Novel Combination Radial/Axial Homopolar Active Magnetic Bearing

Alexei V. Filatov Lawrence A. Hawkins
Calnetix Technologies LLC.
16323 Shoemaker Av., Cerritos, CA 90703
afilatov@calnetix.com lhawkins@calnetix.com

Abstract

A novel combination radial/axial homopolar permanent-magnet-biased electromagnetic actuator for application in active magnetic bearings is proposed. The design combines the best features of the earlier solutions: shorter axial length, lower part count, lower aerodynamic drag, lower negative stiffness and lower cost typical for combination bearings along with better axial bandwidth typically demonstrated in arrangements of separate radial and axial bearings. Furthermore, for most machines, the actuator topology leads to rotor construction that results in a higher first bending mode frequency than previous designs.

1. Introduction

A typical configuration of a rotating machine on magnetic bearings includes two radial bearings supporting two opposite ends of a rotor and an axial bearing [1]. In some machines the functions of a radial bearing and an axial bearing are combined in one device - a so called combination radial/axial magnetic bearing [2]. Each of these solutions (an arrangement of dedicated radial and axial bearings or a combination radial/axial bearing) has its own advantages and disadvantages. Typically, machines using the combination radial/axial bearing benefit from its shorter axial length, lower part count, lower aerodynamic drag (due to a lower actuator target diameter) and a lower negative stiffnesses (both radial and axial). At the same time, dedicated axial bearings can deliver higher dynamic load capacities (bandwidth). A more detailed comparative analysis of these characteristics of two magnetic bearing solutions is provided below.

Fig. 1a shows a typical arrangement of dedicated radial and axial magnetic bearings. An electrically-biased thrust bearing commonly used in this arrangement consists of two electromagnets (Z+ and Z-) located on two axially opposite sides of an actuator target attached to or made as a part of a rotor as shown in Fig.1b.

In order to achieve a linear force-current response, each electromagnet in Fig. 1b is energized with two currents: bias and control (I_0 and I_c respectively) [1]. These bias and control currents can be either both accommodated in a single winding, or two independent windings can be used: one for the bias current and one for the control current. In either case, the arrangement should be such that when the control current adds to the bias current in one electromagnet, it subtracts from it in the other (the bias current is maintained constant). For example, if the control current is added to the bias current in the electromagnet Z+, while being subtracted from it in the electromagnet Z-, the electromagnetic pull from the Z+ electromagnet will be stronger than from Z-magnet and the net force will develop directed towards the Z+ magnet. Reversing the control current reverses the direction of the force.

In all commercial implementations of the actuator shown in Fig. 1b known to the authors, an approach with a single coil accommodating both the bias and control currents is implemented. The advantages of this approach are fewer terminal wires, no separate bias current source, less complexity and less cost, while the disadvantage is a lower dynamic force capacity due to increased inductance of the combined bias/control coil.

The design and operation of an alternative solution, a combination radial/axial bearing historically used by the authors, is illustrated in Fig.2. Fig. 2a shows a partial cross-section of the bearing and explains a mechanism of generating an axial force. In an absence of a current in the axial control coil, permanent magnets generate the same bias magnetic fluxes in the axial gaps between the faces of the actuator target and the axial poles (assuming that the actuator target is centered between the poles), and, consequently, magnetic forces pulling on two opposite faces of the actuator target are the same as well. This results in a zero net axial force.

When an axial control current is applied, however, the magnetic fluxes in two gaps won't be the same anymore, and an axial force will be generated. For example the axial control current directed as shown in Fig.2a will produce an axial control flux that will add to the bias flux in the axial gap on the left and subtract from it in the axial gap on the right. Therefore, the net magnetic flux density on the left side of the actuator target will be

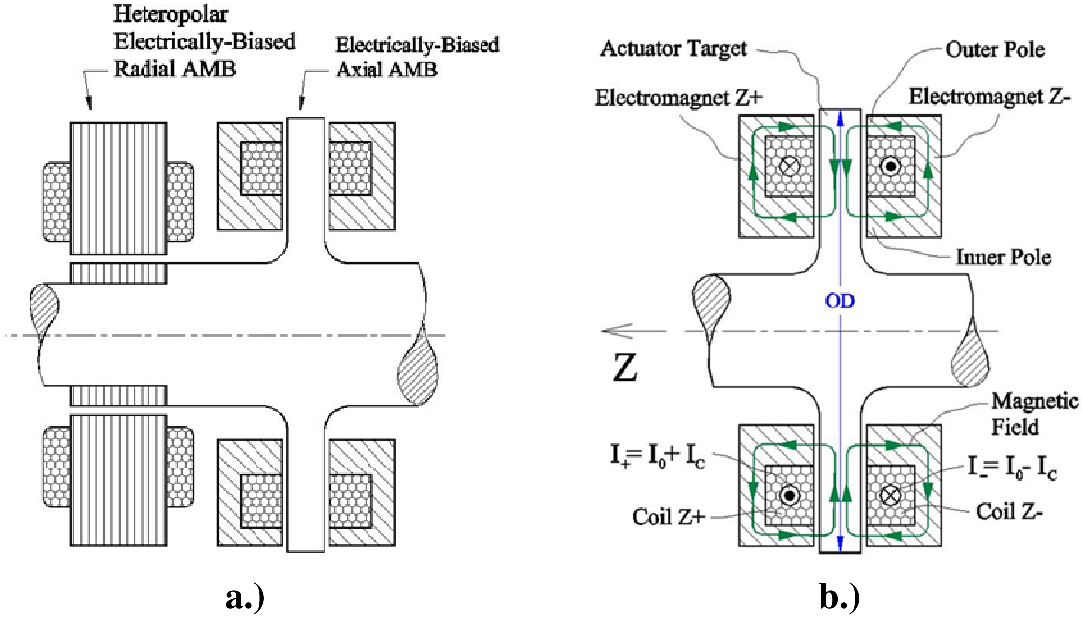


Figure 1: Typical arrangement of separate radial and axial electromagnetic actuators (a) and details of a typical electrically-biased axial actuator (b).

higher than the net magnetic flux density on the right side of the actuator target and there will be a net magnetic force $\mathbf{F_{ax}}$ pulling the actuator target to the left.

The same combination bearing is also capable of generating a radial force. This is clarified by way of an example in Fig. 2b which gives an axial schematic view of the radial actuator portion and illustrates generation of a radial force $\mathbf{F_Y}$ in the vertical Y direction. As can be observed from Figs.2a and 2b, the bias magnetic flux generated by the permanent magnets is directed radially outwards in all radial control poles. When any two diametrically-opposite radial control windings are energized with control currents (e.g. Fig. 2b shows two vertical windings energized), they produce a radial control flux. In the example shown in Fig. 2b this radial control flux adds to the bias flux in the top radial gap and subtracts from it in the bottom radial gap resulting in the magnetic force F_Y directed upwards (towards a larger magnetic flux).

Both standalone axial bearings and axial channels of combination bearings typically have lower axial

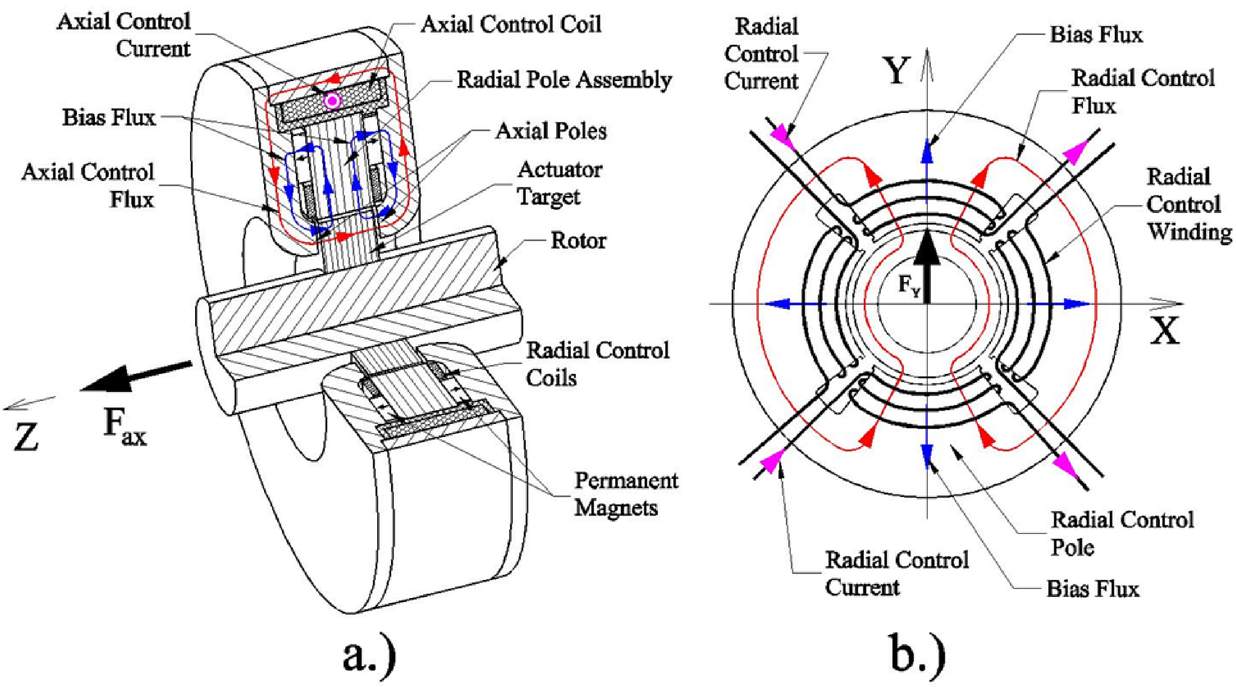


Figure 2: Construction and operation of the original radial/axial combination actuator.

bandwidths than either standalone radial bearings or radial channels of combination bearings - they cannot react to dynamic axial forces as well as radial bearings react to dynamic radial forces. In other words, the axial force that can be produced by either a standalone axial bearing or an axial channel of a combination bearing falls with frequency much sooner than the force of a radial bearing/channel. In addition, the phase lag between the axial force and the axial control current increases with frequency faster, which leads to a requirement of a controller with higher dynamic gain to achieve robust operation.

One reason for a limited bandwidth of the axial bearings and axial channels of the combination bearings is that it is impractical to laminate portions of the bearings containing axial magnetic control flux - something that can be easily done in the radial bearings. Alternating magnetic flux flowing in solid steel induces eddy currents which eventually lead to the bearing bandwidth deterioration [3-7]. Fig. 3a shows a magnetic flux distribution that would be observed at 10Hz in an electrically-biased axial magnetic bearing such as shown in Fig. 1b, whereas Fig. 3b shows a magnetic flux distribution that would be observed at 10Hz in the original combination radial/axial magnetic bearing design of Fig.2. In both designs the magnetic flux gets attenuated and experiences a phase lag with respect to the control current when flowing in a non-laminated iron. The longer flux path in a non-laminated iron, the bigger the attention and the phase lag.

By comparing Figs. 1b and 2a, as well as 3a and 3b, one can see that the length of the axial control magnetic flux path in the original combo bearing is longer than in a dedicated axial bearing; thus a bigger flux attenuation and phase lag. In addition to the longer path, in a combination bearing the axial magnetic control flux path through the actuator target is surrounded by electrically-conductive laminations of the radial actuator portion. Whenever the axial magnetic control flux through the actuator target changes in time, a circular electromotive force is induced around the actuator target in accordance with Faraday's law, which in turn, produces an electrical current flowing in the laminations of the radial actuator portion around the bearing axis. This current then induces its own magnetic field in the actuator target, which reduces the amplitude of the original control field and increases the phase lag between the net control magnetic field and the axial control current.

This situation is illustrated in Fig. 4a, whereas Fig. 4b shows distribution of the electrical current in the original combination bearing calculated with FEA. Changes of the net axial magnetic field translate into similar changes of the axial force exerted on the actuator target.

A combination bearing design improvement described in [8] allows one to eliminate this additional source of the bearing bandwidth deterioration, but at a cost of the increased design complexity. On the contrary, the design proposed here is not any more complex than the original combo bearing and, in fact, is even easier to assemble. It completely eliminates the original source of the bandwidth deterioration caused by having an additional closed current loop around the flux path (see Fig.4). Furthermore, the length of the axial control magnetic flux path lying in a non-laminated iron is often even shorter than in a dedicated axial bearing such as shown in Fig.1b.

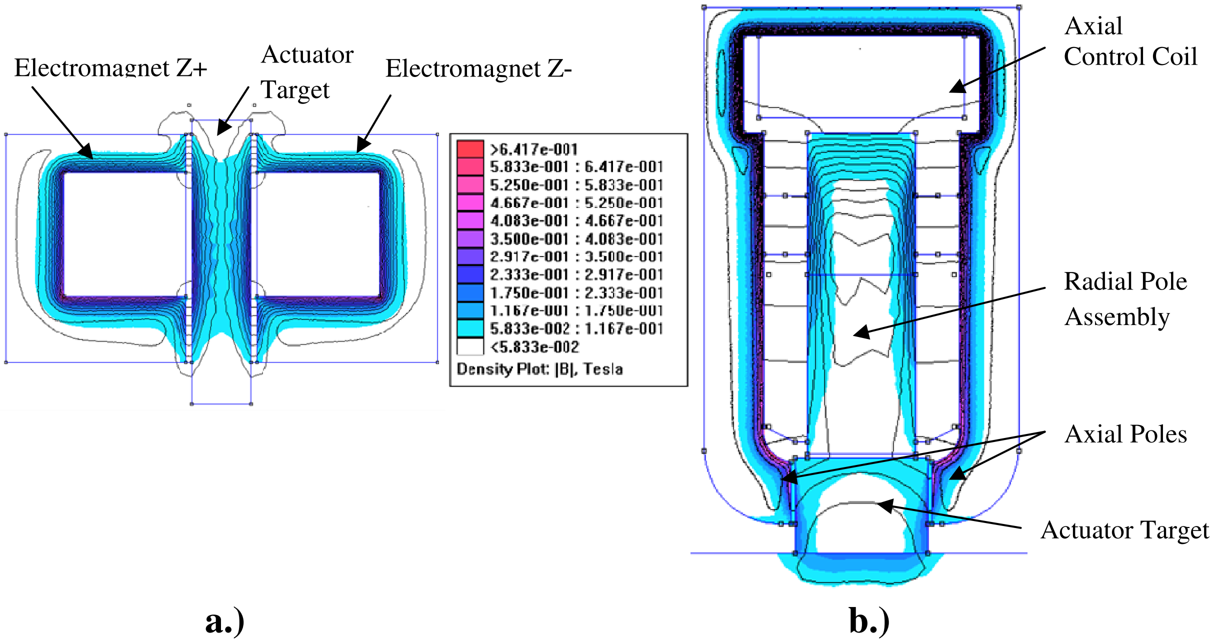


Figure 3: An example of an axial control magnetic flux distribution at 10Hz in an electrically-biased axial actuator (a) and in the original combination radial/axial actuator (b).

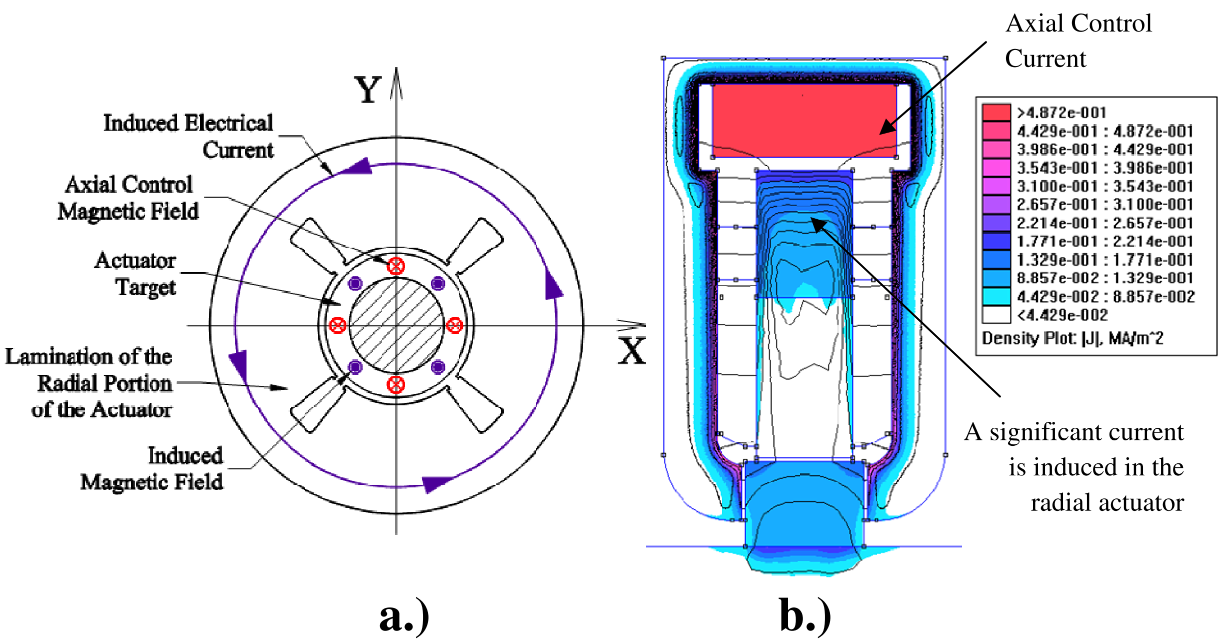


Figure 4: Mechanism of affecting the axial control force through inducing an electrical current in laminations of the radial portion of the original combination actuator (a) and an example of electrical current distribution in the original combo actuator at 10Hz calculated with FEA (b).

2. Bearing Design

The structure of the new combination radial/axial magnetic bearing is illustrated in Figs. 5 and 6. Figure 7 explains the bearing operation. A similar bearing concept has been described previously, for example in [9], but has not been used commercially or even widely known. This is likely because the axially asymmetric nature of this design introduces unique problems, which did not exist in the symmetric version shown in Fig. 2. As will be discussed later, the present design has been proven to overcome those problems and fully realize the potential of an asymmetric combo bearing.

Because in the new bearing of Figs. 5 and 6 the radial and the axial magnetic circuits are located side by side, whereas in the original design of Fig. 2 the radial magnetic circuit was enclosed within the axial circuit, we gave the new design the name *Side-By-Side* (SBS) Combination Bearing.

The radial pole assembly of the new bearing shown in Figs. 5 through 7 is essentially identical to that of the original combination bearing per Fig. 2 and so is the method of generating radial forces. Furthermore, in both the new and the original combination bearings, the axial and the radial bearing channels share the same bias flux generated by a common bias magnet. In contrast to the design shown in Fig.2, however, the new design uses two separate targets to exert radial and axial forces: a laminated target for the radial forces and a solid target for the axial forces. The latter can be also made integral to the shaft.

In practice, having separate targets is mostly an advantage because a solid-steel target can have much higher mechanical strength than a laminated one, especially if it is made integral to the shaft. Since developing certain axial magnetic forces requires certain surface areas of the target faces, the axial load capability of the design shown in Figs. 5-7 is no longer limited by the surface areas of the axial faces of the laminated targets as it is with the original combination bearing. This lends more flexibility to the new design since the axial face areas in the original design are constrained by: 1) desired shaft cross sectional area, which sets the minimum ID, and 2) stresses developed in laminations at speed, which limits the OD (strength of a lamination stack is much lower than strength of a typical solid carbon steel).

Another significant advantage of the new bearing of Figs. 5 through 7 for turbomachinery applications is that the shaft is tapered towards one side, and, as a result, the machine can be laid out so that the rotator gradually reduces in a diameter towards the end - a geometry that normally is desirable to increase the first bending mode frequency.

On the contrary, the diameter of the shaft in Fig.2 is limited by the inner diameters of the axial poles (plus some radial gaps needed to limit magnetic flux leakage from the poles to the shaft) on both sides from the actuator target. Furthermore, since the actuator target in Fig. 2 is laminated, it does not contribute to the bending

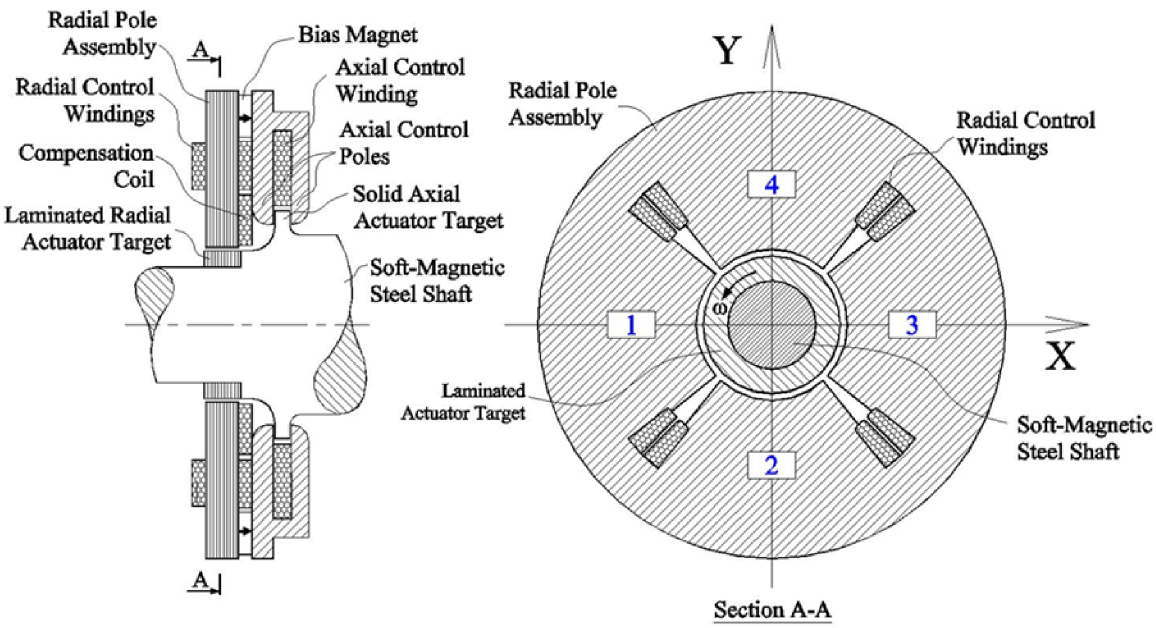


Figure 5: New 'Side-By-Side' combination magnetic bearing design.

stiffness of the shaft but adds a localized mass. All of these normally limit the frequency of the rotor first bending mode.

A big difference between the designs shown in Fig. 2 and Figs. 5-7 is that the latter lacks the symmetry of the design in Fig.2 with respect to the axial middle plane: the bias magnet, the axial control coil and both axial poles are located on one side of the radial pole assembly. The consequence of this fact is that an axial control current will produce a leakage flux illustrated in Fig. 8 in addition to the axial control flux, which will affect the bias flux both directly (by superimposing on the bias flux generated by the permanent magnet) and indirectly, by affecting the operating point of the magnet.

As will become apparent from the discussion of the experimental results, having this leakage flux may have a serious negative impact on both radial and axial load capacities of a bearing. It also would make the bearing control much more difficult, since the radial actuator parameters such as gain and negative stiffness would become functions of the axial control current and the axial force-current dependence would become highly

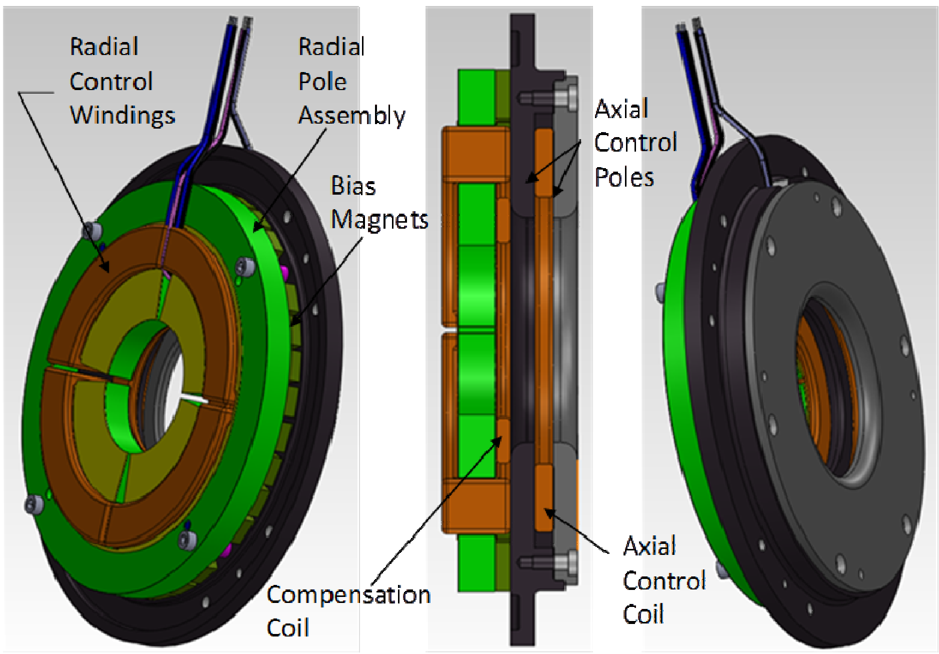


Figure 6: 3D rendering of the new 'Side-By-Side' combination magnetic bearing.

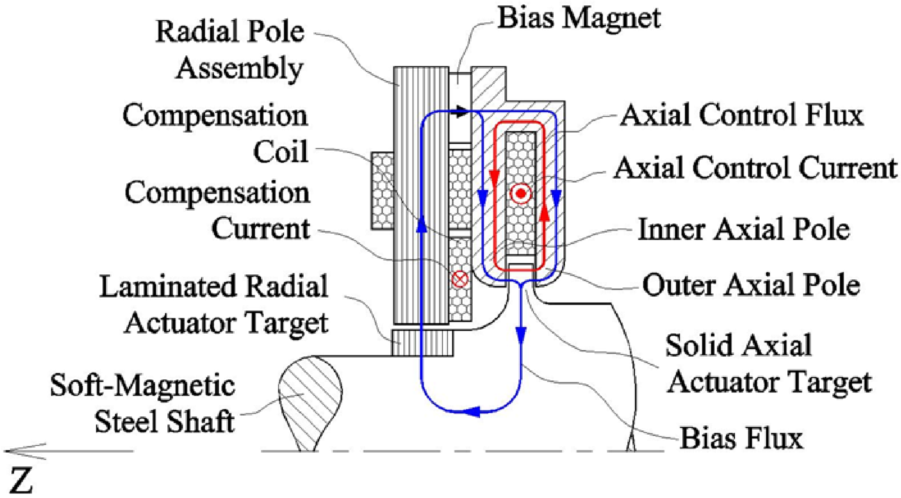


Figure 7: Operation of the new 'Side-By-Side' combination magnetic bearing.

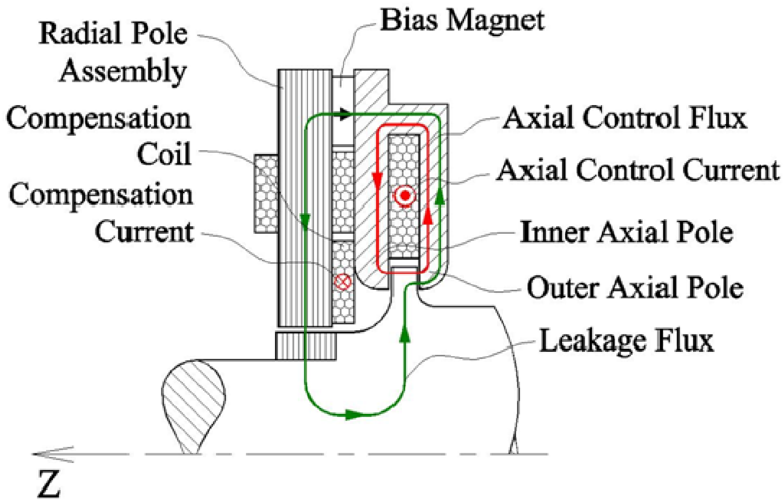


Figure 8: In the absence of a compensation, a leakage magnetic flux produced by the axial control current would affect the bias flux generated by the magnet.

asymmetric (this also would mean different axial load capacities in different directions).

In order to overcome the above problems caused by an asymmetric nature of the new design, a compensation coil is introduced located underneath the bias magnet in between the radial pole assembly and the inner axial pole (see Figs. 5-8). The compensation coil is energized with a current proportional to the axial control current but flowing in the opposite direction in order to produce a compensation magnetic flux opposing the leakage flux shown in Fig. 8. In practice, the compensation coil can be simply connected in series with the axial control coil and wound in the opposite direction. By choosing a proper ratio between number of turns in the axial control coil and the compensation coil, it is possible to effectively eliminate the effects of the leakage flux. With the introduction of this compensation coil the asymmetric combo bearing design presented for example in [9] becomes much more practical.

Figure 9 shows estimated improvements of the axial actuator transfer function by comparing the transfer functions of the original version of the combo bearing (Fig.2) and the current one. Both actuators were sized for 3000N axial load capacity, 1225N radial load capacity and 32000RPM operating speed. The transfer functions were calculated using FEA program FEMM [10].

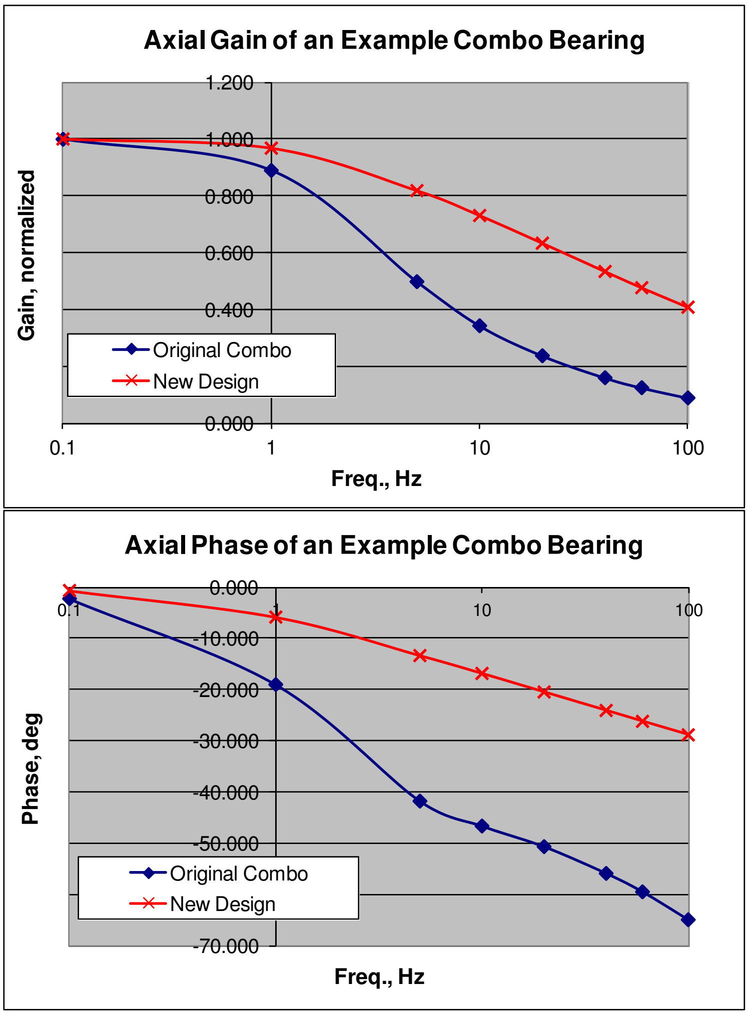


Figure 9: Axial actuator transfer function improvement in an example combination bearing with 3000N axial / 1225N radial load capacities designed for 32,000RPM.

3. Test Setup

The test setup used for evaluating the new bearing is shown in Fig. 10. The bearing evaluated in this setup was built for a commercial machine and has since been commissioned and is operating in several field installations. The bearing has 1070N/350N axial/radial load capacities and has been successfully tested within the machine at 70,000RPM operating speed.

The right end of the rotor mockup was supported by a linear ball bearing, the left end - by a load cell. The radial alignment of the left end was achieved at first with a tool and then by locking the load cell in a position (with the rotor attached to it) using mounting screws. After the load cell was locked, the initial alignment tool was removed. Hall-effect sensors (F.W. Bell FH-520) have been used to measure magnetic flux densities in the radial and axial gaps of the tested combination actuator.

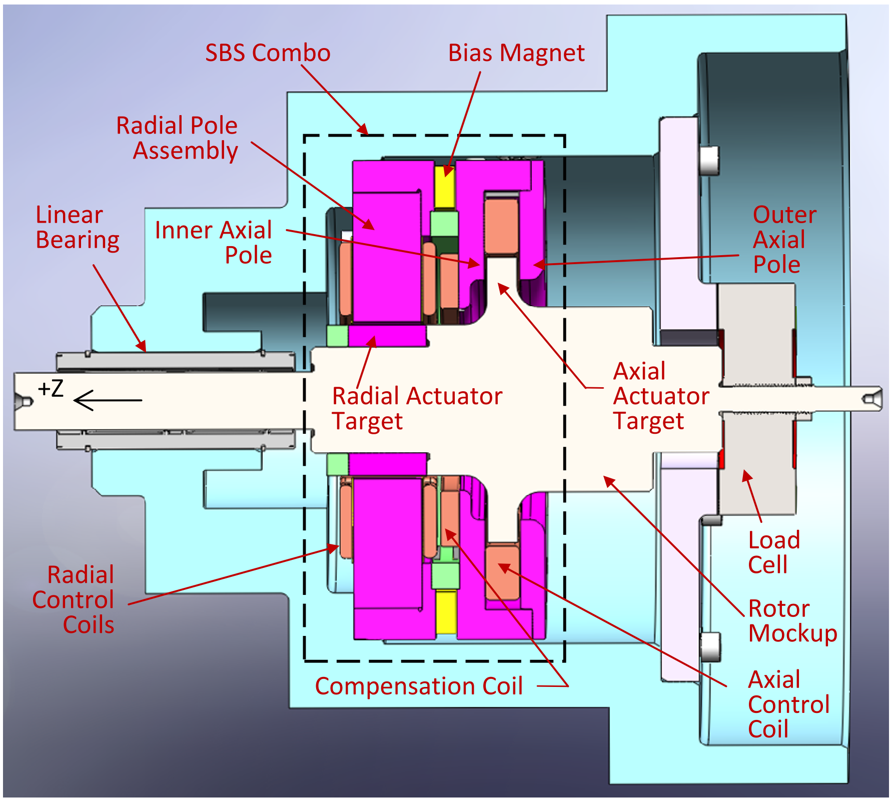


Figure 10: Test rig for evaluating a 'Side-By-Side' Combination Actuator.

4. Test Results

4. 1 Verification of the axial force vs current curve with and without the compensation.

Figure 11 shows the force versus current curve measured on the test rig without energizing the compensation coil along with the theoretical curve calculated for this case. The two curves are sufficiently close to each other with the biggest part of the difference likely being caused by the axial offset of the rotor from the central position in the positive Z direction.

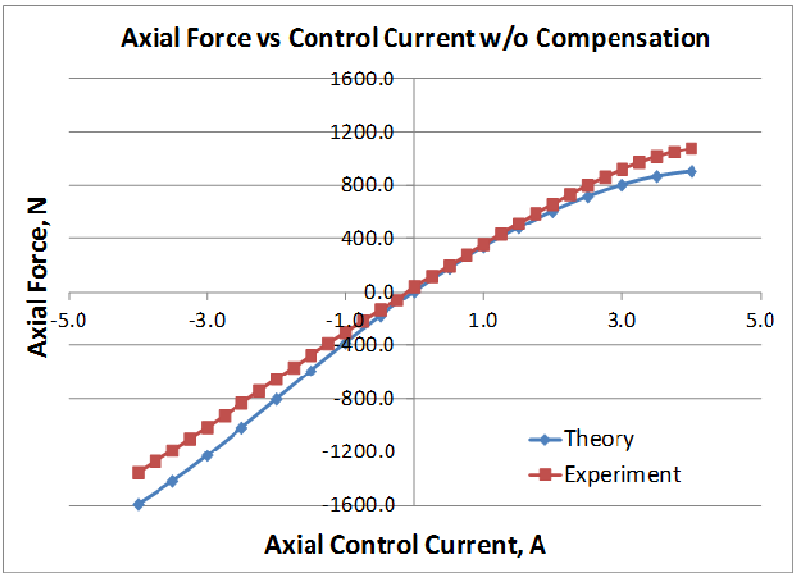


Figure 11: Axial Force vs Current curves measured (calculated) without the compensation coil.

Importantly, both theoretical and experimental curves show significant difference in forces generated by the currents of the opposite polarities but the same magnitudes: more force is generated when a negative current is applied than when a positive current is applied.

Figure 12 shows the force versus current curve measured on the test rig with the compensation coil energized along with the theoretical curve and the curve measured on one of the machines in this configuration. All three curves are sufficiently close to each other with the biggest part of the difference once again likely being caused by the axial offset of the rotor from the central position in the Z direction. In theory, forces in the positive and negative directions obtained with the same current should be approximately equal. In the measurement on the test rig, however, a noticeably higher force was obtained in the positive direction (note that this is actually the opposite of what was observed without the compensation current as shown in Fig. 11: the force then was larger in the negative Z direction). This is also consistent with the rotor being offset from the magnetic center in the positive Z direction – measured force values in Fig. 11 were also biased towards positive values compared to the theoretical estimates.

Figure 13 shows a direct comparison of the measured axial load curves with and without compensation. The compensation is reshaping the curve in the right direction to make it symmetric (increases force at a given current in the positive direction and decreases it in the negative direction), but 'overshoots' the other way. This overshoot, however, is most likely a consequence of the rotor being offset axially from the magnetic center in the positive Z direction, which is also the conclusion that was drawn based on the comparisons with the

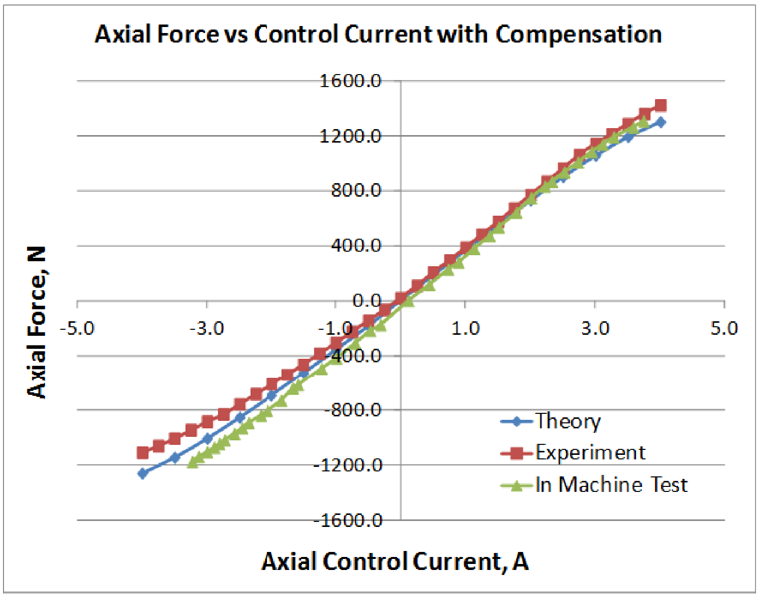


Figure 12: Axial Force vs Current curves measured (calculated) with the compensation coil.

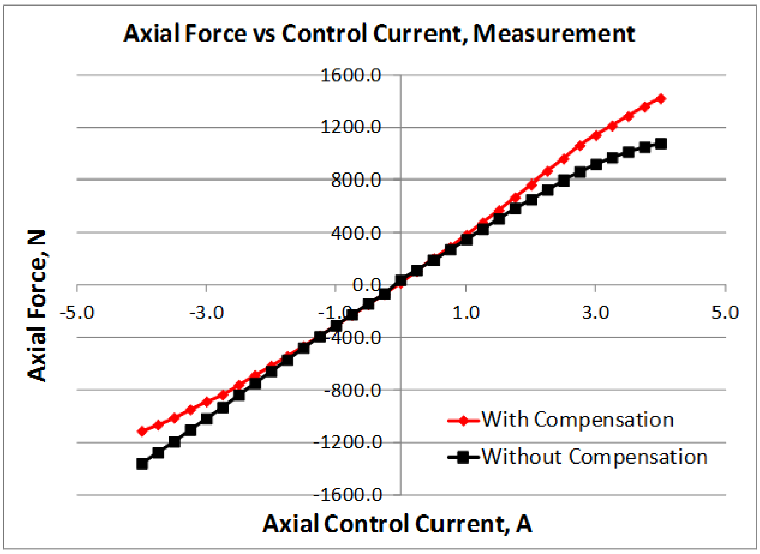


Figure 13: Effect of the compensation coil on the axial bearing load curve as measured in the test rig.

theoretical curves shown in Figs. 11 and 12.

4.2 Verification of the compensation coil effect on the radial bias flux.

Besides making the axial load curve symmetric, the compensation coil has another purpose: eliminate or at least mitigate effects of the axial control current on the radial bias flux and the radial load capacity correspondingly. This second goal is actually often more important than the first one.

Figure 14 shows the effect of the axial current on the radial bias flux density predicted theoretically and observed in the test rig without the compensations coil. The experimental variation of the radial bias flux with the axial control current is in the range of 20-30%.

Figure 15 shows the effect of the axial current on the radial bias flux density predicted theoretically and observed in the test rig with the compensations coil. The experimental variation of the radial bias flux with the axial control current is effectively eliminated.

Figure 16 gives a direct comparison of the effects of the axial control current on the radial bias flux with and without the compensation coil.

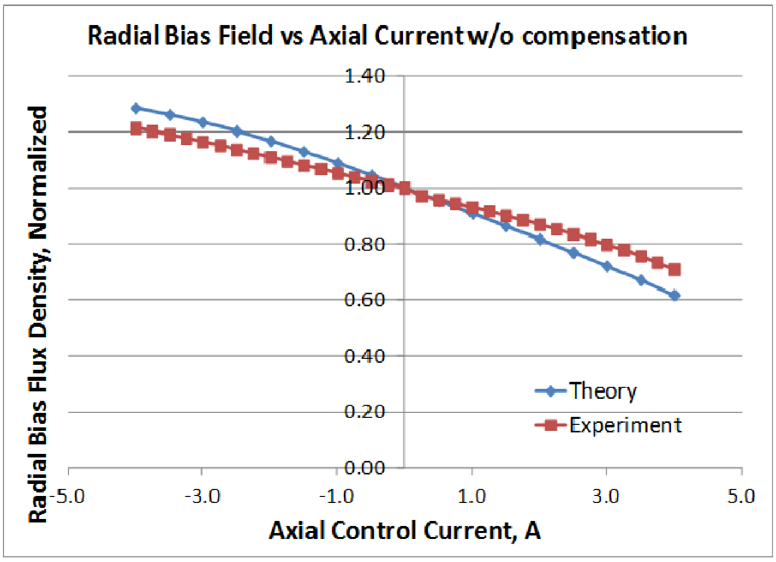


Figure 14: Effect of the axial control current on the radial bias flux WITHOUT the compensation coil.

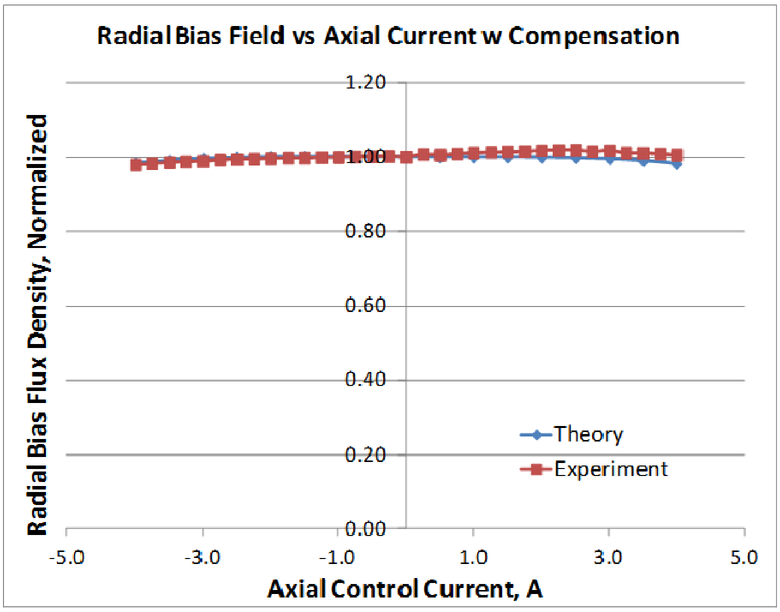


Figure 15: Effect of the axial control current on the radial bias flux WITH the compensation coil.

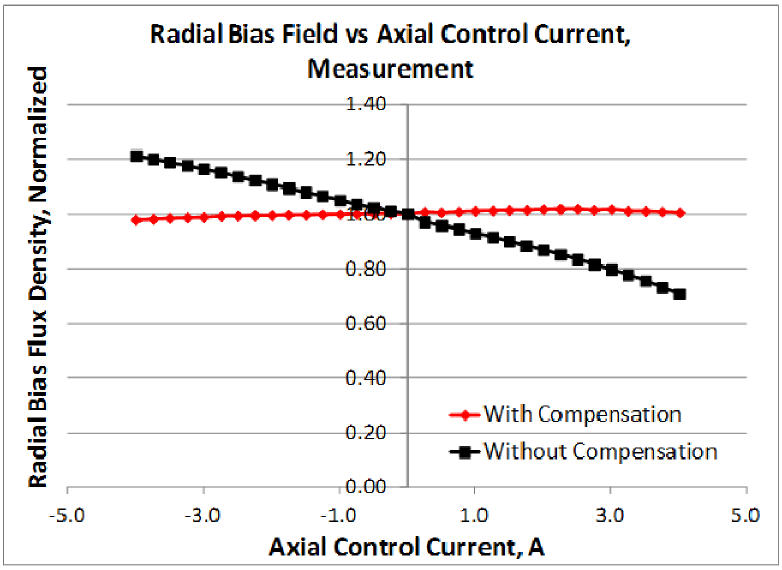
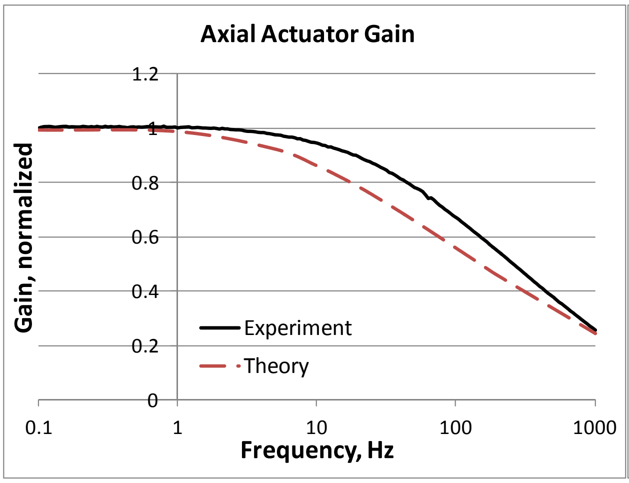


Figure 16: Reduction of the effect of the axial control current on the radial bias due to use of the compensation coil in the test rig.

4.3 Axial transfer function measurement.

At first, an attempt was made to measure the transfer function directly as a ratio between the axial force detected by the load cell and the axial control current measured by a clamp-on current probe. Unfortunately, mechanical resonances in the system made interpretation of the results very difficult. Because of this, the transfer function was measured indirectly as a ratio of the axial control flux density (measured with a Hall sensor located in the axial air gap) and the axial control current (measured with a clamp-on current probe). The result is shown in Fig. 17. The transfer function measured this way is in fairly good agreement with theoretical predictions.



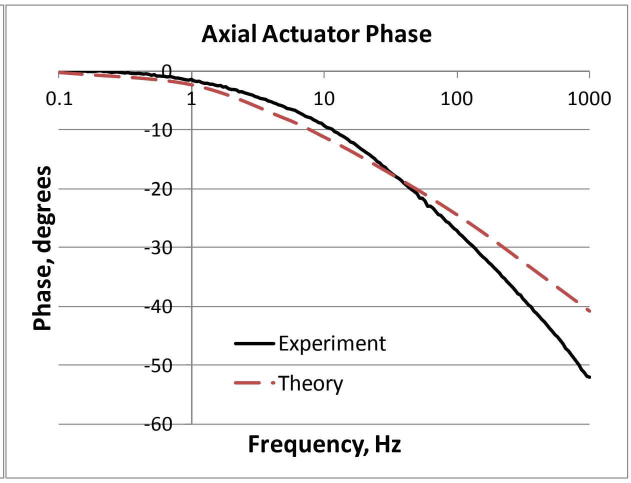


Figure 17: Axial actuator transfer function measured on the test rig with a Hall sensor in the axial air gap.

5. Conclusions

The novel combination radial/axial permanent-magnet-biased homopolar active magnetic bearing described here offers a unique combination of advantageous properties, which have not been found collectively in previous designs. The advantages over an arrangement of separate radial and axial bearings include:

- Shorter axial length
- Lower part count
- Lower aerodynamic drag
- Lower negative stiffness
- Lower cost

The main advantages over the earlier "symmetric" version of the combination bearing include:

- Superior axial bandwidth
- Ability to achieve much higher axial load capacities
- Rotor tapered towards the end (leads to rotordynamic advantages in turbomachinery applications)

The new design is an improvement over an earlier "asymmetric" combination magnetic bearing that has been described in the literature. The earlier design had an asymmetric axial force-current curve and an undesirable bias flux modulation by the axial control current. These characteristics made it impractical for most applications. A compensation coil introduced in the new design has been shown to successfully resolve all these issues.

The first combination magnetic bearing of this type with 1070N/350N axial/radial load capacities and 70,000RPM operating speed has been successfully built and tested in a dedicated test rig and in a commercial machine (up to full speed and full load). The test results fully confirm the expectations:

- The actuator measured axial transfer function was in close agreement with theoretical predictions and the new design was shown to have a substantial improvement in bandwidth compared to the original combination bearing
- The compensation coil in the new design reduced the variation of radial bias flux with axial control current from 20-30% to less than 2% while reshaping the axial force-current curve in the predicted direction.

Several machines utilizing the new design have been shipped and commissioned at customer sites.

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