

# Active Radial Magnetic Bearings Designed to Force Required

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**Abstract:** Magnetic bearings is of increased importance in high-speed tool- and turbo-machines. The right choice of the special type of active bearings for radial journal depends on the disposable overall height and length in many cases. Here the main types of construction and the concerning design parameters are compared to help finding the best solution for an active radial bearing.

## 1 Introduction

Active magnetic bearings offer many new opportunities for control of rotating shafts in electric machines, turbo generators, vacuum pumps, and other drive components [1].

The decisive reason is the controllability over a wide operating range. This is necessary for high-speed drives concerning the different natural vibrations which can be excited during the start-up and braking operation. Other advantages are friction-less rotating, small additional losses, fewer thermal effects and an higher efficiency. Further with help of magnetic forces it is possible to compensate unbalances caused by manufacturing or by load. For bearing rotational shaft in five directions of motion two radial bearings and one axial bearing have to be inserted. The most forces are required in radial direction because the weight of the shaft and unbalance forces must be recorded. In [2] a trial has been made to design a class of radial magnetic bearings from heteropolar type with different pole-numbers. The comment of the authors to the results is that the design will be complicated in the case of more increased

pole-numbers. Furthermore The validity of the optimization results are not secured because local optimum can not be excluded.

Another way is going to construct a radial homopolar bearing consisting of three poles around the inner diameter and the anti-poles in axial direction [3]. Some advantages have been discussed but not tested.

Therefore the study has been focussed on the design of such radial bearings. Another precondition for investigating was to limit the variability of such kind of magnetic bearings which are working in active manner so that the control of shaft position is guaranteed.

## 2. Force superposition

Radial bearings are set to influence the bearing forces of a rotational shaft regarding two lines of action. These directions are orthogonal in the simplest case. This is the reason why the controllable magnetic fluxes must be built crossing the airgap between stator- and rotor side stack. For investigating the potential of design the number of magnetic poles, the main direction of magnetic fluxes, and the kind of premagnetization can differ. Going out from the energy stored in the magnetic field with:

$$W_m = \frac{1}{2} \int_m B H dV = \int_m F ds = \int_m f dV \quad (1)$$

The useable force density under one pole of a magnetic bearing follows with:

$$f = \frac{B^2}{2 \mu_0} \quad (2)$$

Supposing a maximal induction of  $B_{\max} = 1 \text{ T}$  it is obtained a force density of  $400 \text{ kN/m}^2$ . With help of force density and the concerning area of field penetration the magnetic force of one pole bearing can be written as:

$$F_p = \int_m f dA = \frac{B^2}{2\mu_0} l_p \frac{D_i}{2} \cos \theta \quad (3)$$

where:

- $\theta_0$ : pole location angle
- $\theta_p$ : pole pitch angle
- $l_p$ : pole length
- $D_i$ : inner diameter

It is doubt to prefer an heteropolar radial bearing as shown in fig.1 and 2 with a concentric magnetic joke or an homopolar radial bearing shown in fig.3.

The characteristics and advantages of the heteropolar bearing are:

- simple construction with using of one iron stack
- force improvement is possible with increased bearing width and rotor stack diameter
- rotor stack must be laminated because of the eddy currents

For the homopolar radial bearing is valid:

- two similar iron stacks are necessary
- a mixed form with heteropolarity is possible
- force can be improved over the rotor stack diameter
- lamination of the rotor stack is not able
- permanent magnets can be easy mounted

One of the most arguments for using of homopolar bearings, which are indicated, consists of the eddy-current less action. But it has to answered that it depends on the radial skin depth. Therefore a clear preference of one of these bearing types can not be seen. But it is usual to prefer the homopolar-type if the rotor is not permitted to laminate.

For the magnetic force per pole-pair in homopolar bearing we can differ the force components in x-direction (to the top) and y-

direction (to the left):

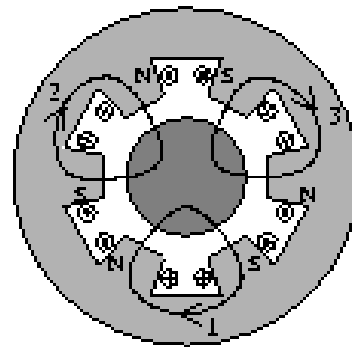


Fig.1: Heteropolar bearing with 3 magnetic pole-pairs

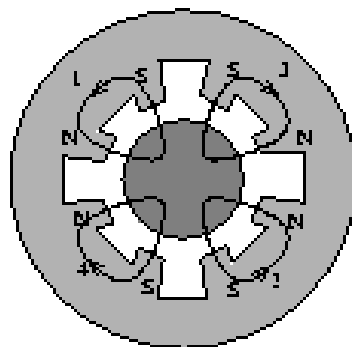


Fig.2: Heteropolar bearing with 4 magnetic pole-pairs

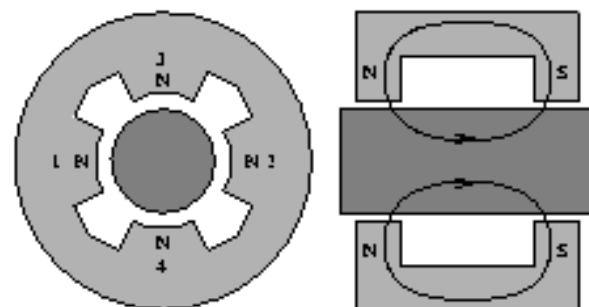


Fig.3: Homopolar bearing with 4 magnetic pole pairs

$$F_x = 2 \sum_{k=1}^p F_{pk} \cos\left(\frac{B}{(k+1)p}\right) \quad (4)$$

$$F_y = 2 \sum_{k=1}^p F_{pk} \sin\left(\frac{B}{(k+1)p}\right)$$

In case of using heteropolar magnetic bearings the pole position between one pole-pairs is needed to consider in the calculation, therefore it follows:

$$F_x = 2 \cos\left(\frac{\alpha}{2}\right) \sum_{k=1}^p F_{pk} \cos\left(\frac{B}{k p}\right) \quad (5)$$

$$F_y = 2 \cos\left(\frac{\alpha}{2}\right) \sum_{k=1}^p F_{pk} \sin\left(\frac{B}{k p}\right)$$

with the pole distance of one journal:

$$B = \frac{2\pi}{N_p} \quad (6)$$

Equ.(4) and (5) shows that the heteropolar bearing has a little reduced pole angle-dependent force production.

For a practical application two different aims of design can be used:

- 1) The maximal force in x-direction is required if well-balanced shaft should be loaded to compensate the weight.
- 2) The minimal force in all directions should be available if unbalanced forces are more higher than the weight.

Magnetic poles and scale of forces are similar in both directions. Three magnetic poles are necessary at minimum to produce negative and positive forces acting in two directions (x,y). If the number of magnetic poles is choiced to 4 then the coupling between these forces in two directions can be minimized. The concerning iron stacks for booth radial bearings are given in fig.1-3. These figures show that the forces must be depended on the angle of the pole position. To obtain the maximal angle dependent force the one bearing coil has to be deactivated which contributes a negative force component. In the case of the radial bearing with three magnetic poles shifted in 120° the radial sumed force is:

$$F_M(\alpha) = 2F_{p1} \cos(\alpha) + 2F_{p2} \cos\left(\alpha + \frac{B}{3}\right) + 2F_{p3} \cos\left(\alpha + \frac{2B}{3}\right) \quad (7)$$

For applying this configuration in horizontal bearing setup it is usual to group the three magnets in a dissymmetric arrangement to the

vertical axis.

In case of using radial bearing with 4 magnetic poles these orthogonal forces are given considering the pole position of multiple 90 degree.

The results for the angle-dependent forces of both bearing-types with different pole-pairs are displayed in fig.4.

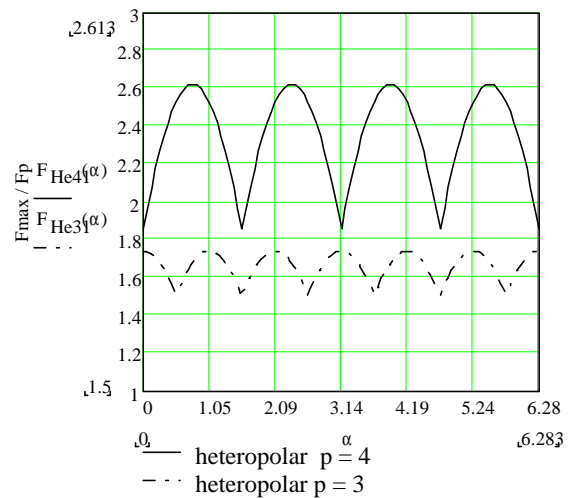


Fig.4: Radial forces of heteropolar types

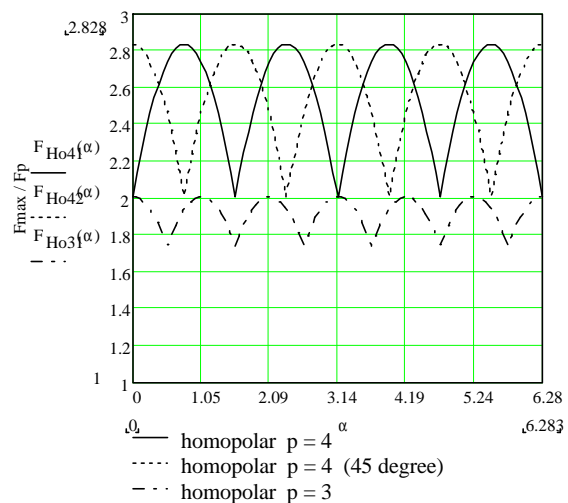


Fig.5: Radial forces of homopolar types

The conclusions of this part are:

- 1) The bearings with the higher number of pole-pairs need a smaller force per pole to reach the highest maximum value and also minimum available values
- 2) The homopolar bearings are more advantageous as heteropolar one with the same number of poles because they need a

smaller excitation per pole for obtaining the equal maximal or minimal forces.

In table 1 the maximal quotients are given for every type of bearing.

Type	He P4	He P3	Ho P4	Ho P3
$F_p/F_{\max}$	0.385	0.577	0.353	0.5
$F_p/F_{\min}$	0.546	0.667	0.5	0.577

**Table 1: Force relation**

It can be seen from table 1 that the order of the different bearing types regarding the force building of maximum and minimum available values are the same.

### 3. Design of a radial magnetic bearing

The design of magnetic bearing is focussed on the dimension of the magnetic circuit consisting of magnetic poles, stator- and rotor jokes and airgap. For many applications the airgap is sized between 0,5 to 1 mm. After that the choice of the electric parameters with coil windings and amperes follows.

It is required for designing such a magnetic bearing to give a special attention of the nonlinear force-position characteristic. In /1/ the well-known differential winding construction has been introduced to premagnetize the iron with help of a constant excited pair of coils. This needs additional size for construction. Many works offer a software.based solution e.g. /4/ with compensating by a nonlinear control law. Another way is to use permanent magnets iased on ferrit materials. These can be inserted in the stator joke located between both magnetic poles. A refined solution has been found with /5/ where the permanent magnetic flux goes the axial way and the electromagnetic flux cross the airgap in radial direction. But the special arrangements to solve this problem of premagnetization should

be not considered for this study

Furthermore the variation of the slot and pole numbers can not be recommended because the usable force is reduced and the flux density of the iron stack is not utilized enough how discussed in /2/. Therefore the studies have been limited on the three and four pole-pairs bearings.

The initial design values of a radial bearing are the maximal needed or minimal available radial forces and the desired air gap. To find are the geometric parameters of bearing with length and diameter.

At first the usual pole-area can be determined with:

$$A_{pFe} = \frac{F_p \mu_0}{B_{\max}^2} \quad (8)$$

Furthermore the place for windings has to be reserved. Considering the m.m.f. required:

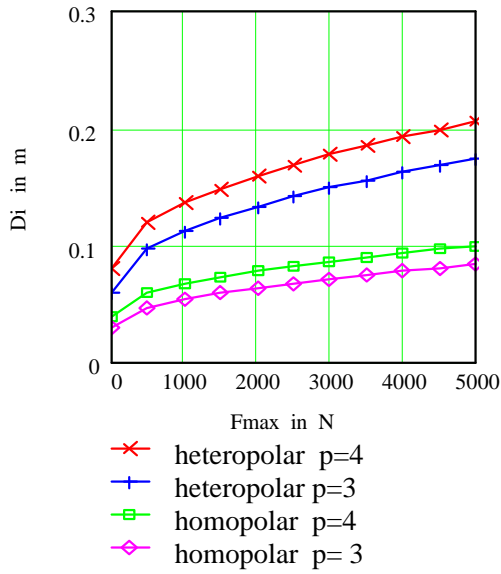
$$1 = I_w = \frac{2 B_{\max}^*}{\mu_0} S @ A_w \quad (9)$$

and the maximal current density permitted of  $4 \cdot 10^6$  A/m<sup>2</sup> the winding area can be obtained with:

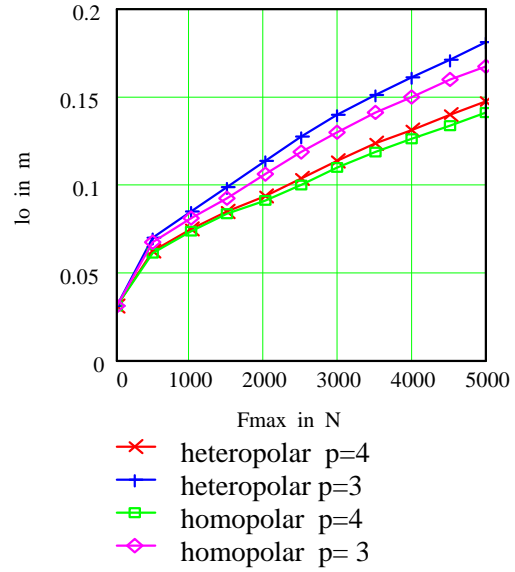
$$A_w = d h_p \$ \frac{2 B_{\max}^*}{\mu_0 n_w S_{\max}} \quad (10)$$

For the choice of the winding window with the pole distance d and pole height h<sub>p</sub> and the winding factor n<sub>w</sub>=0.4, we obtain the minimal axial magnet area with h<sub>p</sub> = d/2.

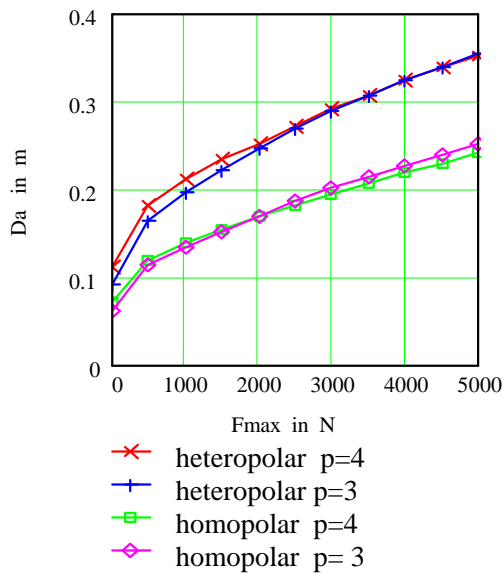
The pole-width and the pole-length can be determined as components of a quadratic area because the electric dimension of coils become the best. From this the inner and outer diameter can be calculated.



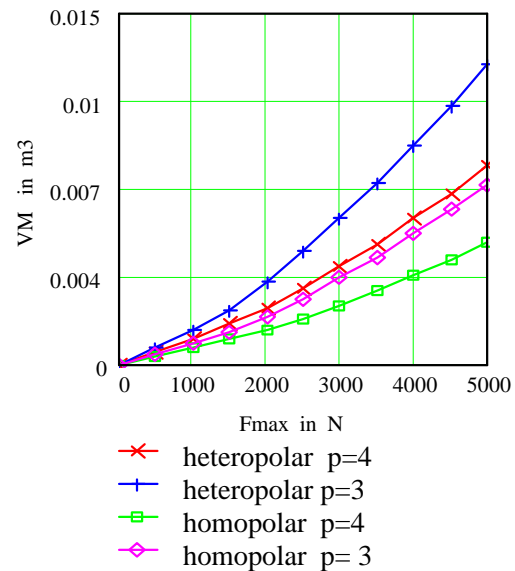
**Fig.6: Inner diameter**



**Fig.8: Total length**



**Fig.7: Outer diameter**



**Fig.9: Total volume**

The calculation results shows with consideration of highest or lowest permitted forces , the smallest inner diameters are given for Ho3 - Ho4 - He3 - He4- types of bearings, see fig.6. The outer diameter of heteropolar types are just as greater than of homopolar one, but the differences for the pole pairs are not significant (fig 7). Here the homopolar ones are advantageous over the heteropolar types. Equally in case of the design regarding the lowest available forces for the outer diameters the pole numbers are not so

important as the mainly flux direction with advantage of the homopolar bearing. The calculated pole-lengths give better results for higher pole-numbers, as shown in fig.8. Finally the magnetic volume shows us a certain disadvantages of all heteropolar magnetic bearings, see fig.9..In general we have a clear preference of homopolar bearings.

#### 4. Conclusion

A comparison of the essential design parameters of radial bearings with diameter, length and volume has been given considering of homopolar and heteropolar types and different number of magnetic poles. An exact dimension of the electric components with coil windings has been neglected. Further studies will be included it.

#### 5. References

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