HYBRID ELECTROMAGNETIC AIR BEARING SYSTEMS

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ABSTRACT
In this paper a study to the challenges of air bearings with dynamic electromagnetic preloading is presented. Two configurations are compared, one in which the electromagnet is constructed into the center of the air bearing and one in which the electromagnet acts at the surface of a compliant membrane air bearing. The membrane air bearing with electromagnetic actuated membrane can also be applied with a non metallic guide surface. Active electromagnets integrated in the bearing structure offer a promising solution of applying a dynamic preload with which a) running accuracy can be improved, b) the load capacity can be increased significantly and c) a near infinite bearing stiffness can be realized. It is studied to what extend the bearing can be adjusted vertically by varying the magnetic preload quasi static and dynamically. With knowledge of the dynamic response of the bearing system, deviations of straightness and elastic response of the guide surface to dynamic loading can be controlled by feed forward.

NOMENCLATURE
A surface area
Aᵣ cross section restrictor
B magnetic field
Cᵧ constriction coeff.
F load capacity
H field intensity
h film thickness
h₀ flying height
M mass flow
pₛ supply pressure
pᵣ restrictor pressure
pₐ ambiant pressure
pᵣ restrictor pressure
r₀ outer radius
r₁ inner radius
T₀ temperature
κ ratio of specific heat
η gas viscosity
μ permeability

INTRODUCTION
Aerostatic bearings are advantageous over contact bearings in high precision motion and position stages because of their near zero friction, smooth operation and high bearing stiffness. Axial bearing stiffness is an important factor in overall performance of stages. Preloading is a method of increasing bearing stiffness. The most frequently applied method of preloading is by configuring two air bearings on opposite sides of a guide rail. This requires two parallel guide surfaces and a suitable bearing housing to keep the bearing assembly pre-stressed.

Vacuum preloading or magnetic preloading offers an elegant solution of preloading without the need of the two parallel guide surfaces and the extensive bearing assembly. Magnetic preloading requires a metallic guide surface generally a chromed steel or metal strips mounted onto a granite or ceramics base. Permanent magnets are often mounted centered between two or three air bearings. The static preload can be adjusted via the air gap between the magnet and the metal surface. In vacuum preloaded bearings the vacuum preload force is created in the center area of the bearing where a vacuum is drawn. The collar bearing around the vacuum area creates a seal preventing contaminants to be vacuumed in the bearing gap.

In this paper a study is presented to the challenges of air bearings with dynamic electromagnetic preloading. Two configurations are compared, one in which the electromagnet is provided with a flat air bearing surface (Figure 1) and one in which the electromagnet acts at the surface of a compliant membrane air bearing (Figure 2). The membrane air bearing with electromagnetic actuated membrane can also be applied with a non metallic guide surface. The analytical modeling of this configuration is further discussed in [1].
Active electro-magnets integrated in the bearing structure offers a promising solution of applying a dynamic preload with which a) running accuracy can be improved, b) the load capacity can be increased significantly and c) a near infinite bearing stiffness can be realized.

FIGURE 1. Electromagnet (left) combined with a flat air bearing surface (right). The air bearing is fed through a simple orifice which is applied in a set screw. This set screw is screwed in the center of the bearing.

FIGURE 2. Electromagnet constructed into a compliant membrane air bearing.

The flying height of the bearing shown in Figure 1 can be adjusted dynamically by varying the preload. It is studied to what extent this vertical displacement can be applied to improve running accuracy by compensating for deviations in straightness of the guide surface and for elastic distortions of the guide as a result of dynamic loading. With knowledge of the deviation of straightness and elastic response to dynamic loading running performance can be optimized by feed forward control.

A static preload improves bearing stiffness at the cost of the load capacity of the bearing. Usually up to 80% of the load capacity of a bearing is consumed in order to preload the bearing assembly. A variable preload makes it possible to compensate for additional forces and thus making the full load capacity of the bearing available for these forces.

A near infinite bearing stiffness is possible by coupling the flying height to the magnetic preload. The research is focused on the coupling of a measurable deviation of the nominal flying height to dynamic control of the magnetic preload. Important issues are the non-linearity and dynamic response of both the stiffness of the electro magnet and that of the air bearing.

HYBRID BEARING MODELLING
The bearing performance of the hybrid bearing is predicted by superposing the characteristics of the air bearing and electro magnet.

Air Bearing
Bearing stiffness is generally created by orifices, porous surfaces or groove compensation. Orifice compensation is the most widely applied in high tech applications, because of the constructive simplicity. The bearing performance can be analyzed by considering the flow resistance of the restrictor and the thin air film created between the bearing and the guide surface.

For the pure inertia flow of a compressible fluid through orifices the mass flow is equal to [2]:

\[
M = C_D \cdot A \cdot \rho_0 \sqrt{\frac{2RT_s \cdot \kappa}{\kappa - 1} \left( \frac{p_r}{p_s} \right)^{\frac{\kappa}{\kappa - 1}} - \left( \frac{p_r}{p_s} \right)}
\]

where \( A \) is the cross section area of the hole for simple orifices, \( C_D \) the coefficient of discharge and \( \kappa \) the ratio of specific heats. The pressure ratio \( p_r/p_s \) is limited at the lower end by the flow velocity which can only go as far as the speed of sound, for air \( p_r > 0.53p_s \).

Basic formulae for the radial flow through a long parallel film (Re<500 and \( (r_0-R_1)/h>40 \)) can be written:

\[
\left( \frac{p_r}{p_s} \right)^2 = \left( \frac{p_r}{p_a} \right)^2 - \ln \left( \frac{r_0}{r_i} \right) \left( \frac{p_r}{p_a} \right)^2 - 1
\]

\[
F = \int_{r_1}^{r_0} 2\pi p(r) r dr - p_a \pi \left( r_0^2 - r_i^2 \right)
\]

\[
M = \frac{\pi h^3}{12\ln\left( r_0 / r_i \right)} \cdot \eta RT
\]
The pressure factor $\beta$ is defined as the ratio of the pressure drop over the film and the total pressure drop:

$$\beta = \frac{p_r - p_a}{p_s - p_a}$$  \hspace{1cm} (3)

The load capacity and flow rate can now be calculated with prescribed radii of the bearing surface, properties of the gas, pressure drop over the film $p_r - p_a$ and flying height $h$. The dimensions of the orifice can be calculated next, with prescribed $C_D$-value.

The bearing stiffness is derived from the change in flying height and load capacity as a result of an infinitesimal increase of the restrictor pressure $p_r$. Various configurations are analyzed in [2] and calculators of these bearing configurations are made available at www.tribology-abc.com. Figure 3 shows the calculated load capacity and stiffness of the orifice compensated circular air bearing as a function of the $\beta$-value and flying height.

The magnetic force can be estimated by:

$$F = \frac{B^2 A}{2 \mu_0} \quad \mu_0 = 4 \pi \cdot 10^{-7} \text{ H m}^{-1}$$  \hspace{1cm} (4)

where $F$ [N] is the force, $B$ [Tesla] the magnetic field, $A$ [m$^2$] is the area of the pole faces, $\mu_0$ is the permeability of free space and $H$ the field intensity. For a closed magnetic circuit can be written:

$$B = \frac{\mu N I}{L}$$  \hspace{1cm} (5)

where $\mu$ is the permeability of the core, $N$ is the number of turns of wire, $I$ [A] is the current and $L$ is the length of the magnetic circuit. Substituting (5) in (4) gives:

$$F = \frac{\mu^2 N^2 I^2 A}{2 \mu_0 L^2}$$  \hspace{1cm} (6)

A strong electromagnet requires a short magnetic circuit with large area. Most ferromagnetic materials saturate around $B=1$ to 2 Tesla. This occurs at a field intensity of $H=787$ Ampere-turn/meter. The maximum load per unit area $F/A$ then ranges between 398 kPa (1 Tesla) and $F/A=1592$ kPa (2 Tesla) respectively.

Figure 4 shows the measured magnetic force of the electromagnet as a function of the air gap $\delta$.

**Electromagnet**

The main advantage of an electromagnet over a permanent magnet is that the magnetic field can be controlled at high frequencies. However, a continuous electric energy is required to maintain the field. A combination of a permanent magnet to supply the stationary preload and an electromagnet to compensate for dynamic loading might be an option. Since the electric energy needed to compensate for both the stationary preload and dynamic compensation was found to be very low the permanent magnet is skipped.

The power needed (2.5 Watt) to stationary preload the air bearing was only 50% of the nominal power of the electromagnet.
Hybrid bearing system

Figure 5 shows a typical characteristic of the flying height in time as a result of a negative load step. The flying height of the orifice compensated air bearing has increased by a decreased bearing load. The slope dh/dt as a result of the load step depends on the damping in the air film.

The recovery of the flying height in the electromagnetically controlled air bearing is obtained by adapting the electromagnetic preload. This requires a continue position measurement as input for a PID controller which determines the current through the electromagnet. The overshoot and settling time are minimized by optimal PID settings.

The stiffness of the air bearing contributes to the semi infinite stiffness realized with the help of the electromagnet. This implies the need of a restrictor. If the flying height is to be adjusted within a wide range it is preferable not to limit the flow rate by means of a restrictor. The stiffness then becomes purely dependent on the controlled magnetic field.

TEST SETUP

Figure 6 shows the actively controlled air bearing in the test setup. The flying height is measured by an inductive probe and used as input for a PID controller which is programmed in LabView. The output of the PID controller is connected to a current supply connected to the electromagnet. The bearing is loaded in the center. A load step is realized by removing a dead weight. The measured overshoot and settling time are studied for a range of PID-settings.

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