# MAGNETIC CIRCUIT ANALYSIS OF HOMOPOLAR MAGNETIC BEARING ACTUATORS

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***Abstract*: This paper describes the development and verification of a design code for permanent magnet bias, homopolar magnetic bearing actuators. This code uses magnetic circuit analysis that provides quick evaluation of candidate bearing actuators. Non-linear material properties are represented, and force versus current characteristics can be calculated as a function of operating speed. Details of code development and description of a user interface created with a commercially available spreadsheet program are presented. Verification is accomplished by comparison with finite element analysis and with experimentally measured actuator performance.**

***Keywords: magnetic circuit analysis, homopolar magnetic bearing actuators***

## I. INTRODUCTION

Permanent magnet bias homopolar (PMBH) bearing actuators are attractive for high-speed rotating machine applications that require low losses, due to inherent low loss characteristics as compared to heteropolar actuators [1]. This paper discusses a modeling approach for homopolar actuators that uses magnetic circuit analysis techniques in an easy-to-use format for quick design evaluation purposes.

When designing magnetic bearing actuators for rotating machines, it is desirable to rapidly evaluate different bearing configurations because actuator dimensions and operating parameters can have a significant impact on overall machine characteristics and performance. This is the case because magnetic bearing actuators often comprise a significant portion of rotating machine volume and weight since their specific load capacity (allowable load per unit area) is quite low compared to rolling element or fluid film bearings [2].

Electromagnetic finite element analysis (FEA) provides a means for thorough and accurate actuator modeling to predict bearing actuator performance, but is generally a cumbersome design tool because of the time required to set up models and evaluate results. Three-dimensional FEA is best used, therefore, as a verification tool, rather than as a design tool.

Magnetic circuit analysis is an alternative analysis approach that allows quick evaluation of candidate actuator configurations for a given application. Although magnetic circuit analysis cannot provide the analysis detail and accuracy provided by FEA, it can provide reasonably accurate results almost immediately. Since the required equations are relatively simple, magnetic circuit codes can be set up in a spreadsheet format that facilitates quick evaluation of potential actuator design parameters. Critical bearing parameters can be easily reviewed in this format and immediate insight into actuator operation can be gained.

Magnetic circuit analysis has been described previously in the literature for heteropolar actuator topologies, usually without provision for modeling non-linear actuator characteristics. The magnetic circuit analysis approach described in this paper is applicable to both conventional and inside-out homopolar actuator topologies (an inside-out topology is one in which the rotating portion of the bearing is located radially outboard of the stationary portion). Furthermore, non-linear B-H material effects are included and the technique is capable of predicting force versus current characteristics as a function of operating speed (this is important for evaluation of inside-out actuators in which the air gap grows larger as a function of speed). In addition, this analysis approach includes automatic geometry plot generation for geometry verification, incorporation of actuator coil design equations, and modeling of leakage and fringing field effects.

To verify circuit analysis code predictions, comparison with three-dimensional FEA is presented for an inside-out bearing system of interest. In addition, an inside-out topology radial test bearing and test fixture were designed and fabricated in which bearing parameters were directly measured, providing experimental verification. Test results are presented and compared to theoretical predictions.

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## II. Bearing Actuator Topologies, Operating Principles, and Equivalent Circuits

The components of a conventional topology permanent magnet bias homopolar bearing actuator are shown in Fig. 1. The actuator pictured is capable of developing radial forces only; inside-out topologies and actuators capable of developing forces in the axial direction will be discussed later. Permanent magnets are used in the actuator to establish bias magnetic fields in the air gap that separates rotor and stator portions of the bearing (Fig. 2). In addition, actuator control coils are provided to modulate the air gap flux distribution to regulate bearing output forces.

Bearing output force is determined by the magnetic flux density distribution in the air gap between rotor and stator laminations. In PMBH bearings, this flux density distribution is created by a combination of bias fields induced by the permanent magnets, and control fields created by the bearing actuator control coils. Moreover, different paths are taken within the bearing by the bias flux and actuator control flux as indicated in Fig. 3, in which the control flux paths are shown. This figure shows assumed control flux paths for the case in which half of the control coils are energized, known as an in-line force case, which produces an output force directed between coil slots, in-line with the actuator poles. For this load case, the bias flux density in quadrants 2 and 4 is unchanged by the control coils, but in quadrants 1 and 3 the actuator control flux adds to the bias flux in one quadrant and subtracts from it in the other. This results in an unbalanced air gap flux density between quadrants 1 and 3, and the generation of a net force. If all control coils are energized with equal currents, then the bias field in all four quadrants is affected, and an output force directed between poles is generated; this is known as a diagonal force case.

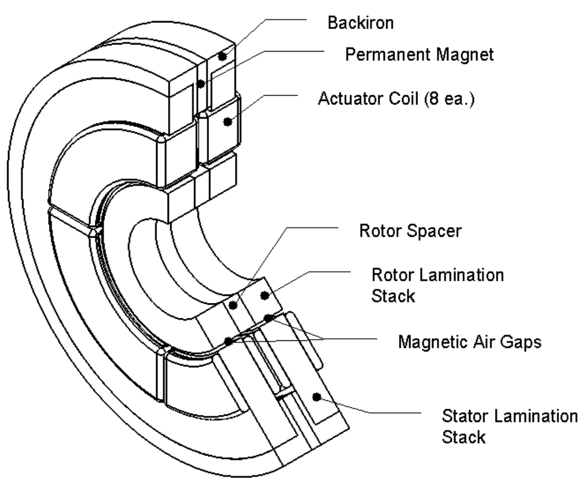


Figure 1. Radial bearing actuator

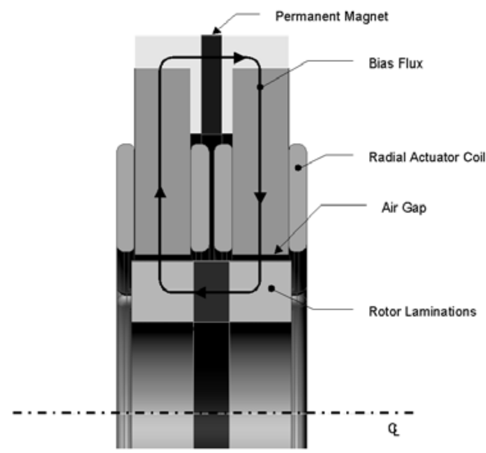


Figure 2. Radial bearing bias magnetic circuit

The bias and actuator control magnetic circuits for the radial bearing can be represented using the simple electric circuit analogs shown in Figs. 4 and 5. Note that these circuits use equations from the "method of permeances" to include the effects of fringing and leakage flux [3]. Air gap fringing paths are represented by P2 through P5 in the equivalent circuits.

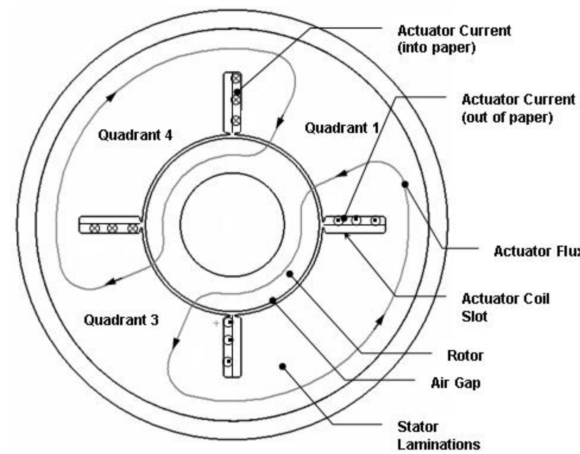


Figure 3. Radial bearing actuator coil magnetic circuit: in-line force case

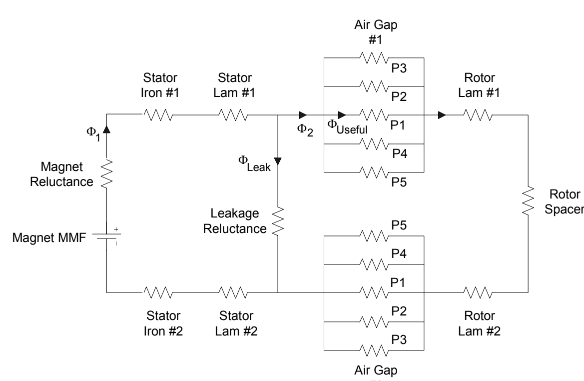


Figure 4. Radial bearing bias magnetic circuit

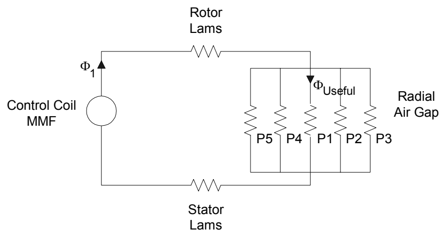


Figure 5. Radial bearing actuator flux magnetic circuit

A PMBH bearing that combines radial and axial force capabilities is called a combination bearing [4]; a conventional topology combination bearing is shown in Fig. 6. This bearing develops radial forces using the same principles as described above for the radial bearing, but also includes axial air gaps where thrust forces are developed. These features are combined into a single bearing for compactness.

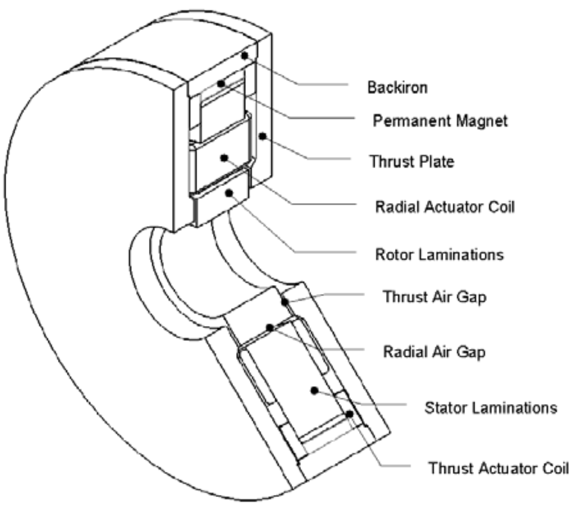


Figure 6. Combination (radial and thrust) bearing actuator

Fig. 7 shows bias and thrust actuator flux paths for the combination bearing. The bias flux path is radial in the center portion of the bearing, due to radially magnetized bias magnets. Near the actuator inner and outer diameters, the bias flux splits and is directed toward the thrust plates. Thus, a single permanent magnet assembly establishes bias fields in both the radial and thrust air gaps. To develop thrust force, thrust coils are activated which add to the bias flux density in one thrust air gap while subtracting from the other. The result is a larger attractive force in one thrust air gap than the other, and the generation of a net axial force. Equivalent magnetic circuits are shown in Figs. 8 and 9 (note that the radial actuator flux circuit is identical to that shown in Fig. 5 and is not repeated here).

In addition to the conventional bearing actuator geometries described above, it is also possible to use magnetic circuit analysis to represent inside-out topologies in which the rotating portion of the actuators is positioned outboard of the stator components. This topology can be advantageous in certain rotating machines where maximizing energy and power density is of prime interest.

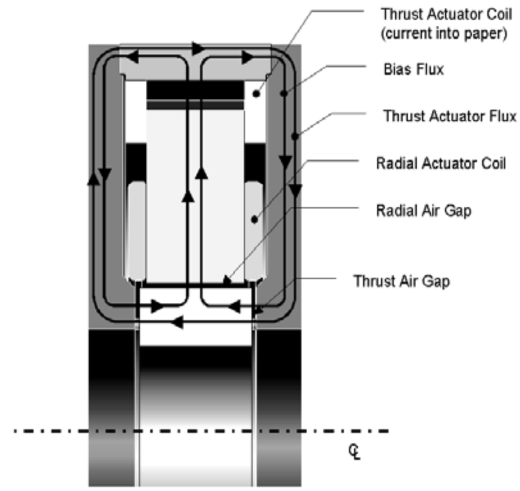


Figure 7. Combination bearing bias and thrust magnetic circuits

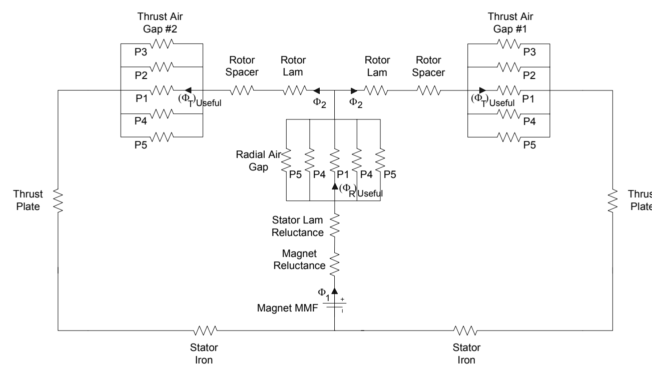


Figure 8. Combination bearing bias magnetic circuit

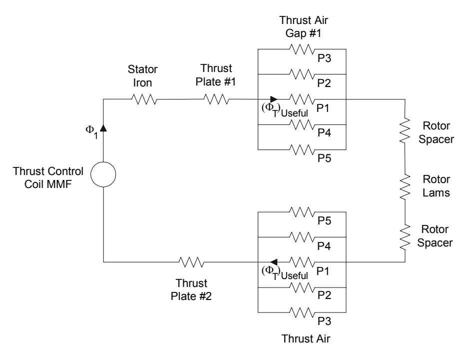


Figure 9. Combination bearing: thrust actuator flux magnetic circuit

A PMBH bearing system was designed for an inside-out topology flywheel alternator at the University of Texas at Austin Center for Electromechanics, with the goal of maximizing energy density in a machine intended to serve as an onboard power supply for future combat vehicles [5]. The inside-out radial and combination bearing actuators for this system were designed using magnetic circuit analysis, and are shown in Figs. 10 and 11.

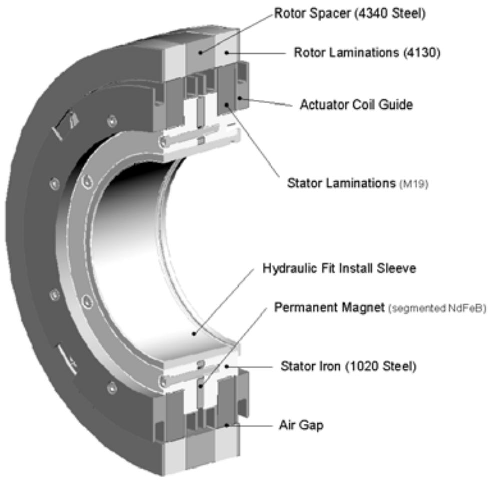


Figure 10. Inside-out radial bearing actuator

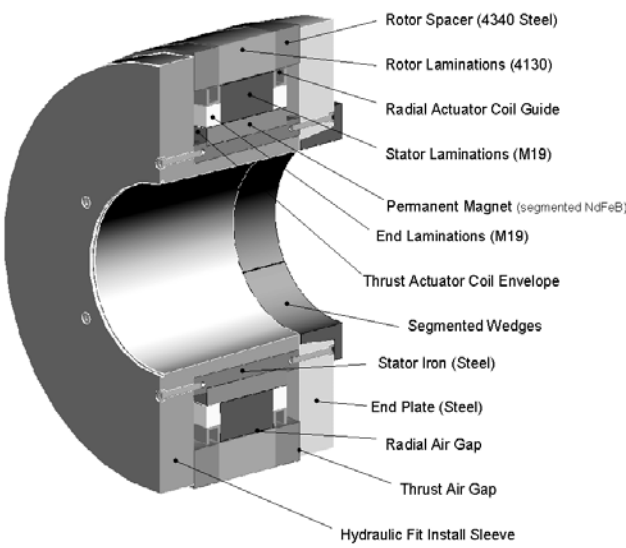


Figure 11. Inside-out combination bearing actuator

## III. MAGNETIC CIRCUIT CODE DEVELOPMENT

Using the equivalent circuits shown above, standard magnetic circuit analysis techniques are used [3] to derive expressions for the reluctances of actuator components, as well as the magnetomotive forces (mmf) due to the bias magnets and actuator control coils. This allows calculation of the total flux associated with bias and actuator coil circuits. At actuator air gaps, this can be converted to bias and control coil magnetic flux densities, which are appropriately summed to give the resultant flux density in each air gap. As stated above, it is the resultant flux density distribution in the actuator air gaps that determines the actuator net output force. For the generation of in-line radial forces, the resultant radial force can be expressed as [6]:

$$F_{result} = \frac{2 B_{bias} B_{coil} A_{quadrant}}{\mu_o}$$

where $B_{bias}$ is the air gap flux density induced by the permanent magnet, $B_{coil}$ is that induced by the control coil, $A_{quadrant}$ is the quadrant area, and $\mu_o$ is the magnetic permeability of free space. Use of this equation allows calculation of the required coil mmf (and therefore coil current) required to generate a desired radial force.

Similarly, for the generation of diagonal forces, the resultant radial force can be expressed as:

$$F_{result} = \frac{2.828 B_{bias} B_{coil} A_{quadrant}}{\mu_o}$$

For reluctance calculations involving ferromagnetic components, the design code accounts for variation in relative magnetic permeability as a function of flux density by using curve-fit polynomial expressions for permeability versus flux density curves. Representative curves and associated curve fits are shown in Fig. 12. Fig. 13 shows locations of flux density evaluation for calculation of the relative permeability for the actuator shown in Fig. 10; if the flux density is evaluated at more than one location within a given component, the maximum value is used for the relative permeability calculation.

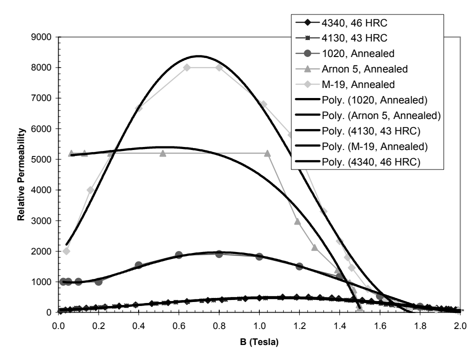


Figure 12. Bearing material permeability curves

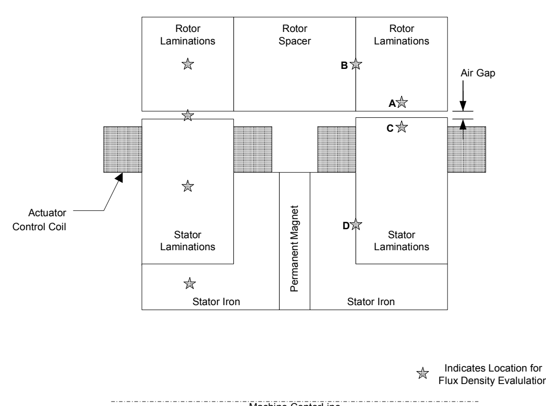


Figure 13. Locations of flux density evaluation

Commercially available spreadsheet programs provide a convenient interface to incorporate the features of magnetic circuit analysis. Fig. 14 is an example of the main worksheet for the inside-out radial actuator shown in Fig. 10.

| ***Radial Bearing: In-Line Force Case: Inputs*** | | | | | |
|---|---|---|---|---|---|
| Req'd Force Capacity | 700 | lbs | ***Bias Magnetic Circuit Calcs (whole brg)*** | | |
| Rotor Lam OD, at zero speed | 14.125 | in | Permanent Magnet Reluct. | 248,359 | A-t/Wb |
| Rotor Lam OD, at speed (approx) | 14.182 | in | Stator Lam Reluct. | 2,011 | A-t/Wb |
| Stator Lam OD | 11.960 | in | Stator Iron Reluct. | 1,573 | A-t/Wb |
| Active Length of Laminations | 1.600 | in | Rotor Lam Reluct. | 29,775 | A-t/Wb |
| Radial Gap @ 20krpm | 0.0485 | in | Rotor Spacer Reluct. | 2,285 | A-t/Wb |
| Stator Lamination ID | 8.750 | in | Air Gap Reluctance | 40,973 | A-t/Wb |
| Magnet ID | 7.200 | in | Total Circuit Reluctance | 386,987 | A-t/Wb |
| End Turn Length | 0.750 | in | Bias N-I | 7,686 | A-t |
| Magnet Length | 0.325 | in | Useful Air Gap Bias Flux | 0.01478 | Wb |
| Magnet Radial Thickness | 1.500 | in | | | |
| Magnet Br | 1.17 | T (Alloy N36SH) | | | |
| Lamination Fraction | 0.05 | | ***Actuator Magnetic Circuit*** *(4 of 8 coils active)* | | |
| Number of Coil Turns (ea.coil) | 90 | turns/coil | Rotor Lam Reluct.(ea.side) | 638,564 | A-t/Wb |
| Air Magnetic Permeability | 1.257E-06 | H/m | Stator Lam Reluct. w/slots (ea.side) | 73,932 | A-t/Wb |
| Rotor Lam Relative Permeability | 470 | (4130 Steel) | Air Gap Reluctance | 352,608 | A-t/Wb |
| Stator Lam Relative Permeability | 2311 | (M-19 Steel) | Total Circuit Reluctance | 1,065,105 | A-t/Wb |
| Stator Solid Steel Rel. Perm. | 1549 | (1020 Steel) | Req'd Actuator B in gap | 0.29 | T |
| Coil Slot Width (dovetail avg.) | 0.717 | in | Req'd Useful Actuator Flux (ea.side) | 0.00132 | Wb |
| Coil Slot Depth | 0.698 | in | NI Actuator Coils (ea.side) | 1,603 | A-t |
| Length Diff: Rotor Lam - Stator Lam | 0.150 | in | Amps, Actuator Coil (ea.coil) | 8.90 | A |
| | | | L, Actuator Coil (ea.coil) | 13.32 | mH |
| Radial Gap @ zero speed | 0.020 | in | Coil Area (ea.coil) | 0.2502 | $in^2$ |
| Approx. rotor IR grwth @ 20krpm | 0.0285 | in | Coil Current Density (min) | 3,203 | $A/in^2$ |
| | | | | | |
| ***Calculated Bearing Dimensions*** | | | | | |
| Rotor Lam ID | 12.057 | in | | | |
| Actuator Area | 55.53 | $in^2$ | | | |
| Projected Actuator Area | 12.50 | $in^2$ | | | |
| Overall Bearing Length | 3.100 | in | | | |
| Permanent Magnet OD | 10.200 | in | | | |

| ***Flux Density Calcs*** | | |
|---|---|---|
| Rotor Lam Hoop Field | 1.011 | T |
| Rotor Lam Resultant Field-location A | 1.119 | T |
| Rotor Lam Resultant Field-location B | 1.139 | T |
| | | |
| Stator Lam Hoop Field | 0.795 | T |
| Stator Lam Hoop Field (inside slot) | 1.407 | T |
| Stator Lam Resultant Field-location C | 1.119 | T |
| Stator Lam Resultant Field-location D | 0.908 | T |
| | | |
| Stator Iron Field | 1.180 | T |
| | | |
| Bias B in gap | 0.825 | T |
| | | |
| Bias Circuit Leakage Coefficient | 1.262 | |
| Actuator Circuit Leakage Coefficient | 1.142 | |

Figure 14. Inside-out radial bearing, full speed in-line force case

## IV. CODE VERIFICATION

Predicted current sensitivity curves for the inside-out radial actuator at zero and full speed are shown in Fig. 15. Note that this actuator generates substantially higher force per unit current at zero speed than at full speed (20,000 rpm). This behavior is due to an increase in the radial air gap from 20 mils at zero speed to more than 48 mils at full speed. This is an important consideration in the design of inside-out topology actuators [5,6,7].

Although not obvious from the previous discussion, the curves shown in Fig. 15 are valid for input currents of moderate to high frequency, but not for very low frequencies. This can be explained by examination of Fig. 3, and consideration of the assumed flux paths for the actuator control flux. The implicit assumption with the paths shown is that the control flux is confined to laminated rotor and stator components, an assumption that is valid for high frequency (ac) control flux, but not for steady-state (dc) flux. For dc input currents, the flux is no longer confined to laminated materials, but is also present in solid steel components. Thus, dc current sensitivity for the actuator can be expected to exceed the ac current sensitivity.

To verify predicted performance, a commercially available finite element analysis (FEA) code was used to examine ac and dc behavior, and a radial test bearing actuator and test fixture (Fig. 16) were constructed to measure actual bearing parameters. Predicted versus measured ac current sensitivity is shown in Fig. 17.

Good agreement is observed between measured ac results and those predicted by both the magnetic circuit analysis and FEA approaches. However, the slow turnaround time for ac FEA analysis makes it a poor design tool for initial actuator design studies. The magnetic circuit analysis code can characterize force versus current characteristics in a matter of minutes for a candidate bearing geometry; the same ac analysis conducted with FEA would likely take weeks or months to complete with a state-of-the-art desktop computer.

On the other hand, for dc actuator performance, the magnetic circuit analysis code significantly under-predicts current sensitivity, as shown in Fig. 18. However, magnetostatic FEA predicts dc performance quite well (Fig. 19), with much more reasonable computation times than for ac analysis.

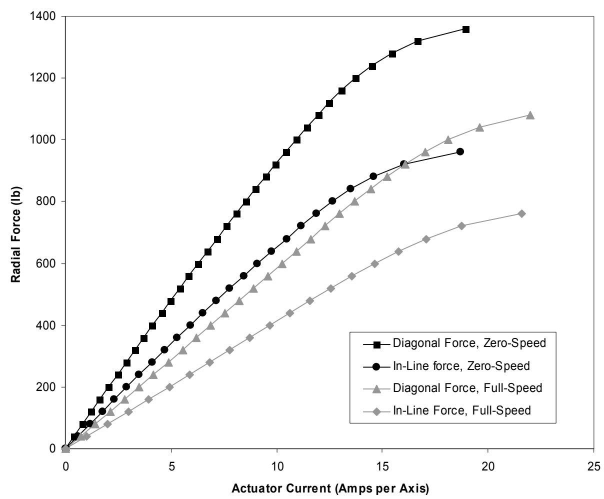


Figure 15. Predicted radial actuator current sensitivity

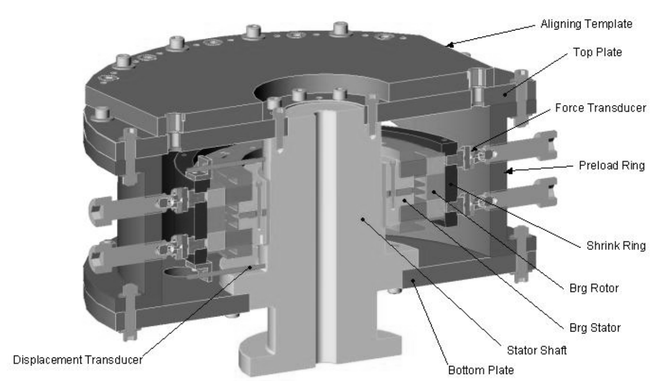


Figure 16. Radial bearing actuator test fixture

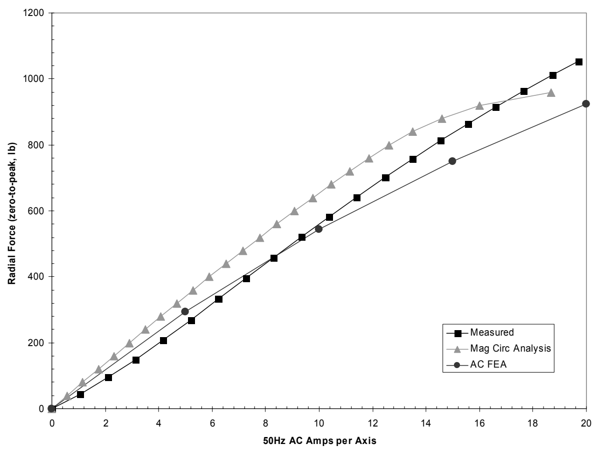


Figure 17. Predicted versus measured 50Hz performance (zero speed)

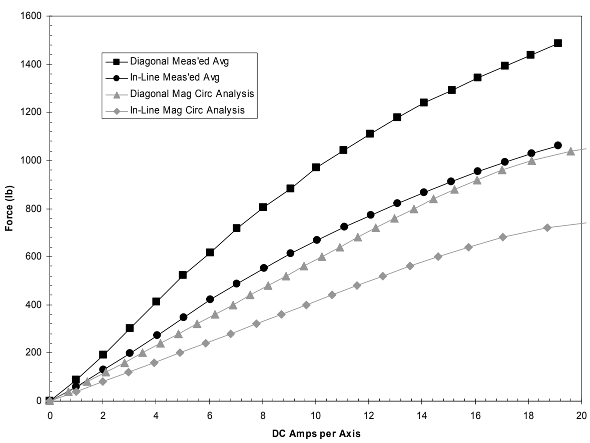


Figure 18. DC output force, full speed air gap, magnetic circuit analysis versus measured

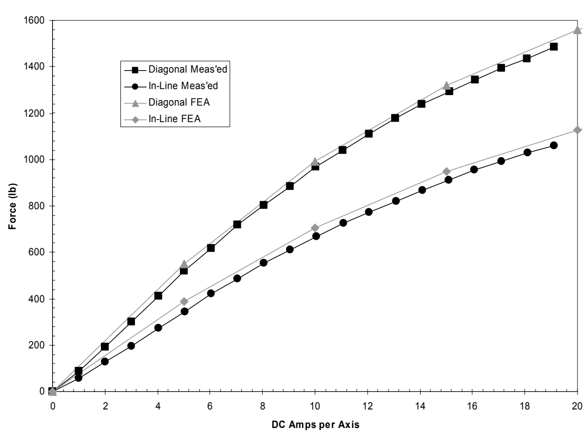


Figure 19. DC output force, full speed air gap, FEA predicted versus measured

These results indicate that the magnetic circuit analysis approach provides sufficient accuracy to be a useful design tool for predicting ac actuator performance. Since magnetic bearings for rotating machines must deal with oscillating and transient forces, and since PMBH bearing actuators inherently have more capacity under dc conditions, it can be argued that ac performance prediction is the most critical requirement for an actuator design code. However, once a promising set of actuator design parameters have been identified using magnetic circuit analysis, it is recommended that FEA be conducted for verification.

## V. CONCLUSIONS

For preliminary design of PMBH bearing actuators, the magnetic circuit analysis approach described in this paper gives reasonably accurate results except at low frequencies, where the code under-predicts actuator force output. Although the easiest case to model with FEA, magnetostatic behavior of bearing actuators is of minimal importance to bearing system performance in most rotating machine applications. This is due to inherent higher load capacity of PMBH actuators at low frequencies. In contrast to magnetic circuit modeling, FEA modeling of moderate and high frequency ac actuator characteristics can be a daunting task because of convergence difficulties and long solution times. It is therefore concluded that the magnetic circuit analysis modeling techniques presented here provide a highly relevant and useful design tool for homopolar bearing actuator design.

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