses), from these results it has been proven [11, 12] that $F_D/F_L= v_0/v$.

In fact, consider a magnet moving with a constant velocity v acted by external forces equal and opposite to lift and drag force produced by image magnets. The power provided by external force is equal to $F_D v$ and it has to be equal to power going to receding images $F_L v_0$.

As consequence of the above results, it can be concluded that, at low velocity where $F_D \propto v$, $F_L \propto v^2$. At high speed, instead the flux repelling prevails. This effect is independent from velocity, so $F_D \propto v^{-1}$, and the power dissipation is constant. Practically, drag force goes to zero at both low and high velocity and it must have a maximum at an intermediate value that is the threshold between a dissipative and a repulsive regime where levitation is possible.

MAGNETIC LEVITATION BY EDDY CURRENT

There are many methods for a passive magnetic levitation [1, 2, 3, 13]. As demonstrated in [4], it is just possible to achieve a partial levitation without using diamagnetic or superconductor materials, in particular using a set of fixed permanent magnets, and much research was aimed to optimising magnet configurations as load relievers.

Passive magnetic levitation without superconductors

To induce eddy currents in a conductor material a variable magnetic flux is necessary. The variable magnetic flux can be provided by AC-coils or by the rotation of the journal. The second case is examined here. The experimental measurements were aimed to validate theoretical analysis [13-19].

Description of the system

In this first phase of the research, we started to analyse forces produced by induced currents between a set of static magnets and a rotating copper tube for different rotational speeds. A test set-up was developed to measure the forces produced by an elementary electro-dynamical system (Figure 1).

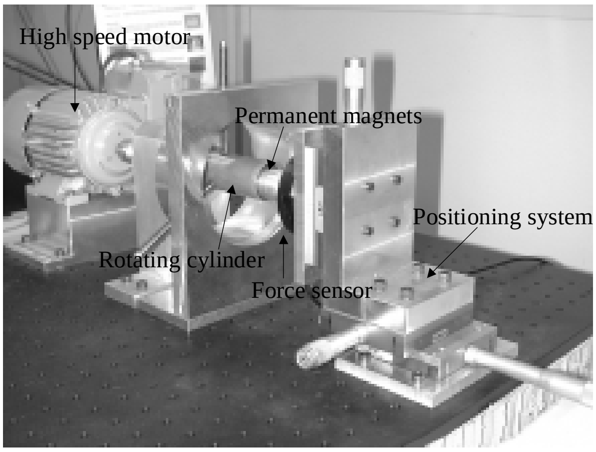
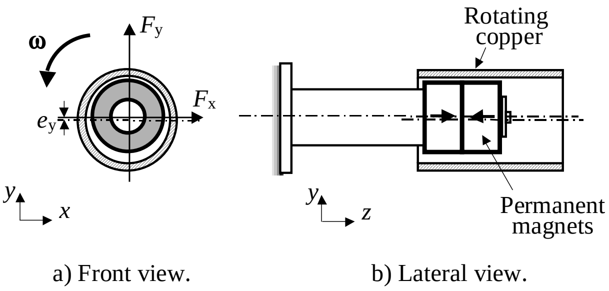


FIGURE 1. Test set-up at the Department of Micro-technique at the EPFL.

The developed system (Figure 2) is composed by a couple of stationary cylindrical NdFeB permanent magnets (outer diameter 27.85 mm, inner diameter 10 mm and height 12 mm) and rotating a cylinder of copper (external diameter 35 mm, inner diameter 32 mm and height 80 mm). The stationary permanent magnets were assembled in a repulsive mode to maximise the magnetic flux intersecting the copper tube (Figure 3).

To rotate the copper cylinder, we used a 500 W motor with a digital speed control (up to 30.000 rpm unloaded). The position of the magnets is guaranteed by a set of three micrometric tables with 10^{-2} mm sensitivity. And, finally, a Schunk FT3260 six axes force sensor (sensibility 0.05 N, range 65 N), measures the force between the copper tube and magnets for different rotational speeds. Force measurements were made by monitoring the voltage output of the sensor with an oscilloscope (100 MHz, 500MS/s) in averaging configuration. All voltage measurements were performed in a stabilized operation mode.



a) Front view. b) Lateral view.

FIGURE 2. Representation of the experimental system.

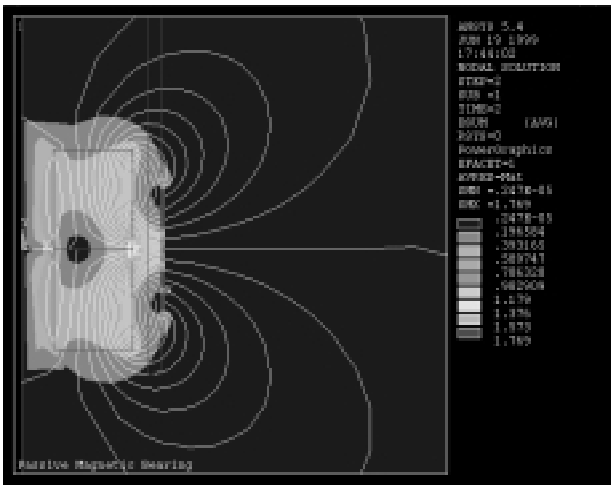


FIGURE 3. Magnetic flux produced by permanent magnets: the red zone (saturated) is a thin layer of ferro-magnetic material not used for preliminary measurements.

When the tube rotates co-axially with static magnets, no variable flux and no eddy currents are produced within the tube (no Joule effects). If the tube rotates eccentrically (Figure 3), eddy currents flow in the copper tube and a magnetic restoring force component is produced.

EXPERIMENTAL RESULTS

Two components of the force exchanged between the eddy currents and the magnets were measured for different rotational velocity and eccentricities of the permanent magnets. The first component is parallel to the displacement and opposite to the eccentricity (restoring force). The second component (crossing force) is perpendicular to the first and to the axis of rotating tube.

In Figure 4 the experimental results are resumed for a particular configuration of the system where we displaced the magnets in the direction of the vertical axis (*y*-axis) from the origin (y = 0 mm) in both directions.

Experimental results were interpolated in order to estimate crossing and restoring stiffness, as function of angular velocity (Figure 5). It can be noted that each component is proportional to the speed.

In Figure 6, we reported the angle between the resultant force and eccentricity in three different cases. The first configuration (curve a) is the same of Figure 4, as expected the angle is near constant (see also Figure 5) but it increases slightly as angular velocity increases.

In the second case (curve b), we concentrated the magnetic flux by a stationary ferromagnetic ring outside the rotating copper tube; the results are similar to the first case.

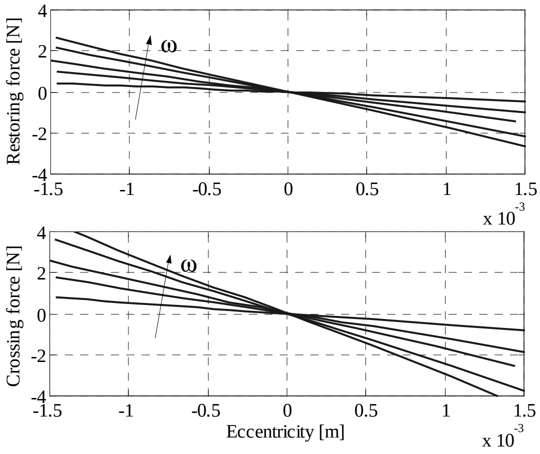


FIGURE 4. Experimental results: in the above diagram the reaction forces due to eddy current are plotted for different values of rotational velocity (from 1000 rpm to 5000 rpm). In the upper graph the restoring component of the force is shown; the lower graph reports the crossing component, the sign of this component is depending from rotation direction.

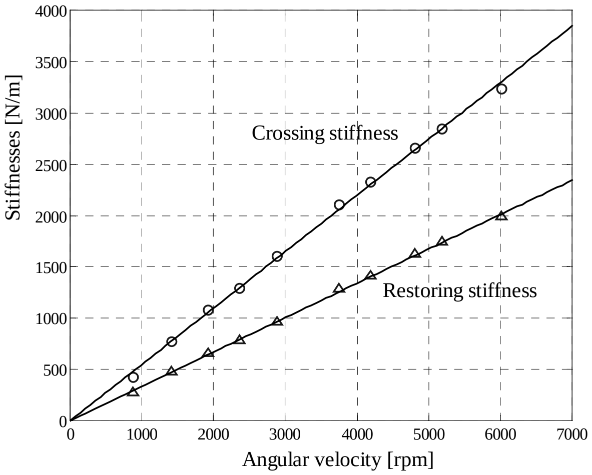


FIGURE 5. Experimental stiffnesses.

In the last case (curve c), we added a thin layer of ferromagnetic material on the rotating copper tube. In this case, there is a static negative (unstable) stiffness that has to be discarded from measurements to analyse just the force produced by eddy currents. As the preceding cases, the angle increases with angular speed, but this trend is more important at low velocity.

CONCLUSIONS & DISCUSSIONS

In this paper we presented preliminary measurements of forces made at the Department of Micro-technique of the Swiss Federal Institute of Technology, Lausanne (EPFL). The forces were produced by the interaction of eddy currents and static magnetic fields from magnets.

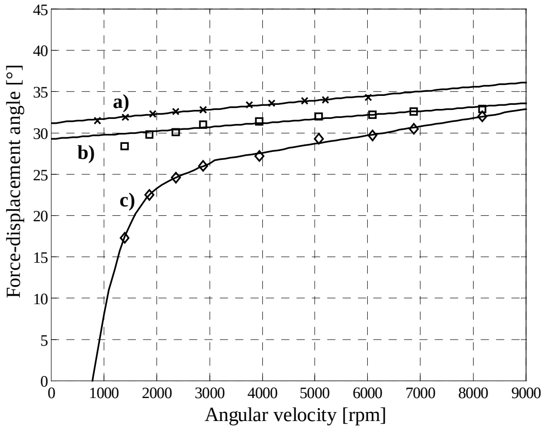


FIGURE 6. Angle between the resultant forces in diverse eccentricity conditions for three different configurations of the system: a) copper tube rotates in the flux produced by permanent magnets fixed, b) the flux of permanent magnets is concentrated by a stationary ferromagnetic ring outside of copper tube, c) the flux from magnets is concentrated by a ferromagnetic ring that rotates with the copper tube.

More experimental measurements are needed to develop a general theoretical analysis; especially the behaviour of axial torque generated by eddy currents should be examined.

Moreover the configuration of eddy currents flowing in the stationary part of the system because of rotating magnets is more interesting for a real eddy currents bearing and it should be examined.

The experimental set-up developed can be used for these purposes

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