EDDY CURRENT BEARINGS FOR MICRO-STRUCTURE LEVITATION

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ABSTRACT

Passive contact free suspension of micro structures attracts great interest due to the recent advances in the field of micro actuators and micro systems.

The goal of the presented project is to explore the potential of eddy current type bearings for micro structure levitation and micro positioning. The basic equations for eddy current forces and losses are derived. The thermal equilibrium of levitated micro structures show the potential of eddy current bearings for very small structures. The theoretical results are verified on different experimental setups with structures sizing a few millimeters. The investigation indicates that micro structure devices of micrometer size can be levitated by eddy current forces without serious thermal problems.

Some interesting arrangements for micro rotor systems which have been realized, are discussed. Three experimental protoypes, two axially levitated micro disc-rotor systems (Fig. 7/8) and a fully levitated micro tube rotor (Fig. 9), are presented. In all cases, the eddy current bearing is not only used for levitation, but also to spin the rotor. Due to their simple mechanical and electronical design, they represent an interesting alternative to active magnetic bearing systems.

1. INTRODUCTION

Work in the field of micro-motors has shown that frictional forces play a dominant role in the dynamics of micro-machines. There are two general ways to cope with this problem. Friction is either used as an integral part of the actuator system or it is removed using non-contact bearings. The first principle was recently studied extensively leading to solutions, as for example impact drive actuators, ultrasonic motors or inch-worm drives. Some of these are already applied in industrial products. Nevertheless, the need for non-contact levitation remains, especially for high speed applications where mechanical wear and longevity is crucial. There are many interesting methods for non-contact levitation [1], [2], [3], [4], [5]. Roughly, we can distinguish the physics of the suspension force (air pressure, electromagnetic, electrodynamic and electrostatic forces) and the method of activation (passive and active systems).

A survey concerning different principles of passive levitation is presented, and then the paper focuses on eddy current bearings. Compared with active electromagnetic and electrostatic bearings, a passive eddy current bearing does not require a sensor system nor a feedback loop. Thus the required space of the actuator and the required electronic devices are minimal. The basic principles of using the repelling forces, caused by eddy currents induced in conducting materials by an oscillating magnetic field, have already been investigated for various large scale applications. However, practical realisations in large scale systems have failed due to thermal problems.

2. PRINCIPLES OF PASSIVE LEVITATION

For contract free levitation of macro structures active magnetic bearings have already proven their feasibility in various industrial application. In active systems, contact free levitation is achieved through a controller which is driving an electromagnetic coil based on a displacement sensor signal. In a passive system, no controller and no sensor system is required. For micro bearing applications, the size of the sensor can be very crucial, due to the limited space. Thus, due to their smaller size, passive bearings seem to be optimal candidates for micro structure levitation.

2.1 Passive Levitation in Static Fields

Passive levitation in a static magnetical field is only possible if the body to be levitated is diamagnetic or superconducting [6]. The reachable forces acting on diamagnetic material in a static magnetic field are very limited and therefore only of minor interest. This is not true for the well known superconductor based bearings [7], which allow moderately high forces. Their major disadvantage is that superconductivity is still only available far below 0° Celsius.

2.2 Passive Levitation in dynamic fields

Various principles for passive levitation in dynamic electrical and magnetic fields have been known for many years [6,8]. The most interesting candidates are the so called LC-Resonance bearings or eddy current type bearings.
Eddy current bearings are the major topic of this paper and will be described in the following chapters.

Electrostatic LC-Resonance Bearings.

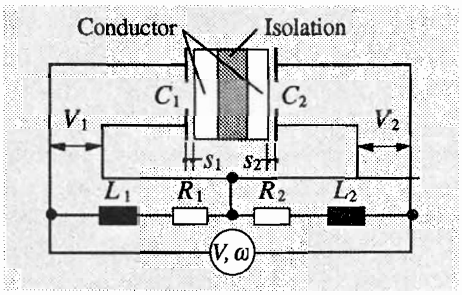

FIGURE 1: Electrostatic LC-Resonance Bearing

The resonance circuit of an electrostatic LC-resonance bearing consists of two capacities (C_1,C_2), two inductivities (L_1,L_2) and two resistors (R_1,R_2). The levitation force is produced by the two capacities C_1 and C_2 acting on the structure to be levitated. The suspended structure consists of two conductor plates which are isolated from each other. For levitation, the resonance circuit, which is driven by an AC-voltage source (V,ω), has to be tuned properly.

Electromagnetic LC-Resonance Bearings.

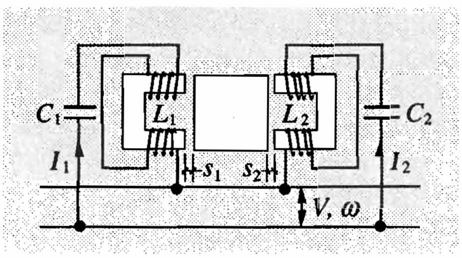

FIGURE 2: Electromagnetic LC-Resonance Bearing

The principle of the electromagnetic LC-resonance bearing is similar to that of the electrostatic type, but the levitation force is produced by the two electromagnetic coils L_1 and L_2 acting on the ferromagnetic structure to be levitated.

3 EDDY CURRENT TYPE BEARINGS

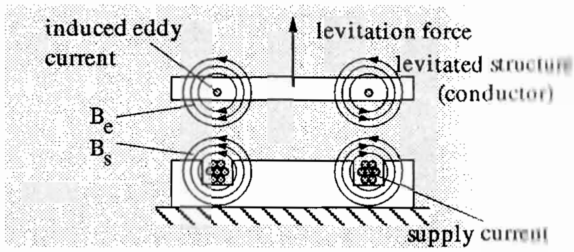

FIGURE 3: Eddy current type bearing

The eddy current type bearing takes advantage of the induced current in the conducting material. The magnetic field B_s produced by the sinusoidal supply current in the coil induces eddy currents in the structure to be levitated. The eddy current itself then produces a magnetic field B_e. The resulting net field B_r is horizontal in the air gap and thus, according to the law of Biot-Savart, a repulsive force is created between the coil and the levitated structure.

3.1 Calculation of the Eddy Current Forces

Experiments with eddy current type bearings have been documented for many years [9], but quantitative layout equations are unknown to the authors.

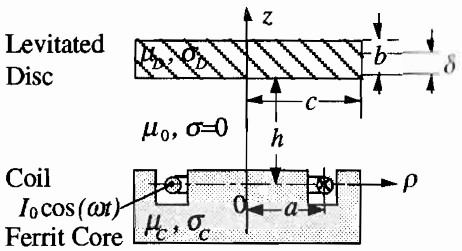

FIGURE 4: Single coil model of an eddy current bearing

A single-coil model of an eddy current bearing was studied first to gain understanding and verify the equations for the repulsive force (1) established by Neubauer in an earlier work.
According to figure 4, a circular AlMg disc with a diameter of $2c$ is levitated by a coil with a diameter of $2a$, carrying the sinusoidal current $I_0\cos(\omega t)$ on its N windings

The coil is centered in the plane $z = 0$ below a conducting half-space $z \geq h$ in which the eddy-currents of skin-depth $\delta = (\pi f \sigma \mu)^{-1/2}$ are induced. This spin-problem involves 3 subdomains and characterizes a second order boundary value problem which is subject to an external boundary condition at the cylindrical surface $\rho = c$ that requires the normal magnetic flux component to vanish. Solutions are integer order Bessel functions of the first kind and of real arguments. The repulsive force was found to be

$$F_D = -\mu_0 N^2 I_0^2 \pi \langle \frac{a}{c} \rangle^2 \sum_{i=1}^{\infty} Re \left\{ \frac{1-\lambda_i}{1+\lambda_i} \right\} \frac{J_1^2\left(\rho_i \frac{a}{c}\right)}{J_0^2(\rho_i)} e^{-2\rho_i \frac{h}{c}}$$

$$\lambda_i = \sqrt{1 + j \frac{2}{\rho_i^2} \left(\frac{c}{\delta}\right)^2} \qquad \delta = \sqrt{\frac{1}{\pi f \sigma \mu_0}} \qquad (1)$$

$\mu_0 = 4\,\pi \cdot 10^{-7}$ Vs/Am (permeability of air)
J_0: zero order Bessel function
J_1: first order Bessel function
$\sigma = 35\ 10^6\ m^{-1}$ (conductivity of levitated disc)
$j = \sqrt{-1}$

Quantity ρ_i denotes the zeros of the first order Bessel function of the first kind. The excitation current amplitude I_0 and the levitation force required to suspend the disc at a certain height h was calculated according to equation (1).
A comparison between calculated and measured results show Figure 5 and 6. Equations 1 allows at least for a rought layout of an eddy current bearing.

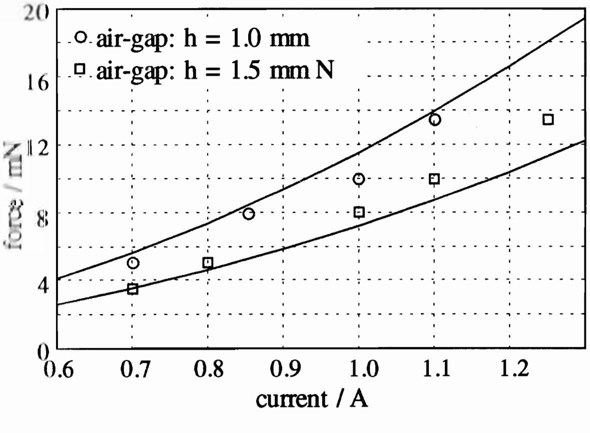

FIGURE 5: Measured and calculated eddy current forces as a function of the current in the coil.
N=100; a= 6.5 mm; b= 0.4 mm; c= 10 mm;
f= 18 kHz; σ=35 10^6 m^{-1};

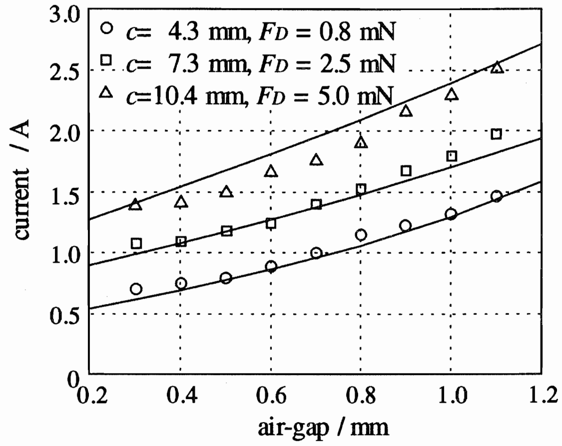

FIGURE 6: Measured and calculated current for different air-gaps and levitation forces.
N=42; a= 3 mm; b=0.55 mm; c= 10 mm;
f= 43 kHz; σ=35 10^6 m^{-1};

3.2 Thermal properties of eddy current bearings

In macroscopic applications, eddy current bearings have not been very successful due to their thermal problems. Nicolaisen [9] reported temperatures above 100° Celsius for his experimental rotor system. Nevertheless, a reduction of the thermal problems is expected for micro structure levitation.
Quantitative calculations of the eddy current losses are very difficult and were not carried out in this project. However, a qualitative description of the eddy current losses was found to be:

$$P_e = k \cdot F_D \sqrt{\frac{f}{\mu_0}} \qquad (2)$$

A similar result has also been reported by other authors [10]. The constant k is dependant on the conductivity of the levitated structure.
The measured eddy current losses for a levitated disc of 20 mm diameter shown in table 1 qualitatively confirm equation (2). However, additional measurements are required to properly quantify the constant k and to verify the frequency dependence.

TABLE 1: Measured eddy current losses for different bearing forces. f=18 kHz

Bearing Force F_D	Eddy Current Losses P_e
$3.5 \cdot 10^{-3}$ N	1.19 W
$7.0 \cdot 10^{-3}$ N	2.56 W
$10.5 \cdot 10^{-3}$ N	4.2 W

For the thermal layout of an eddy current bearing, the thermal equilibrium between heat production by the eddy current losses P_e in the structure and the cooling by convection P_c. For a horizontal platform (disc) we can find in the literature [11].

$$P_c = \frac{dQ}{dt} = \alpha A_L \Delta T = P_e \tag{3}$$

A_L: convection area
α: convection parameter

Parameter α depends on the geometry of the setup, of the material properties, and the flow characteristic. It can be estimated using appropriate values found in data books or, for more accurate results, it has to be identified by experimental measurements.
For our example setup, the temperature of the levitated disc ($A_L = 3.14 \cdot 10^{-4}$, diameter 20 mm, thickness 0.4mm) was measured. Based on the temperature measurement, the convection parameter α was calculated according to equation (3) and the measured eddy current losses (table 1). As expected, the calculated convection parameter is nearly constant for all measurements with a minor improvement for high temperature difference.

TABLE 2: Measured temperature differences and calculated

Bearing Force F_D	Temperature ΔT	Calculated Convection Parameter α
$3.5 \cdot 10^{-3}$ N	56° K	67 W/Km²
$7.0 \cdot 10^{-3}$ N	123° K	66 W/Km²
$10.5 \cdot 10^{-3}$ N	169° K	79 W/Km²

The bearing force of $3.5 \cdot 10^{-3}$ N represents the weight of the levitated disc itself. With its temperature rise of 56° Kelvin, an absolute temperature around 75° Celsius is reached which is not unusual for a rotor system.

4. EXPERIMENTAL PROTOTYPES

Various prototypes of eddy current type bearings have been investigated.

Levitated disc with continuous rotation. The first multiple-coil levitation system consists of six stationary ferrite pot coils (figure 7) In this arrangement the coils 1,3,5 and 2,4,6 are connected in series. A capacity is in series with the coils, building an oscillating circuit with a resonance frequency of $\omega = 1/\sqrt{LC}$. The oscillating circuit is driven by a square wave voltage source with an adjustable frequency around 50 kHz. The current amplitudes are in the range of 500 mA. The asymmetric aluminium rotor is levitated 1 mm above the coils. If the activation of coils 1,3,5 and 2,4,6 are alternated, the rotor turns around the centre pole in steps of 60 degrees.

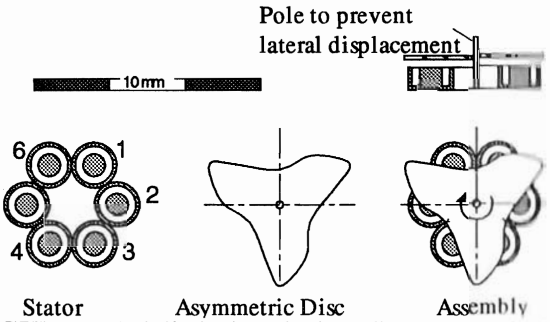

FIGURE 7: Axially levitated micro disc-rotor system with integrated stepping motor.

Levitated disc with continuous rotation. The second design, similar to the first design, consists of six stationary ferrite pot coils (figure 8). However, in this arrangement only the coils S1, S2 and S3 used to levitate the AlMg-disc of 34 mm diameter and 0.55 mm thickness. The drive coils L1, L2 and L3, with half shaded pole tops as displayed, allow the suspended disc to rotate continuously if supplied with 120° phase displaced sinusoidal currents. Speeds up to 800 rpm have been reached.
The intended operational mode, however, is rotation or multi-directional linear disc positioning in microsteps. This was realized with driving currents of carrier frequency $f_c = 50$ kHz, modulated by short pulses $f_m \leq 1$kHz [12].

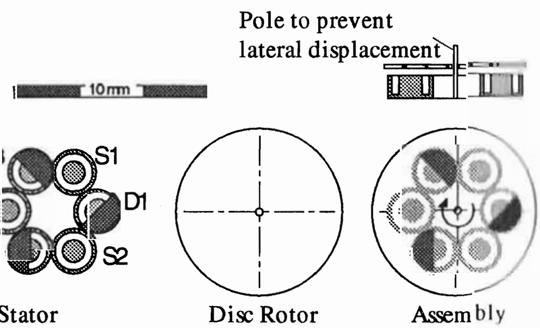

FIGURE 8: Levitated micro disc-rotor with integrated continuous drive

Levitated rotor with continuous rotation. The third design consists of a fully levitated aluminium rotor. The little tube rotor with a diameter of 5 mm and a length of 20 mm is levitated with an air-gap of about 1 mm. All coils are driven by a single oscillation circuit. By partially shading the coils in the *xz*- or *yz* -plane the rotor starts to spin without any additional electronic hardware. With

a well balanced rotor, speeds up to 1000 rpm have been reached. Rotor temperatures in the range of 70° Celsius were observed, depending on the levitation height.
This design represents the simplest and cheapest electromagnetic bearings system with a fully levitated rotor and an integrated motor drive. Possible applications are micro gyros or other sensor systems.

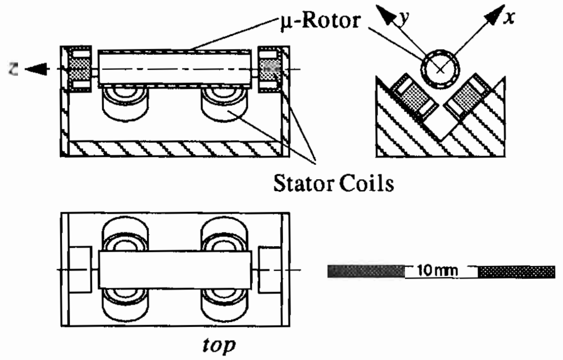

FIGURE 9: Levitated micro tube-rotor

5 SUMMERY AND OUTLOOK

Basic layout equations for eddy-current bearings have been established and verified at different prototypes. For microstructure levitation moderate rotor temperature of 60° to 100° Celsius have been reported. The results have shown the potential of passive levitation with eddy current bearings for small structures.
Eddy current bearings can therefore be a simple and cheap alternative to active electromagnetic or electrostatic bearings. The results of the project can easily be extended to even smaller structures, e.g. for rotors sizing less then 1 mm.
Future investigation, to combine the eddy current bearing with micro positioning, have already been started [12]. New designs have to be found to improve the poor damping values of eddy current bearings.

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