DESIGN EXAMPLE OF RADIAL ACTIVE MAGNETIC BEARING FOR HIGH-SPEED MACHINE

David Rura
Doctoral Degree Programme (1), FEEC BUT
E-mail: david.rura@vutbr.cz

Supervised by: Jan Barta
E-mail: bartaj@vutbr.cz

Abstract: Development of high-speed electrical machines reopened a door for further development in a field of magnetic bearing. Conventional ball bearings reached their limits and can't bear such as high-speed in many modern turbo applications. Another way is to use air bearing which perform lower load capacity and stiffness. Hence, magnetic bearing seemed to be an advantageous solution in many application. The main cons of active magnetic bearing (AMB) are its space requirement and in case of active bearing also power amplifier and controller. In this paper the design of radial AMB for a motor 12 kW, 45000 rpm is calculated. Typically, analytical solution excludes side phenomenons and thus analytically modelled radial AMB is optimized numerically. This paper provides a full design of AMB including design geometry and performance properties.

Keywords: radial magnetic bearing, radial AMB, design of radial AMB, high-speed

1 INTRODUCTION

Magnetic bearings are dated to 70s when the development of solid-state components was in progress and finally had properties needed for AMB controllers. There were numerous successful applications around the world, mostly in the oil industry in which first AMBs were adopted in large centrifugal pumps. Oil-free operation and low maintenance costs brought them into other fields of industry as well as into the field of medical devices where AMBs found a spot in heart blood pumps [1].

Last years the development of high-speed machines were conducted and magnetic bearing took a place in these machines. Currently, hybrid AMBs are demanded because of their low space requirement. Unfortunately, the traditional approach is considered in many applications where a pair of radials and one axial bearing are adopted in such an application. The example rotor system configuration is sketched on fig. 1.

In this paper, mechanical and electromechanical design constraints are discussed. The analytical approach provides pretty accurate results but is worth to undergo that the numerical solution includes side effects.

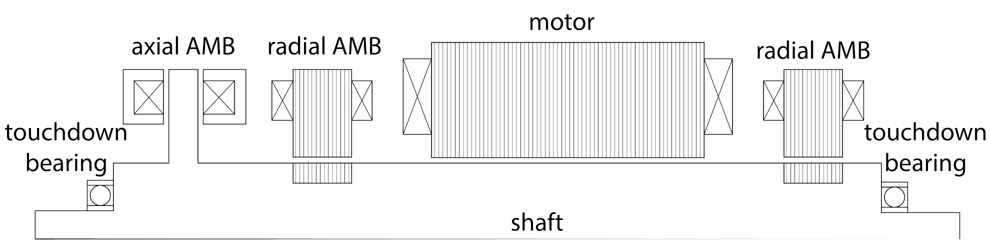

Figure 1: Rotor system with magnetic bearings [5]

2 MAGNETIC BEARING DESIGN APPROACH

In general, the design steps of AMB are not different from any other electrical machine. There is a specification of parameters followed by multi-physics design where each step can influence the results obtained in previous or subsequent design step. Hence, solving a whole design is looped in iterative multi-physics simulations with cross-coupled results. The solving ends when the solution at last step fulfils initial conditions.

Part of the initial design is to choose properly the AMB topology. The magnetic bearing can be passive/active or hybrid - combining passive an active part in one design. Passive bearings don't require external power supply and control but the stiffness is much lower compared to active magnetic bearing. Hybrid systems use permanent magnets for bias flux and active coils for control [2].

For current design, the 8-pole hetero-polar design has been selected. This model is the most conventional and used in many application. Also, provides better adaptability for control loops [3]. There are also other types of magnetic bearing like electrodynamical where the force is developed between induced eddy currents and the magnetic field generated in the stator.

3 MECHANICAL DESIGN

For radial AMB, the critical parameter is maximal circumferential speed v_{max}. It is mostly dependent on geometry and material. Maximal circumferential speed allowed in typical materials used in electrical machines are listed in the tab. 1.

In motor design material AISI 1018 has been used for solid rotor with grooves and ferromagnetic material M250-35A has been selected for stator sheets. Numbers in the table are given by eq. (1) for both cylindrical and ring shaped rotating element [4]. It has to be kept in mind that the machine has to work in certain safety limits. Typically, for mechanical stress at least 1.2 safety factor is considered to perform the safe operation.

$$v_{max_{cylinder}} = \sqrt{\frac{8\sigma}{(\nu+3)\rho}} \qquad v_{max_{ring}} = \sqrt{\frac{4\sigma}{\left((1-\nu)\frac{r_i^2}{r_o^2}+(\nu+3)\right)\rho}} \tag{1}$$

Where σ is mechanical stress, ν is a Poisson number, r_i and r_o are the inner and outer radius and ρ is a material density.

According to v_{max}, the maximal radius at certain rotational speed can be determined as

$$r_{max} = \frac{v_{max}}{\omega_{max}} = \frac{v_{max}}{\frac{2\pi n_n p}{60}} \tag{2}$$

Material	AISI 1018	M250-35
σ - max mechanical stress [MPa]	300	450
ν - Poisson number	0.29	0.3
ρ - material density	7860	7600
r_{max} - cylindrical geometry [mm]	64.6	80.4
v_{max} - cylindrical geometry [m/s]	304	379
r_{max} - ring geometry ($r_i = 18$)[mm]	44.9	56.2
v_{max} - ring geometry [m/s]	212	265

Table 1: Comparison of v_{max} and r_{max} for different materials at 45000 rpm [5]

4 ELECTROMECHANICAL DESIGN

In the electromechanical design of radial AMB, an air-gap plays the main role. Large gap causes high magnetic reluctance and high magneto-motive force (MMF). High MMF can be obtained by current i raise or/and by increasing number of turns N which increases inductance L by square. For fast control loops lower L is required. Large L has a large time constant that degradates the control response. Contrary, larger air-gap provide easier linearization that speeds up control loop. For conventional AMB an air-gap can be considered $0.4 - 1$ mm according to application. The rotor rotates within play x_{max} given by safety or touch-down ball bearing substituting AMB in case of malfunction of AMB power supply. This shows that maximal force is developed at $g = g_0 + x_{max}$ [2].

Other parameters that have to be selected in the initial design phase are magnetic flux density B in an air-gap and number of poles n_p.

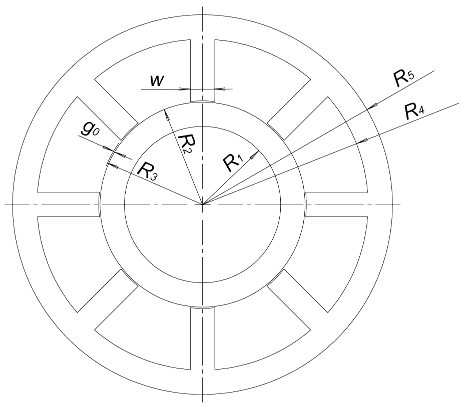

Figure 2: Geometry of radial AMB [5]

During the operation when the highest force is demanded ferromagnetic material shouldn't be over-saturated. Thus, the B_{sat} should be chosen under the knee of the BH curve. For M250-35 the knee is around 1.25 T, therefore, $B_{sat} = 1.2$ T has been selected [5].

The number of poles for AMB has been selected $n_p = 8$. A high number of poles are usually chosen for large rotor diameter when there is enough room to fit AMB. In this case, dimensions were limited by maximal inner and outer diameter. Maximal diameter to fit current design and minimal diameter to allow rotor to go through stator bore [3]. Because of this, the maximal journal diameter has been selected the same as rotor system diameter. (all dimensions are summed up in the tab. 2)

Another important parameter of AMB is load capacity. It is a weight that AMB can support steadily. Force developed by AMB compensates the gravitational force and dynamic forces acting on rotor system. Usually, there are pair of AMBs, hence each of them bears half of rotor system weight. The required load capacity of AMB comes from the motor load analysis. In this case, the load is an unknown and general rule is to consider that AMB supports load equals three times rotor weight [7].

As soon as all parameters mentioned in previous paragraphs the dimensions of AMB can be obtained. From general electromechanical theory co-energy is given as follow:

$$W_{co} = \int_0^i \psi di = \int_0^i Lidi = \frac{1}{2}Li^2 = \frac{1}{2}\frac{N^2}{R_m}i^2 \tag{3}$$

Partial derivation of co-energy defines force:

$$F_{im}(i,g)|_{i=const.} = \frac{\partial W_{co}}{\partial g} = -\frac{N^2\mu_0 S_{Fe}}{\left(\frac{l_{Fe}}{\mu_{r_{Fe}}}+2g\right)^2} i^2 \tag{4}$$

From the amperes law, the magnetic field strength in a circuit included a horseshoe-shaped core separated from another ferromagnetic element by 2 air-gaps is as follow:

$$Ni = H_{Fe}l_{Fe} + 2H_g g \tag{5}$$

Substituting relation between magnetic flux density and magnetic field strength $B = \mu_0\mu_r H$ in eq. 5, the MMF can be calculated:

$$Ni = \frac{B}{\mu_0\left(\frac{l_{Fe}}{\mu_{Fe}}+2g\right)} \tag{6}$$

Substituting this equation in eq. 4 gained the form where only S_{Fe} is unknown variable:

$$F_{im} = -\frac{B^2 S_{Fe}}{\mu_0} \tag{7}$$

The negative sign describes the nature of the force that the force acts in the direction of diminishing air-gap [6]. The magnetic reluctance of ferromagnetic element used to be much smaller than the air-gap itself $\frac{l_{Fe}}{\mu_{r_{Fe}}} \ll g$, hence can be neglected in the calculation.

The required slot area is given by MMF and considered current density J_{max} with copper fill factor k_c:

$$|NI| \leq k_c J_{max} S_{cu} \tag{8}$$

When it comes to dynamic modeling, force eq. 4 is rewritten into form including current K_i and position K_x stiffnesses.

$$F \approx \left.\frac{\partial f}{\partial x}\right|_{i_p=0} x + \left.\frac{\partial f}{\partial i_p}\right|_{x=0} i_p = K_x x + K_i i_p \tag{9}$$

5 RESULTS

To compensate the side effect like fringing numerical optimisation has been done. The sweep parameter for optimisation was the length of the AMB core. Analytically computed length develops 145.3 N so extending the length to 19 mm provides desired force 150 N. So, there is a difference between analytical and numerical solution about 4.4%. All computed data are listed in the tab. 2.

6 CONCLUSION

Magnetic bearings are suitable for high-speed machines in which ball bearings cannot be used. Even AMBs have some cons, the oil-free operation and low maintenance costs provide high long-term reliability. In this paper one example for a certain application is presented. 8 pole radial AMB is widely accepted design because of its simplicity, reliability, controllability and a low number of power controllers. Designed AMB fulfils all requirements on rotor system suspension. In total, the rotor system will bear a pair of radial AMB that provide support in 4 degrees of freedom. All parameters presented here can be used to design a controller as well as to manufacture the AMB. Maximal current is given by power amplifier.

weight of rotor system [kg]	8.5
force of single AMB [N]	150
air-gap g + max offset x_{max} [μm]	800
pole cover τ_p	0.3
copper fill factor k_{Cu}	0.5
mag. flux density B_{sat} [T]	1.2
R_1 [mm]	24.7
R_2 [mm]	32.4
R_3 [mm]	32.8
R_4 [mm]	52.3
R_5 [mm]	60
length of AMB l [mm]	19
slew rate df/dt [kN/s]	706.9
magnetomotive force MMF [A]	763.9
current stiffness K_i [N/A]	24.2
position stiffness K_x [kN/m]	-198

Table 2: Calculated parameters of radial AMB [5]

7 ACKNOWLEDGEMENT

This research work has been carried out in the Centre for Research and Utilization of Renewable Energy (CVVOZE). Authors gratefully acknowledge financial support from the Ministry of Education, Youth and Sports under institutional support and BUT specific research programme (project No. FEKT-S-20-6379)

REFERENCES

[1] WEISE, David A. a Frank D. PINCKNEY. *An introduction and case history review of active magnetic bearings*.

[2] SCHWEITZER, G. and Eric H. MASLEN. *Magnetic bearings: theory, design, and application to rotating machinery*. New York: Springer, [2009]. ISBN 978-3-642-00496-4.

[3] CHEN, Rui, Hongwei LI a Jing TIAN. The relationship between the number of poles and the bearing capacity of radial magnetic bearing. *2017 Chinese Automation Congress (CAC)*. IEEE, 2017, 2017, , 5553-5557. DOI: 10.1109/CAC.2017.8243771. ISBN 978-1-5386-3524-7.

[4] LARSONNEUR, Rene. *Design and control of active magnetic bearing systems for high speed rotation*. s.n, 1990. DOI: 10.3929/ethz-a-000578355.

[5] RURA, D. *Design of a Magnetic Bearing for an Electrical Machine. Brno, 2019*, 72 s. Master thesis. Brno University of technology, Faculty of electrical engineering and communication, Department of power electrical and electronic engineering

[6] POLLANEN, R, J NERG a O PYRHONEN. Reluctance network method based dynamic model of radial active magnetic bearings. In: *INTERMAG Asia 2005. Digests of the IEEE International Magnetics Conference, 2005* [online]. IEEE, 2005, s. 1429-1430 [cit. 2019-05-21]. DOI: 10.1109/INTMAG.2005.1464144. ISBN 0780390091.

[7] SKF workshop - Magnetic bearing for high speed machines.
(https://www.skf.com/us/services/training)