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Design of Active Magnetic Radial and Thrust Bearings for High Speed Turbo Aerator

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Abstract

The thrust and radial active magnetic bearing (AMB) designs are presented for a 135 kW vertical axis high speed turbo aerator operating at maximum speed of 27,000 rpm. The thrust AMB is a double acting configuration with upper and lower stators and a single coil. The radial AMB is a 12 pole E-core design. The results of magnetic circuit design, 2-D finite element, and 3-D finite element modeling are presented, indicating that the simple magnetic circuit model is a good initial design tool for both thrust and radial AMBs. The AMBs were actuated with a steady state bias current and a time varying perturbation (control) current. The current gain and open loop stiffness for the AMBs are evaluated, showing the linearity of the bearings. Also, the coil resistance and inductance were evaluated. The bearings were successfully operated in the initial testing. The rotating AMB components must be attached to the rotor securely using shrink fits. The principal and shear stresses induced in the thrust AMB disk and the radial AMB lamination stack were evaluated and found to be in the safe range.

Key words : Thrust Bearing, Radial Bearing, Design, Open-loop Stiffness, Current Gain

1. Introduction

The detailed design of active magnetic bearings (AMB) is a topic that is useful to describe for new users of magnetic bearings. This paper describes a set of radial and thrust bearings developed for a high speed industrial turbo-aerator used in such applications as activated waste water treatments. The turbo aerator is described in detail in the ISMB 15 paper 10134 entitled “Initial Levitation Testing and Design of Magnetic Bearing System for High Speed Turbo-Aerator” provided in this same Symposium. The operating speed range of this turbo-aerator is 16,000 rpm to 25,000 rpm.

This paper gives the development of the AMBs using a simple magnetic circuit model, 2-D finite element modeling, and 3-D finite element modeling. The AMB geometry was optimized to have the required load capacity for a given shaft diameter but have the smallest overall geometry. The objective was also to evaluate the load capacity, material properties, current gain, open loop stiffness, coil resistance, inductance and other properties. The magnetic circuit model, 2-D finite element modeling, and the 3-D finite element modeling results are compared for accuracy.

An important feature of magnetic bearing design is the evaluation of the stresses in the rotating component of the AMBs.

2. Thrust Bearing Magnetics Design

The thrust bearing is a conventional all electromagnetic AMB design as illustrated in Fig. 1. The rotor has a vertical axis operating orientation. The design thrust load is 1,700 N, which takes into account both static weight load and dynamic forces times a factor of safety of approximately 3. This thrust AMB has a single coil pack and two poles on each side of the bearing connected with a back iron. The thrust bearing material is solid ANSI 4340 steel. A photograph of the final thrust bearing is shown in Fig. 2. The stator of the thrust bearing is segmented into 8 poles to reduce eddy currents.

The thrust disk has inner and outer diameters of 102.5 and 165 mm respectively. The initial magnetic circuit model design properties are shown in Table 1. The thrust bearing axial length is 69 mm. In the thrust AMB, the coil currents are

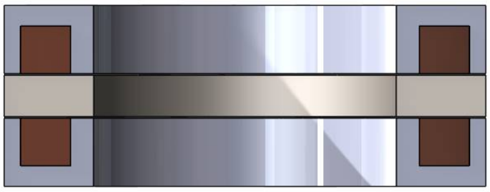
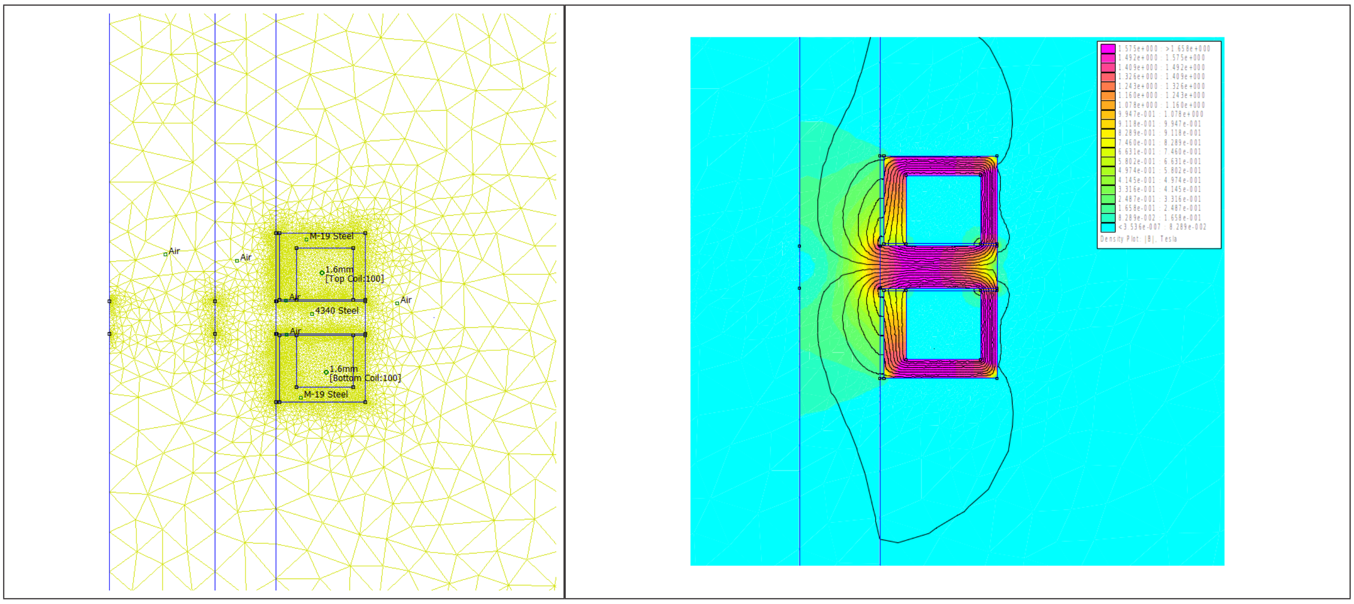


Fig. 1: Geometry of thrust AMB with single coil and two poles

Fig. 2: Photograph of thrust bearing showing the segmented poles and the coil winding



(a)

(b)

Fig. 3: Axisymmetric symmetric 2-D finite element model of thrust bearing left side is geometry and finite element mesh right side is magnetic flux density

divided into two parts: the bias steady state current and the perturbation (control) current. The properties in Table 1 give the current gain of k_i = 570 N/A, open loop stiffness of k_z = -8850 N/mm, coil resistance R = 0.36 Ω, and inductance L = 54 mH. The thrust bearing force vs. perturbation current plot is shown in Fig. 4, used to obtain the linear current gain. Also, the thrust bearing force vs. axial displacement is given illustrating the linearity of the bearing in Fig. 5.

The thrust bearing 3-D analysis is shown in Fig. 6. The magnetic circuit model gives the load capacity of 1,700 N. The 2-D finite element model gives a decrease of 4.4%, to 1,625 N, but the 3-D finite element analysis, at 1,789 N, is approximately 9% larger than the 2-D analysis and 5% larger than the magnetic circuit analysis. The conclusion is that the magnetic circuit models give good results for preliminary thrust AMB design.

3. Radial Bearing Magnetics Design

The radial AMBs are a 12 pole E-core design as shown in Fig. 7. The design load capacity is 1,000 N, including the unbalance forces, the unbalanced pull from the motor, and the external fluid forces. The radial bearing does not undergo any gravitational load. A factor of safety of 3 was used for the radial AMB load capacity. A photograph of the radial AMB is given in Fig. 8 with coils shown. Table 2 gives the dimensions and properties of the radial bearing.

Table 1: Thrust AMB design parameters obtained from magnetic circuit model

Parameter	Value
Linear Load Capacity	1700 N
ID	102.5 mm
OD	165 mm
Axial Length	69 mm
K_i	570 N/A
K_x	-5580 N/mm
R	0.36 Ω
L	54 mH
S_{max}	224 MPa (FS 1.86)

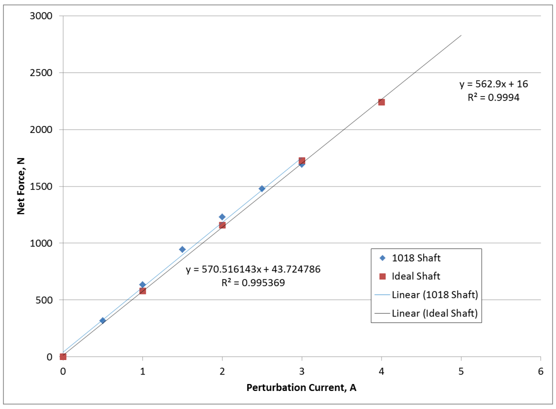


Fig. 4: Thrust bearing force vs. perturbation current plot and current gain

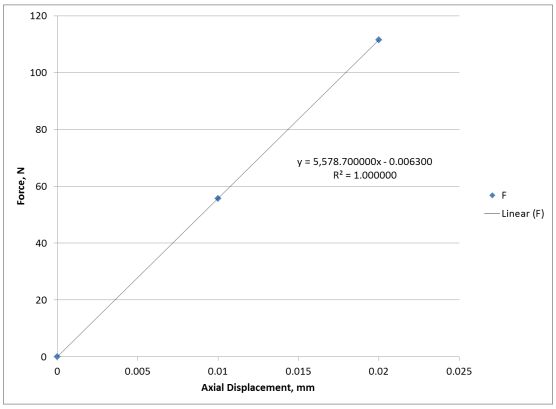


Fig. 5: Thrust bearing force vs. axial displacement and open loop stiffness

The radial AMB inner diameter is 102.5 mm and outer diameter is 182 mm. The axial length is 78 mm. The current gain is k_i = 136 N/A. the open loop stiffness is k_x = -2400 N/mm, the coil resistance is 21 mΩ, and the coil inductance is 3 mH. The radial bearing coil winding and winding connection arrangement is shown in Fig. 9. The poles – North (N) or South (S) are shown in Fig. 9.

In the radial AMB, the coil currents are divided into two parts: the bias steady state current and the perturbation (control) current. A planar 2-D finite element model of the radial bearing was carried out with results given in Fig. 10.

The plot of radial AMB load capacity vs. perturbation current is given in Fig. 11. It shows the linearity of the radial AMB and the current gain. Also, the plot of radial AMB load capacity vs. radial displacement and open loop stiffness is given in Fig. 12.

A photo of the lower radial bearing installed in the turbo aerator is shown in Fig. 13. The upper radial AMB was installed in a similar manner.

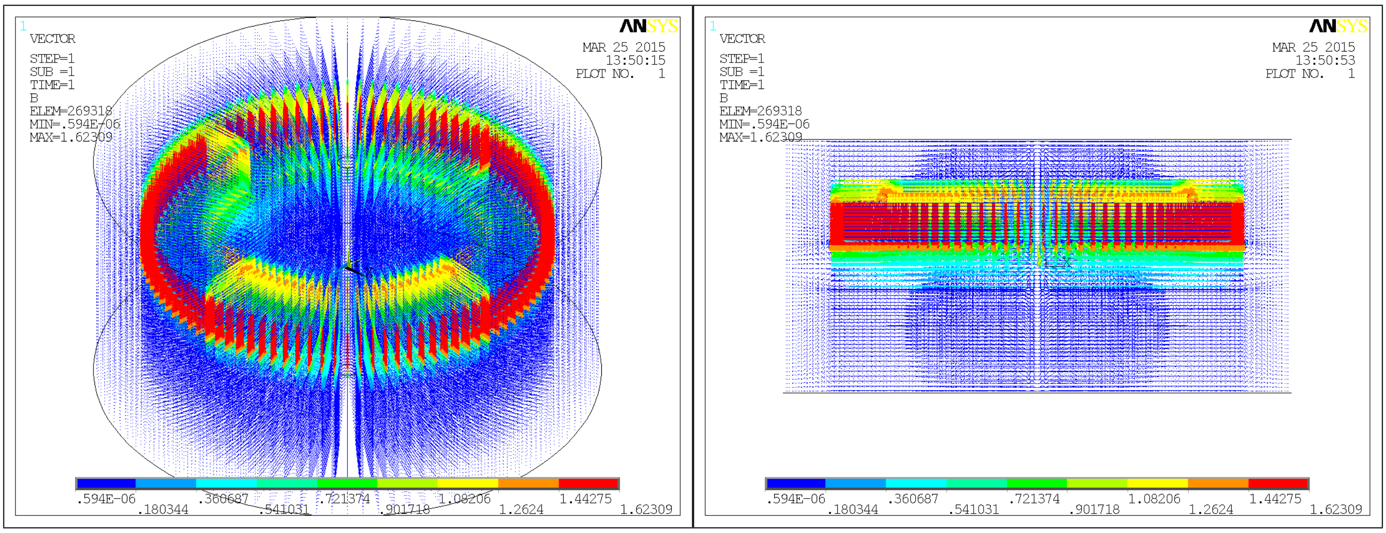
4. AMB Stress Analysis and Design Properties

The AMB rotating parts must be securely attached to the rotor. This means that they must not yield over the operating range. The AMB parts are held on via friction with an interference fit. The thrust disk is shown in Fig. 14, with 4340 solid magnetic steel material, and the radial AMB lamination stack, with laminated M19 laminated silicon iron, is illustrated in Fig. 15. Calculations were performed to determine the required fit and check the corresponding stresses at maximum speed.

The thrust disk stresses are relatively simple calculations. These are equations for a uniform disk undergoing high speed rotation. The disk centrifugal growth formula is

$$u_d = \rho\omega^2 \frac{r}{E} \frac{(3+\nu)(1-\nu)}{8} \left(b^2 + a^2 + \frac{1+\nu}{1-\nu}\frac{a^2 b^2}{r^2} - \frac{1+\nu}{3+\nu} r^2 \right) \quad (1)$$

Figure 16 shows the calculated disk stress levels vs. rotating speed. For the thrust AMB disk, the maximum calculated stress value is 224 MPa, as given in Table 1. The shear strength the 4340 thrust disk material is 416 MPa. The calculated radial AMB peak stress is 132 MPa, as given in Table 2. The shear strength for M19 material is 227 MPa.



(a) (b)

Fig. 6: Three dimensional finite element modeling of thrust AMB giving magnet flux density plots

The rotor growth due to external pressure – due to the shrink fit – and rotation formula is given by

$$u_s = \frac{r}{E}(1-\nu)\left\{-p_o + \frac{\rho\omega^2}{8}\left[\left(3+\nu\right)b^2 - \left(1+\nu\right)r^2\right]\right\} \tag{2}$$

The net diametral change formula is

$$\Delta = 2(u_s - u_d) = 2p_f\left\{\frac{n^3}{E_2\left(q^2-n^2\right)}\left[\left(1-\nu_2\right)+\left(1+\nu_2\right)\frac{q^2}{n^2}\right]+\frac{n}{E_1}\left(1-\nu_1\right)\right\} \tag{3}$$

The radial lamination stack shrink fit and stress levels were evaluted with these formulas.

5. Results and Conclusions

The design of the high speed thrust and radial AMBs is described in detail. The thrust bearing was modeled using magnetic circuit analysis, 2-D finite element model, and 3-D model. The magnetic circuit calculated load capacity was 5% less than the full 3-D analysis, indicating that the magnetic circuit model is a good initial design tool for AMB design. The 2-D axisymmetric model result was less than the 3-D model by approximately 9% so it is not as accurate as the other two. The force vs. current plots were established for both the thrust and radial AMBs showing that they were linear over the operating range of current with perturbation (control) currents subtracted and added to the bias current. Also, the force vs. displacement plots were obtained showing that the plots were linear over the expected operating range. The principal and shear stress design formulas are presented and applied to the AMBs in this turbo aerator application. The thrust and radial AMBs were successfully designed and operated in the turbo aerator over the expected operating range. While there were some issues to overcome in the initial testing, the final outcome was as desired. Many more details on the rotor and control of the bearings is given in the ISMB 15 paper 10134 titled "Initial Levitation Testing and Design of Magnetic Bearing System for High Speed Turbo-Aerator" provided in this same Symposium.

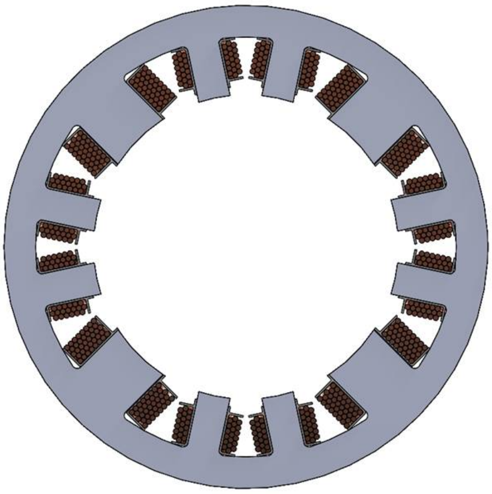


Fig. 7: Radial AMB 12 pole E core configuration

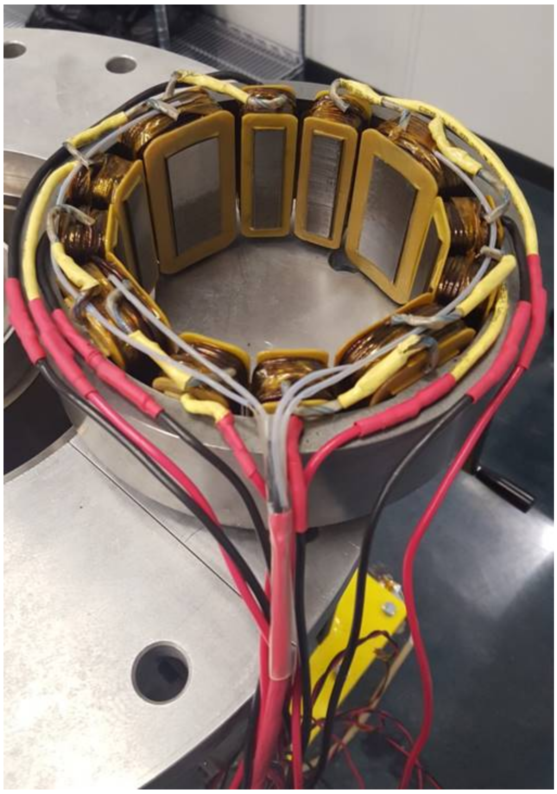


Fig. 8: Photograph of radial AMB

Table 2: Radial AMB design parameters obtained from magnetic circuit model

Parameter	Value
Linear Load Capacity	1000 N
ID	102.5 mm
OD	182 mm
Axial Length	78 mm
K_i	136 N/A
K_x	-2400 N/mm
R	21 mΩ
L	3 mH
S_{max}	132 MPa (FS 1.72)

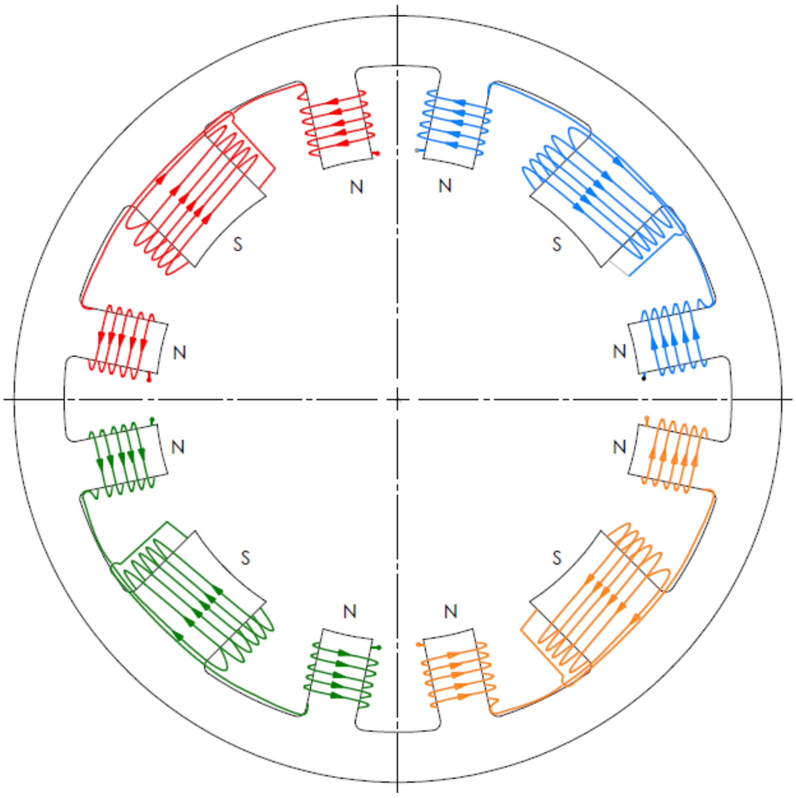
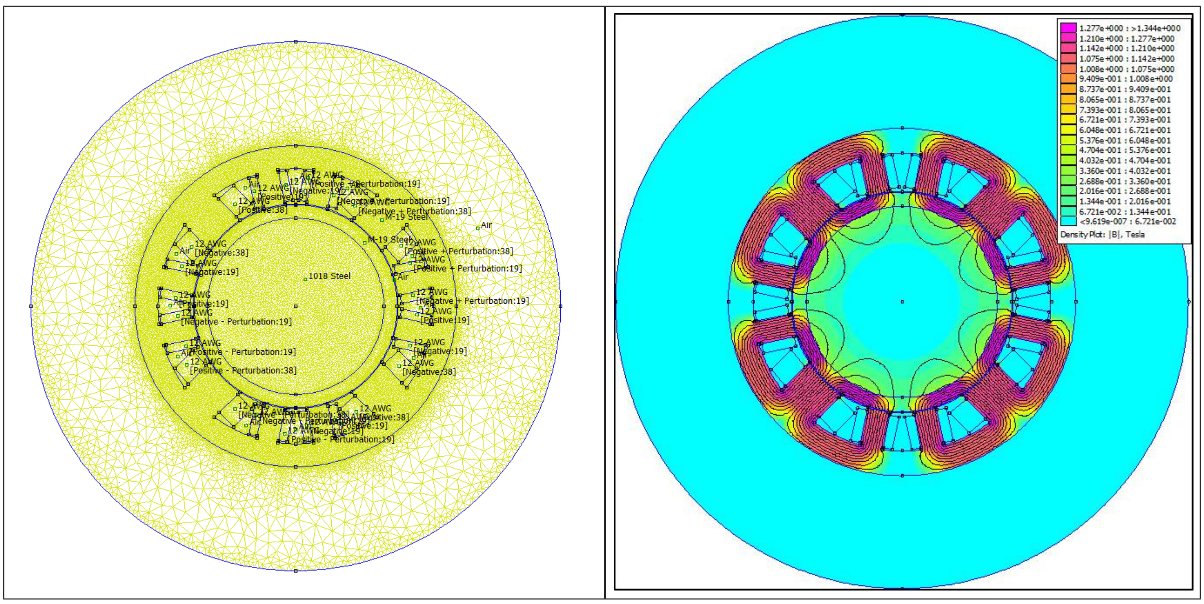


Fig. 9: Radial AMB coil winding, north and south poles, and winding connection arrangement. Red is circuit 1, blue is circuit 2, orange is circuit 3, and green is circuit 4.



(a) (b)

Fig. 10: Two dimensional planar finite element analysis of radial AMB left side is dimensions and finite element mesh right side is magnetic flux density

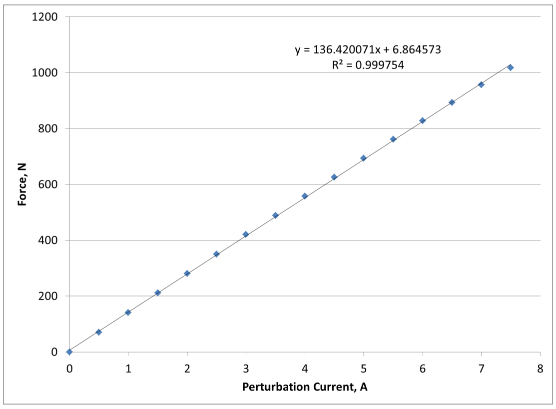


Fig. 11: Radial bearing force vs. perturbation current plot and current gain

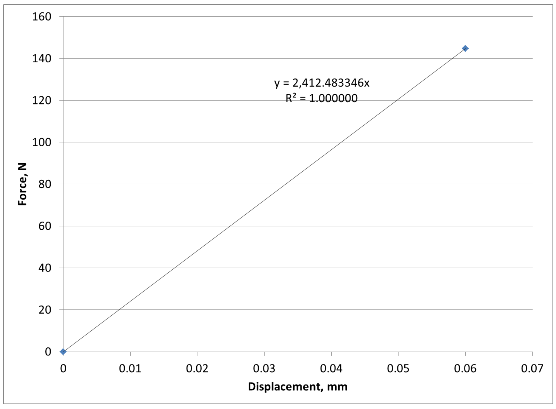


Fig. 12: Radial bearing force vs. axial displacement and open loop stiffness

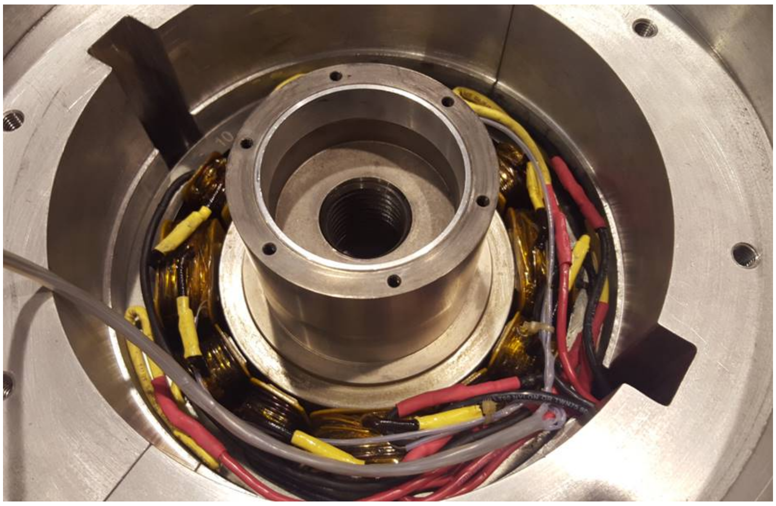


Fig. 13: Lower radial AMB installed in the turbo aerator

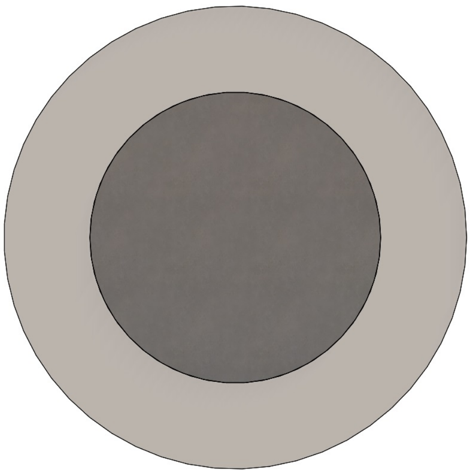


Fig. 14: Thrust AMB disk geometry

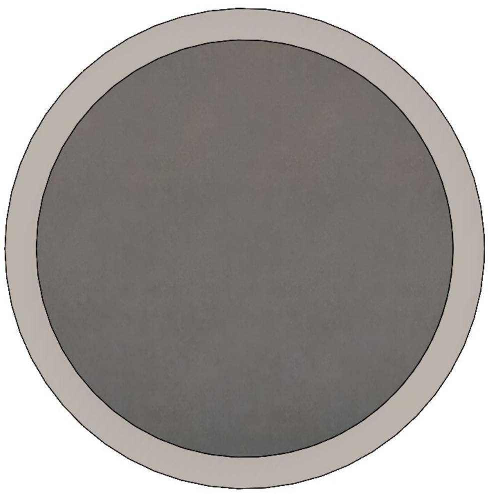


Fig. 15: Radial AMB rotor lamination stack geometry

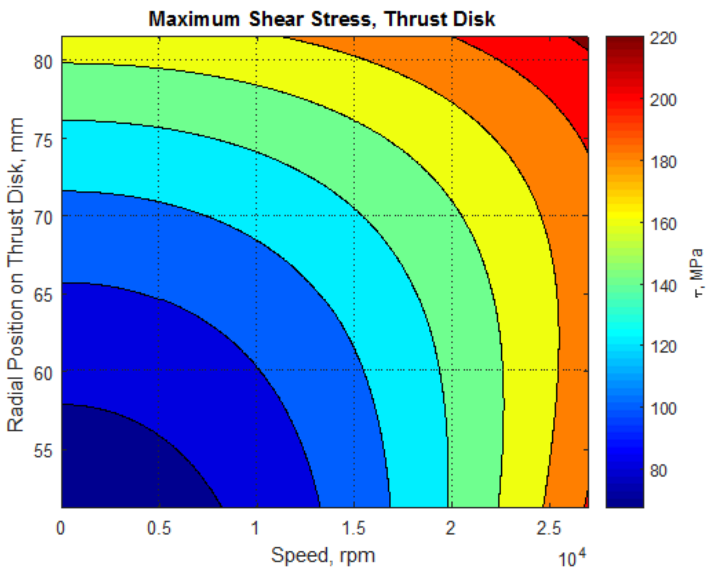


Fig. 16: Thrust AMB disk stresses vs. speed