The 15th International Symposium on Magnetic Bearings, August 3-6, 2016, Mojiko Hotel, Kitakyushu, Japan

ISMB15

Low Cost Active Magnetic Bearings - Concepts and Examples

Paul ALLAIRE*, Brad NICHOLS*, Tim DIMOND*, Jianming CAO* and Simon MUSHI*

* Rotor Bearing Solutions International, LLC

3277 Arbor Trace, Charlottesville, Virginia 22911, USA

E-mail: paul.allaire@rotorsolution.com

Abstract

The objective of this paper is to present innovative new thrust and radial magnetic bearing designs using permanent magnet bias not previously published. They are expected to be significantly lower in cost than conventional all electromagnetic bearings. The new designs use permanent magnet bias in a way not introduced before. The resulting magnetic bearings are able to use only half of the number of power amplifiers than conventional magnetic bearings, as well as consuming significantly less operating power in the bearing coils. However, the bearings are generally not larger than conventional all electromagnetic bearings. Finally, these new permanent magnet bias bearing designs are generally not longer axially than all electromagnetic bearing designs, unlike other types of permanent magnet bias designs such as homopolar magnetic bearings. This is important from the rotor dynamics point of view. This innovation has the potential to reduce the overall magnetic bearing system hardware volume production cost by 20% to 30% as well as reduce coil current operating costs in the range of 35% to 40%.

Key words : Active Magnetic Bearing, Thrust Bearing, Radial Bearing, Permanent Magnet Bias, Low Cost AMB

1. Introduction

Currently the cost of a typical set of active magnetic bearing (AMB) to support an industrial rotating machine is approximately two to three times that of comparable fluid film bearings. There are several advantages of AMBs such as removal of oil lubrication and pumping system, high reliability, lower power consumption compared to oil lubricated bearings, among others. However, the higher production costs are a significant factor limiting their use at this time as compared to oil lubricated bearings.

This paper presents an evaluation of some significant cost-reducing, new AMB designs and their implications. In the following discussion, we assume that an AMB system for a rotating machine includes a five axis suspension system- two radial bearings with two lateral axes for each bearing, and one thrust bearing with one axis of axial motion. Typically, these designs have electromagnetically (EM) generated fluxes in all of the axes. Two example designs and their working principles are discussed in this work to provide specific examples of lower cost AMBs.

A significant way to improve the performance of magnetic bearings is to use permanent magnet (PM) bias. Two of the first published works on PM bias radial magnetic bearings employed (Sortore et al., 1990, Maslen et al., 1996) a two plane structure with one plane having radial EM poles and a simple uniform pole with a separate PM homopolar bias flux placed between the two pole planes. Generally, it is good practice to not pass the primary EM flux path through the permanent magnets as the permanent magnet material has very high magnetic permeability and acts as an air gap. Typically, conventional PM bias bearings are designed to keep the PM flux path and EM flux paths largely separate from each other except for providing a uniform PM flux in the pole faces and airgaps. Homopolar radial AMBs employ a PM bias where the PM is located in the back iron connecting the two sets of EM poles, which has the advantage of not passing the EM flux through the PM material (Lee et al., 1994, Fukata and Yutani 1998, Murphy et al., 2004). An alternative form of this design places the PM component on the rotating shaft (Sun et al., 2016).

A large number of PM designs have been employed in artificial heart pumps where the primary feature is to reduce the heat generated in the AMBs to avoid overheating the blood by using PM bias for the bearings or using PMs for axial force capabilities to center the rotating impeller (Khanwilkar et al., 1995, Allaire et al., 1998, Bearnson et al., 1998, Allaire et al., 1998 (2), Baloh et al., 1998, Allaire et al., 1999, Baloh et al., 1999, Hilton et al., 1999, Allaire et al., 2001, Jiang et al., 2001, Jiang et al., 2007).

Combined magnetic bearings with radial and axial pole structures including permanent magnet bias have been developed (Hawkins, et al., 1999, Blumenstock and Brown, 2000, McMullen et al., 2000). However, they have not been widely used in industry.

The cost of AMBs is commonly compared to fluid film bearings for most rotating machines. Fluid film bearings have a significant advantage in that their specific load (load per unit area) is approximately two or more times higher than that for magnetic bearings. A typical specific load for fluid film bearings is 2.8 MPa to 4.1 MPa while for AMBs it is approximately 1.0 MPa. Thus, the size of the AMB must be approximately twice as large as the fluid film bearing for the same load capacity. Often, the overall machine size (i.e. bearings, housings, shaft) is somewhat larger for an AMB supported machine when compared to a fluid-film bearing supported machine. Generally, the clearance in the radial AMBs is significantly larger than oil film bearing clearances so somewhat larger amplitudes of motion are allowed in magnetic bearing applications than the oil-film bearings. It is an interesting point that the cost of the supporting AMB power electronics (i.e. amplifiers, digital controller, sensors, etc.) are usually factored into the cost of the AMB system, but the cost of the supporting oil delivery system (i.e. pump(s), heat exchanger or chiller, filters, etc.) is not usually included in the total cost of the fluid-film bearing system.

2. Factors in AMB Costs

The list of production costs for AMBs includes 1) AMB actuators, 2) power amplifiers, 3) digital signal processor, 4) A/D and D/A components, 5) sensors, 5) wiring, 6) digital control software and 7) auxiliary bearing systems. Of these items, the highest cost item typically is the high quality class D pulse width modulated power amplifiers where 10 amplifiers are typically required for a 5 axis AMB suspension system. The cost of the amplifier is directly related to the power output required of that amplifier. Thus, one objective of this cost study is to reduce the cost of the amplifiers. The next highest cost items include the AMB actuators and the sensors. Typically the cost of the AMB actuators is directly related to the size of the bearing the smaller the bearing, the lower the cost is. This is true unless the desired bearing is extremely small. The sensors are all typically induction position sensors employed to provide the feedback control signal to the controller. Normally, there are two sensors per control axis, with the two sensors used on opposing sides of the AMB in differential mode. Thus 10 sensors are commonly used in a 5 axis AMB control system. In the case of sensors, the accuracy and reliability of the sensors is the most important factor in the cost. The last few items in the cost calculation are the digital signal processor, wiring, and digital control software.

3. Electromagnetic Bias vs. Permanent Magnet Bias AMB Design

Perhaps the most important difference between an all EM AMB design versus a PM bias design, in terms of cost, is the system method of biasing the bearing for linear operation. As is well known, the AMB typically has a steady state magnetic flux either from an electromagnetic (EM) bias current or permanent magnet (PM) bias- plus a time varying control current to make it suitable for operation in the linear range of the magnetic material. The PM bias design only requires approximately half of the total current supply that the EM bearing requires. This paper shows that a new, innovative PM bias design employs only half as many amplifiers as the EM design, or 5 amplifiers for a 5 axis system instead of 10 amplifiers for typical all EM systems. For this PM bias bearing design, the amplifier power requirement, based upon the coil power, is approximately 40% lower than the EM bias design, potentially greatly reducing the cost of those components.

PM bias bearing designs have been well known for many years but are not widely used in industry. The mindset here seems to be that the existing, widely available EM designs from the larger AMB suppliers are well known, available and quite reliable in fact more reliable than fluid film bearing supported machines. However, the cost of these systems remains high. Many industrial firms, from OEMs to end users would like to have significantly lower cost AMB systems if they were available.

If cost is an important factor in the AMB design, then the only ferrous material likely to be employed is common silicon iron - for example M19 for laminated materials - or 4340 non-laminated materials for thrust bearings. Higher laminated magnetic strength materials such as Hiperco are as much as ten times as expensive as silicon iron. Thus, they are not discussed further in this paper.

The cost of the AMB could potentially be reduced if the physical size of the bearing could be reduced; however, the size of the AMB is determined primarily by the required pole face areas. These are, in turn, determined by the external design loads that must be supported. Because the external load is normally considered fixed prior to the AMB design, the choice of EM bias or PM bias makes very little difference in regard to the required pole face areas. For the PM bias design, the magnetomotive force required from the coil windings is about half of that of an all EM design, thus, for a given coil current, the number or coil turns required are about half. The overall bearing size envelope is not significantly different between the two designs.

4. New Low Cost PM Bias Thrust Bearing Design Concept

We start with the AMB thrust bearing design, as it is simpler than the radial bearing design. An all electromagnetic thrust bearing design schematic (only the upper half is shown) is given in Fig. 1. The stator has two sides, each consisting of an EM coil and two annular pole faces. The thrust disk is in the center of the thrust bearing, attached to the shaft. The electromagnetic coils generate a bias magnetic flux with a bias current that is varied by adding and subtracting a control, or perturbation, current from either side of the bearing in response to dynamic load conditions.

An example, conventional all EM design thrust bearing with a maximum load capacity of 4000 N was considered for comparison to the new PM bias design. Figure 2 illustrates the resulting magnetic flux density plot of a 2-D axisymmetric FEA analysis under maximum load conditions. Two amplifiers are required to operate this EM thrust bearing one for the left side coil and one for the right side coil. On each side, the amplifiers are used in mono-directional mode to either increase or decrease the control current, and in turn, the associated control magnetic flux, above or below the constant bias current level. For the case illustrated by Fig. 2, the maximum control current is added to the left coil and subtracted from the right coil, generating the maximum current, and in turn, the maximum force, on the left side of the thrust disk. The dimensions for this particular example will be presented later in this section when compared to the new PM bias design.

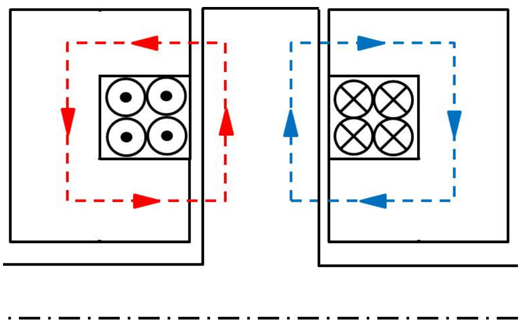

Fig. 1: Typical all electromagnetic thrust bearing design concept with magnetic flux paths.

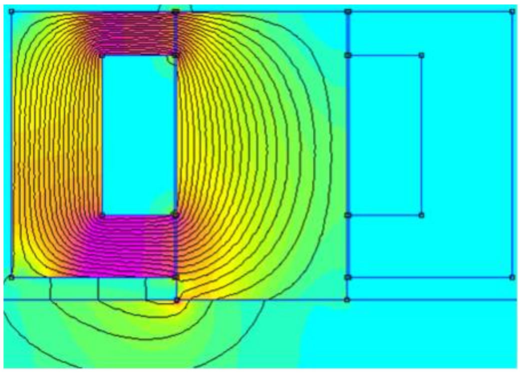

Fig. 2: All EM thrust bearing example magnetic flux density for maximum load capacity (4000 N) on left side of thrust disk.

The new low cost PM bias thrust bearing design concept is illustrated schematically in Fig. 3, where again only the upper half of the symmetric thrust bearing geometry is shown. There is only one EM coil, at the top of the thrust disk, enclosed in ferrous magnetic material, in what is called the bridge, where the coil current operates in a bidirectional manner with either a positive or negative current direction. Permanent magnet annular rings embedded in a ferrous material backing are present on both sides of the thrust disk. The pole faces on either side of the thrust disk consist of two parts: a soft-metal, ferromagnetic face of approximately one half of the disk radius, and a permenant magnet face. The PMs generate a constant flux path on either side of the thrust disk that serves as the bias flux. The electromagnet flux generated by the control current combines with the PM bias in the soft-metal airgap on one side of the disk while subtracting from the PM bias on the opposite side of the the thrust disk, depending on the direction of the current flow. By providing the bias flux through the thrust disk, the PMs help generate the desired thrust load acting on the thrust disk.

An example new PM-biased thrust bearing was designed with the same load capacity as the above all EM design. Table 1 provides a comparison of the geometries of the two designs while Fig. 4 provides a labeled geomtry of this new PM-biased design. It should be noted that the axial length of the new PM bias design is slightly shorter than the all EM design while the overall outer diameter is slightly larger (due to the addition of the bridge component). The new PM bias design requires about half the number of coil turns as the all EM design leading to a smaller coil pack. In both bearing designs, the thrust disk and backiron, as well as the bridge in the new design, is constructed of non-laminated M19 silcon iron. As discussed in more detail later, the PM material for the new bearing design is NdFeB 44.

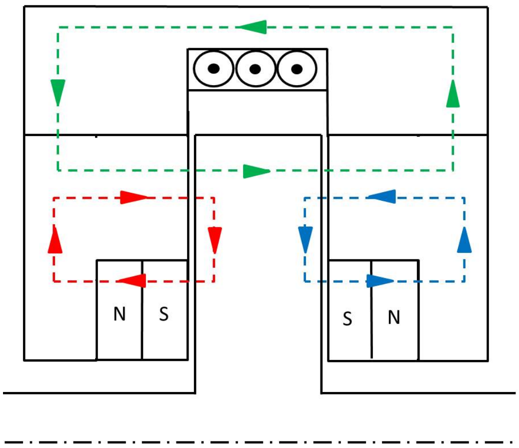

Fig. 3: New PM bias thrust bearing design concept with magnetic flux paths.

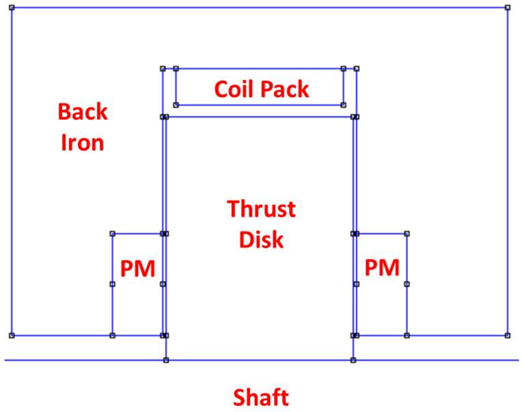

Fig. 4: New PM-biased thrust bearing design geometry.

Table 1: Example thrust bearing geometries (All EM vs. PM Bias Designs).

	All EM	New PM Bias
D_{shaft} (mm)	70	70
D_{disk} (mm)	172	151
L_{disk} (mm)	30	30
g_0 (mm)	0.5	0.5
$D_{actuator}$ (mm)	172	187
$L_{actuator}$ (mm)	89	79
I_{max} (A)	28.5	28.5
N (turns)	34	18

Figure 5 illustrates the 2-D FEA results of the magnetic flux density at maximum load capacity. In this figure, the current flow in the coil pack is oriented out of the page such to create the maximum load capacity in the left air gap. The maximum flux density is generated in the soft metal airgap on the left side of the thrust disk while conversely, almost no flux passes through the soft metal airgap on the right side of the disk.

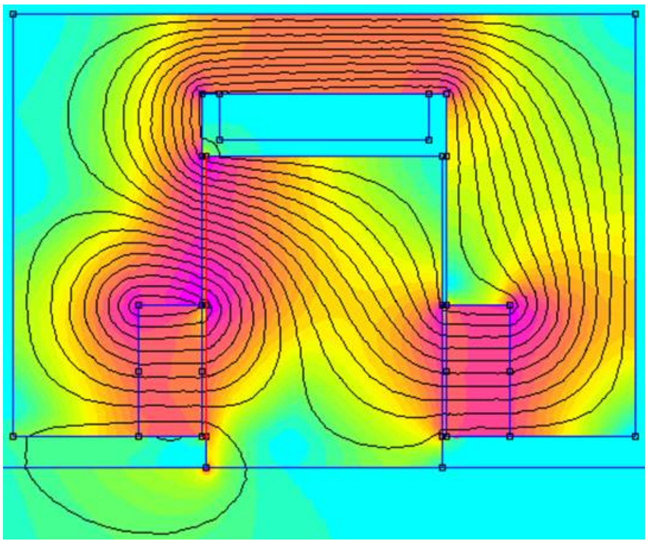

Fig. 5: New PM bias thrust bearing example magnetic flux density for maximum load capacity (4000 N) on left side of thrust disk.

More details of the magnetic flux in the airgaps are presented in Figs. 6&7. The air gap magnetic flux density in the left airgap is shown in Fig. 6 while the right airgap flux density is shown in Fig. 7. We note that the left airgap flux density associated with the permanent magnet shown in Fig. 6 is approximately 1.12 T where the PM flux density in the right air gap, illustrated in Fig. 9, is approximately -1.2 T. Being close in magnitude but with opposite directions, the flux densities in the airgaps directly in front of the PMs on either side of the thrust disk almost cancel each other out. They are considered to have a negligible effect on the net force imparted on the thrust disk when considering these portions of the airgaps.

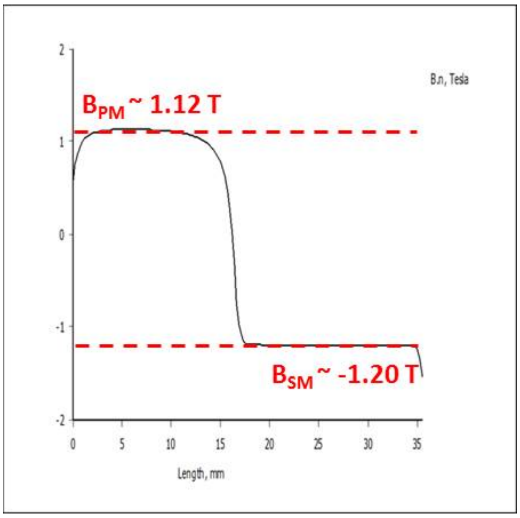

Fig. 6: Magnetic flux density in left airgap for new PM bias thrust bearing design at maximum load capacity.

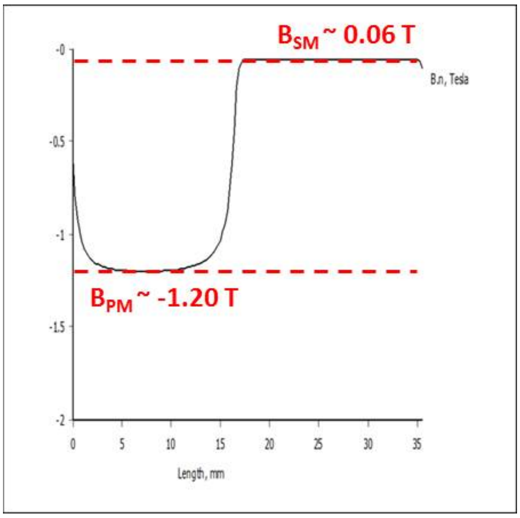

Fig. 7: Magnetic flux density in right airgap for new PM bias thrust bearing design at maximum load capacity.

Fig. 6 shows that the PM bias flux combines with the EM flux in the soft metal airgap (designated 'SM') summing to -1.2 T of flux in this gap. The opposite is true in the right gap, illustrated in Fig. 7, where the PM bias and EM flux effectively cancel each other out generating close to zero flux in the soft metal air gap. These figures illustrate the operating principles of the new PM bias design.

It is seen from Fig. 5 that the EM flux passes through the PM material. Fig. 8 illustrates the demagnetization curve for the PM material, NdFeB44, as well as the PM operating flux density and magnetic field values. The operating flux density is 1.18 T and the magnetic field value 129 kA/m, which are suitable for the PM properties to move along the demagnetization curve as the EM flux increases or decreases without either demagnetizing the PM material or exceeding the remnant flux density for the PM material.

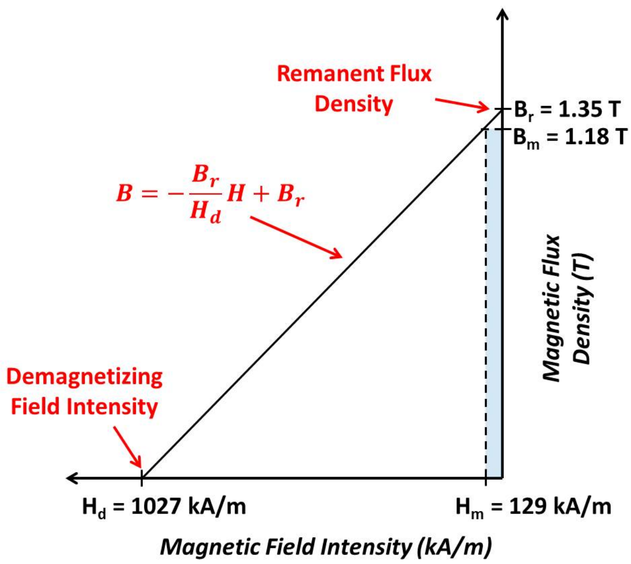

Fig. 8: NdFeB 44 demagnetization curve and new PM bias thrust bearing design operating point.

As obtained from the 2-D FEA analysis, the relation between the axial force generated by the example thrust bearing and the coil current is given in Fig. 9. It is easily seen from this plot that the new PM biased thrust bearing is linear up to the maximum designed coil current of 28.5 amps. Thus the AMB is linear through the operating range of the bearing. The bandwidth of the bearing was also calculated using the current gain shown in Fig. 9, the coil inductance as calculated by the FEA, and a presumed amplifier output voltage of 200 V. As illustrated in Fig. 10, the bandwidth under these conditions for this example is 150 Hz. It should be noted that this bandwidth value can be modified by changing the amplifier voltage output, or the number of turns and coil current in the EM windings.

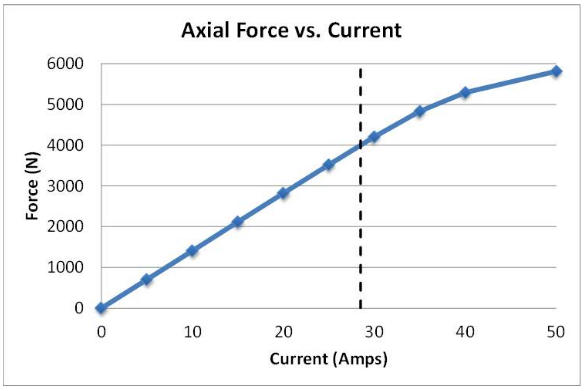

Fig. 9: New thrust bearing force versus coil current.

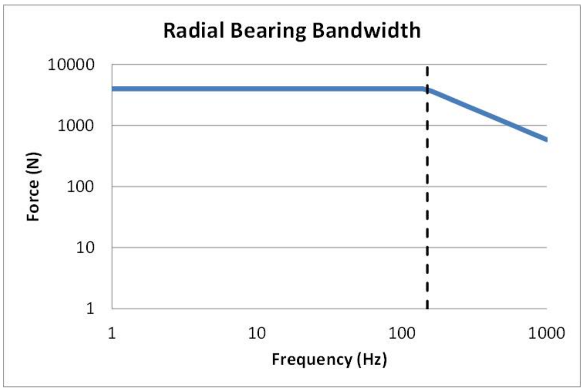

Fig. 10: New thrust bearing bandwidth.

Figure 11 illustrates the bidirectionality of the new bearing design showing the FEA results for maximum force generation on the other side of the thrust disk. Force in this direction is accomplished by simply changing the direction of the current flow in the coils. In the case of Fig. 11, the current in the coil pack is oriented into the page.

This bearing design only requires one amplifier to operate in a bidirectional mode with coil currents in the positive and negative directions. The high performance class D pulse width modulated amplifiers used for AMBs are normally used for brushed motors and have the capability to operate in a bidirectional mode. Thus, the number of amplifiers required in the all EM thrust bearing is reduced by one half.

Another factor is the power loss in the bearing which relates to the operating cost, rather than the production cost. It can be shown that the coil current resistive losses in axial AMBs can be significantly reduced in the new PM bias design, as compared to an all EM design. For the PM bias design in this example, the power consumption calculated via FEA as 25.6 W as compared to the EM design with a power consumption of 39.1 W, or a reduction of 35%. This reduction is due to the fact that the PM provides the bias flux without any power consumption. No eddy current and hysteresis loss factors are considered in this work.

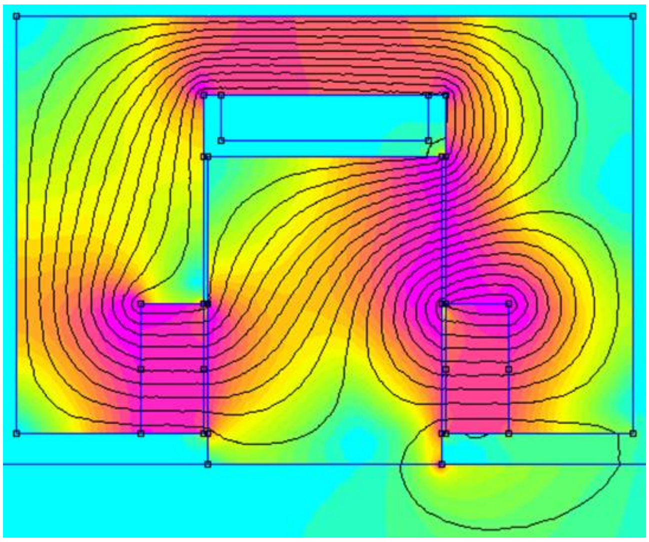

Fig. 11: New PM bias thrust bearing example magnetic flux density for maximum load capacity (4000 N) on right side of thrust disk.

5. New Low Cost PM Bias Radial Bearing Design Concept

The new low cost PM bias radial bearing schematic is shown in Fig. 12, while the labeled geometry of an example finite element model is illustrate in Fig. 13. It is a short axial, planar design. The poles, coils, and PMs are all located in a single plane, instead of in two or more planes. This means that the new radial PM bias design is axially shorter than the other PM biased radial bearing designs reported in the literature. There are a total of eight poles in this configuration, four EM poles consisting of soft metal wound by coils and four PM poles used to generate the bias flux. The new PM bias radial bearing example is designed for a maximum load capacity of 3000 N. The backiron and lamination stack is considered to be made of low cost, laminated M19 silicon iron.

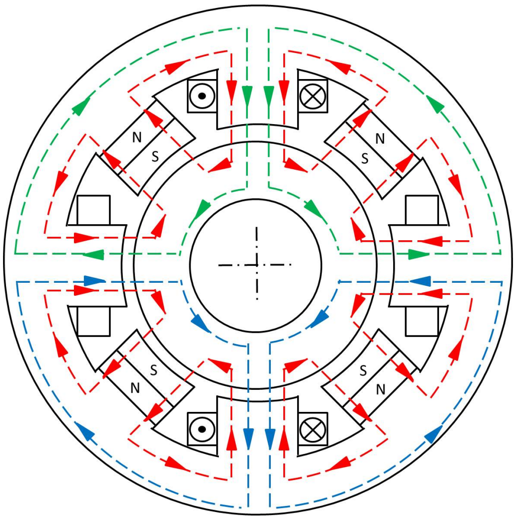

Fig. 12: New PM bias radial bearing design concept with magnetic flux paths.

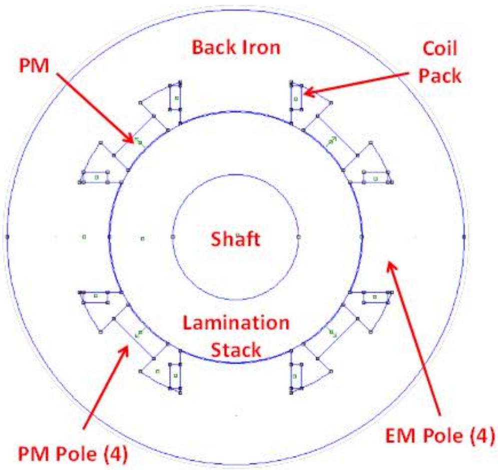

Fig. 13: New PM-biased radial bearing design geometry.

Figure 14 shows the resulting flux density plot from a planar 2-D FEA analysis at maximum load capacity. The calculated maximum flux density in the airgaps is approximately 1.3 T. This design employs a series winding for opposing EM coils in such a manner that the currents are bidirectional (i.e. positive and negative) through the power amplifiers. Thus, only two power amplifiers are needed for one radial AMB (i.e. one amplifier per control axis) instead of the four amplifiers typically required by all EM designs.

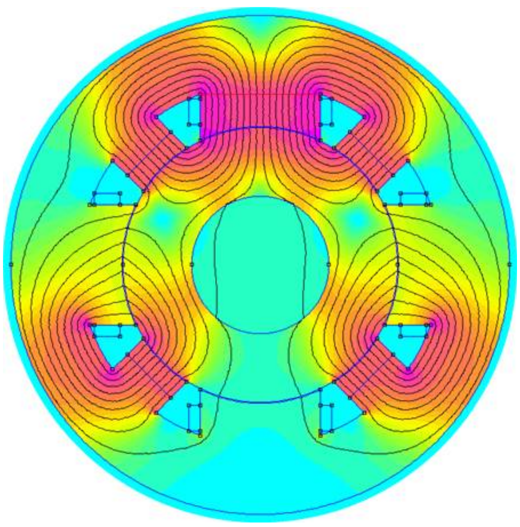

Fig. 14: New PM bias radial bearing example magnetic flux density for maximum load capacity (3000 N) in upward direction.

Again we use NdFeB 44 materials with an operating PM flux of 1.2 T. This is similar to the thrust bearing design

PM demagnetization curve shown in Fig. 8. As with the PM bias thrust bearing design, the combination of PM and EM magnetic flux passing through the PM material is well above the demagnetizing magnet field but below the remnant flux density for this PM material.

The calculated force vs. coil current, as obtained from the 2-D finite element analysis, is given in Fig. 15. It is easily seen from this plot that the new PM biased radial bearing is linear up to the maximum design coil current of 24 amps. Thus, the radial AMB is linear through the operating range of the bearing. As with the thrust bearing, the bandwidth was calculated with the coil inductance and a presumed amplifier output voltage of 200 V. The bandwidth, shown in Fig. 16, of the radial bearing in this example is 300 Hz. Again, this value can be modified by changing the amplifier voltage output, or the number of turns and coil current in the EM windings.

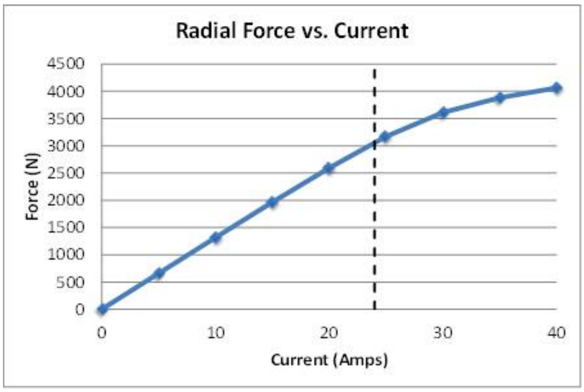

Fig. 15: New radial bearing force versus coil current.

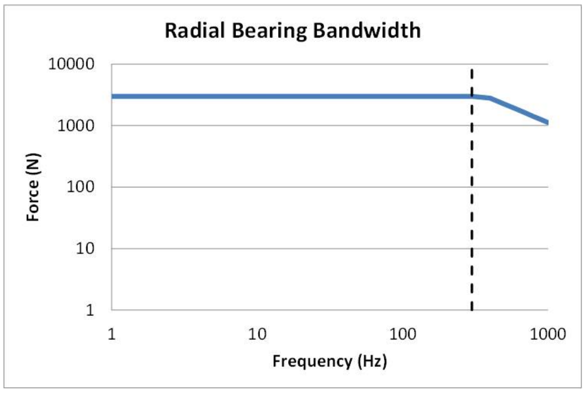

Fig. 16: New radial bearing bandwidth.

A conventional all EM 8 pole magnetic bearing was developed for the same maximum load capacity for comparison with the new PM bias design. Table 2 details the important geometries of both bearing models. The overall size envelope of the two bearings are nearly identical. As in the thrust bearing, the PM-biased design requires about half of the coil windings as the all EM design for a given coil current. An 2-D FEA analysis was performed on the all EM design in order to compare the calculated power consumption of the two designs. The airgap flux level of the top soft metal pole was approximately 1.3 T for the maximum load capacity case. For the PM bias design in this example, the power consumption was calculated as 18.6 W as compared to the EM design with a power consumption of 31.6 W, or a reduction of 41%. Like the thrust bearing, a significant decrease in amplifier power consumption is realized with the new PM bias design.

Table 2: Example radial bearing geometries (All EM vs. PM Bias Designs).

	All EM	New PM Bias
D_{shaft} (mm)	70	70
D_{pole} (mm)	141	141
g_0 (mm)	0.5	0.5
$D_{actuator}$ (mm)	250	254
$L_{actuator}$ (mm)	83	81
I_{max} (A)	24	24
N (turns)	20	12

6. Summary and Conclusions

A new method of designing and constructing low cost magnetic bearings with PM bias has been developed for both thrust and radial bearings. The PM components are placed in the pole face ferrous iron materials in such a way that the PM bias flux is guided into combining with the EM flux in one or the other airgap to enhance the load capacity of both the thrust and radial bearings. This unique design approach has not been reported in the literature previously for AMB designs. This approach leads to significant cost reductions in AMB systems.

The number of amplifiers for a 5 axis system has been reduced by one half or 5 amplifiers for this system as compared to the normal 10 amplifiers. The cost reduction here is thus 50%. Further, the coil power consumption during operation is significantly reduced for the PM bias so the amplifier size requirements are additionally reduced, by approximately

35-40% for the example AMBs designed here, potentially leading to requiring less powerful amplifiers and thus lower cost. Overall, the estimated production hardware cost reduction of an AMB system is estimated as 20% to 30%.

The number of coil turns required for the PM bias designs explored in this work are reduced by about one half as compared to the all EM design; however, this is not a major cost factor. Also, the small amount of PM material used in the pole faces of both the thrust and radial bearings is small and estimated to not represent a significant increase in AMB system cost.

Overall, the reduction in number of amplifiers and their required power rating indicates that there will be some cost savings in wiring in the AMB control cabinet. Also, lower power consumption in the amplifiers and AMBs will allow for some reduction in system cooling. At this point, the numerical value of the cost reduction in this area has not yet been quantified.

The size of the PM bias thrust and radial AMBs is generally not reduced. This is due to the physical limitation that the force is related to the pole face area and the linear limit for low cost materials such as M19 or 4340. Thus, this area does not lead to significant cost reductions.

Finally, the PM bias thrust and radial bearing designs given here are generally about the same axial length as the all EM designs. However, for the radial bearings, they are significantly shorter in the axial direction than homopolar PM biased radial bearings. With the general push in AMB systems to avoid increasing the length of the rotor, and thus, decreasing the first bending critical speeds, the issue of axially shorter, lower cost radial AMBs is significant. The planar radial PM bias bearing design here is significantly shorter than other PM bias bearing designs is regarded as a significant advantage for potential industrial use.

References

Sortore, C. K., Allaire, P. E., Maslen, E. H., Humphris, R. R. and Struder, P. A., Permanent magnet biased magnetic bearings, Proceedings of ISMB 2 (1990), pp. 175-182.

Lee, A. C., Hsaio, F. Z. and Ko, D., Analysis and testing of a magnetic bearing with permanent magnet bias, JSME Int. Journal, C-37(4) (1994), pp. 774-782.

Khanwilkar, P., Olsen, D., Bearson, G., Allaire, P., Maslen, E., Flack, R. and Long, J. Using hybrid magnetic bearings to completely suspend the impeller of a ventricular assist device, Artificial Organs, Vol.20, No.6 (1996). Presented at 3rd Congress of Rotary Flow Blood Pumps, Houston, Texas, August 24-27, 1995.

Maslen, E. H., Allaire, P. E., Noh, M. and Sortore, C., Magnetic bearing design for reduced power consumption, ASME Journal of Tribology, Vol.118 (1996), pp.839-846.

Fukata, S. and Yutani, K., Characteristics of electromagnetic systems of magnetic bearings biased with permanent magnets, Proceedings of ISMB 6 (1998), pp. 234-243.

Allaire, P. E., Decker, J., Bearson, G. B. and Khanwilkar, P. S., Hybrid EM/PM magnetic bearing design for centrifugal blood pump, Presented at 44th ASAIO Annual Meeting, New York, April 23-25 (1998).

Bearnson G., Olsen, D., Khanwilkar, P., Long, J., Sinnott, M., Kumar, A., Allaire, P., Baloh, M. and Decker, J., An implantable centrifugal pump wih hybrid magnetic bearings, ASAIO Journal, Vol.44, No.5 (1998), pp.733-736.

Allaire, P., Decker, J., Baloh, M., Bearnson, G. and Khanwilkar, P., Magnetic bearing design with electromagnets and permanent magnets, Presented at 6th Congress of Rotary Flow Blood Pumps, Park City, Utah, July 25-27 (1998).

Baloh, M. J., Allaire, P. E., Hilton, E. F., Wei, N., Maslen, E. H., Baun, D., Flack, R. D., Olsen, D. B., Bearnson, G. B and Khanwilkar, P. S., Magnetic beairng system for continuous flow ventricular assist device, Artificial Organs, Vol.45, No.5 (1998).

Allaire, P., Bearnson, G., Flack, R., Maslen, E., Baloh, M., Hilton, E., Baun, D., Noh, D., Khanwilkar, P., Olsen, D., Goshorn, A. and Waters, T., Continuous flow magnetically suspended centrifugal flow pump for ventricular assisit device- (CFVADIII): design and testing, Artificial Organs, Vol.22, No.6 (1999), pp.475-480.

Baloh, M. J., Allaire, P. E., Hilton, E. F., Wei, N., Baun, D., Flack, R., Bearnson, G. B., Olsen, D. B. and Khanwilkar, P., Characterization of a magnetic bearing system and fluid properties for a continuous flow ventricular assist device. Artificial Organs, Vol.23, No.8 (1999), pp.792-796.

Hawkins, L. A., Murphy, B. T., and Kajs, J., Application of permanent magnet bias magnetic bearings to an energy storage flywheel, Fifth Symposium on Magnetic Suspension Technology, December (1999).

Hilton, E. F., Allaire, P. E., Decker, J., Baloh, M., Lee, J. and Long, J., Magnetic suspension of an artificial heart pump using EM/PM bearings, Proceedings of the NASA Fifth International Conference on Magnetic Suspension Technology, Santa Barbara, California, December 1-3 (1999).

Blumenstock, K. A. and Brown, G. L., Novel integrated radial and axial magnetic bearing, Proceedings of ISMB 7 (2000), pp. 467-471.

McMullen, P. T., Huynh, C. S. and Hayes, R. J., Combination radial axial magnetic bearing, Proceedings of ISMB 7 (2000), pp. 472-478.

Jiang, W., Allaire, P. E., Olsen, D. B., Baloh, M. J., and Wood, H., Permanent magnet suspension system for artifical heart pumps, ASAIO Annual Meeting, New York, June 6-9 (2001).

Allaire, P. E., Zhang, X., Baloh, M., Jiang, W., Tao, G., and Wood, H. G., Optimum four axis stable permanent magnet bearing suspension for artificial heart pump applications, Internation conference on rotary blood pumps, Artificial Organs, April (2001).

Murphy, B. T., Ouroua, A., Capio, M. T., and Herbst, J. D., Permanent magnet bias homopolar magnetic bearings for a 130 kW-hr composite flywheel, Proceedings of ISMB 9 (2004).

Jiang, W., Evans, S., Allaire, P. E., Wood, H. G. and Untauroiu, A., Design and testing of the LifeFlow total magnetic suspension, 15th Congress of the International Society for Rotary Blood Pumps, Sydney, Australia, November 2-4 (2007).

Fang, S., Sun, J., Xu, X. and Wang, X., A new structure for permanent magnet biased axial hybrid bearings, IEEE Transactions on Magnetics, Vol.45, No.12 (2009).

Sun, J., Bai, G., Le, Y. and Peng, C., Analysis and design of permanent magnet biased magnetic bearing based on hybrid factor, Advances in Mechanical Engineering, Vol.8, No.3 (2016).