Design and comparison of different kinds of radial magnetic bearings

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ABSTRACT

This paper discusses the design of the electromagnetic part of a radial bearing. Especially the result of the choice between four and three pole-pairs per bearing and homopolar / heteropolar are discussed.

Main result is that more or less the total volume of the bearing depends on this design decisions. However one can see that homopolar bearings are longer then heteropolar ones. Comparing bearings with four or three pole-pairs per bearing the bearings with three pairs are also a little bit longer than the correlating ones with four pairs.

INTRODUCTION

Magnetic bearings are used for linear drives as well as to bear rotors. Main advantage is the missing of friction which both reduces losses and noise. Problems of the motion control because of stick-slip effects can be avoided too.

The most interesting bearings are the radial bearings which have to carry the weight but also the sinusoidal forces of unbalances.

One problem of magnetic bearings are the space requirements comparing to conventional rolling contact bearings. Therefore this paper discusses four kinds of radial bearings focusing the size of each.

THE RELUCTANCE FORCE

A radial bearing normally can be taken as three or four electromagnets. For the design of the bearing, the maximum force of each magnet is the crucial value. Therefore this maximum force has to be calculated. The typical way is to use the method of the virtual work[1]. This leads to

$$F_{mag} = \frac{AB^2}{\mu_0} \quad . \qquad (1)$$

The parameters are

- μ_0 which is constant
- B which is limited by the saturation to 1 T–2 T
- A which is the surface of each pole

Therefore only A which is also the cross section of the magnetic path is subject of the design process.

DESIGN DECISIONS

This contribution discusses four variants which are deduced from the decisions

- homopolar / heteropolar and
- 3 pole-pairs / 4 pole-pairs per radial bearing.

Three or four pole-pairs

The simplest radial bearing is built of four pole-pairs placed on the circumference. Two facing ones make a bearing axis which produces forces in positive and negative direction. As advantage of this configuration, the two axes can be controlled independently.

Three pole-pairs are enough to produce forces in every direction but make the control a little bit more complex because of the coupling. This can easily be overcome using a digital controller.

***TABLE 1:** Maximal Force*

	0°	30°	45°	60°	90°
3 pole-pairs	1	$\cos(30^\circ) \approx 0.86$		$2\cos(60^\circ) \approx 1$	$\cos(90^\circ) \approx 0.86$
4 pole-pairs	1		$\cos(45^\circ) \approx 1.4$		1

In both cases the maximal force can only be produced for certain directions. The preferred directions of the 4 pole-pair bearing are 45°, 135°, 225°, and 315°, which are placed between two adjacent pole-pairs. They produce 1.4 times the force of one pole-pair. The 3 pole-pair bearing has 6 preferred directions which are placed every 60°. This may be an advantage of a 3 pole-pair bearing.

If we compare the ratio between the maximum and minimum force of both bearings we get

$$f_3 = \frac{0.86}{1} = 0.86 \text{ and } f_4 = \frac{1}{1.4} = 0.71 \quad , \qquad (2)$$

which can be rated as advantage of the 3 pole-pair bearing as a ratio of 1 would be optimal.

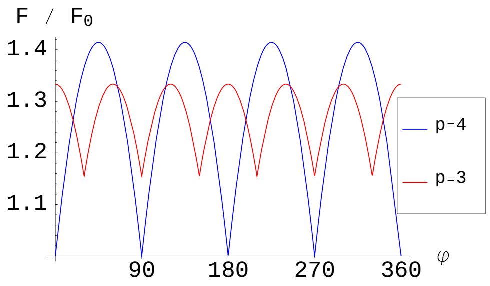

***FIGURE** 1: Maximum force of a 4- and a 3 pole-pair bearing*

Actually each pole-pair of a 3 pole-pair can use 4/3 of the space of a 4 pole-pair bearing which means it can produce approximately 4/3 of the force a 4 pole-pair bearing. Figure 1 shows the maximum force as a function of the direction. The values are scaled to the force F_0 of one magnet of the 4 pole-pair bearing to compare them.

Another advantage of the 3 pole-pair bearing is the number of magnetizations which is 3/4 of number of 4 pole-pair bearings (table 3).

Homo- and heteropolar bearings

The three or four pole-pairs can be mounted either such that both poles are placed tangential or axial to the rotor. The first variation is called HETEROPOLAR the other HOMOPOLAR bearing.

The lower half of figure 2 shows the front and the sideface of a homopolar bearing.

This variant has only 3 or 4 poles –instead of 6 or 8– per revolution. This reduces the number of magnetizations to the half. Transferring the results of [2] to homopolar bearings we can assume that the losses grow with the number of poles per circumference independently from the question whether the magnetization is north-gap-north or north-gap-south.

As the flux path in the rotor is axial normal stacks cannot reduce eddy-currents. Therefore the homopolar bearing is preferred in cases where a solid rotor is needed for mechanical reasons[3].

Naming

This two decisions can be combined and lead to the four types of bearings shown in table 2

***TABLE** 2: Four bearing types*

	n=4	n=3
heteropolar	He P4	He P3
homopolar	Ho P4	Ho P3

***TABLE** 3: Poles on the circumference*

Name	Ho P3	Ho P4	He P3	He P4
Number of Poles = Magnetizations per revolution	3	4	6	8

DESIGN OF A RADIAL BEARING

Figure 2 shows all sizes needed for the design of an heteropolar (upper part) and a homopolar (lower part) bearing.

The design is done in four steps:

1. Setting of the needed force depending on the heft and the expected unbalance force
2. Calculating of the pole-face area
3. Calculating the other sizes
4. Recalculating

The last step can be done using FEM. If the mass of the rotor becomes larger then expected, step 1 can be repeated. If the force is too small, the pole face can be enlarged and we can start again at step 3.

Calculation of the needed bearing force

The radial bearing has to carry the unavoidable unbalance forces as well as the weight assuming a horizontal rotor. The unbalance force can be as large as the weight or larger. With this deliberation a minimum force F_{min} which must be produced in all directions and a maximum force F_{max} which may needed for a certain direction can be calculated.

As the force acts perpendicular to the rounded surface, only a part of the force can be used in axis direction. This usable part can be calculated for the heteropolar bearing by

$$F_u = 2\int_{\frac{\varphi}{4}-\frac{\psi}{2}}^{\frac{\varphi}{4}+\frac{\psi}{2}} \cos\theta \frac{F_{mag}}{2\psi}\, d\theta \qquad (3)$$

$$\approx F_{mag}\cos\left(\frac{\varphi}{4}\right) = \begin{cases} 0.92F_{mag} & 4 \text{ pole-pairs} \\ 0.86F_{mag} & 3 \text{ pole-pairs} \end{cases} \qquad (4)$$

and for the homopolar

$$F_u = 2\int_{-\frac{\psi}{2}}^{\frac{\psi}{2}} \cos\theta \frac{F_{mag}}{2\psi}\, d\theta \quad . \qquad (5)$$

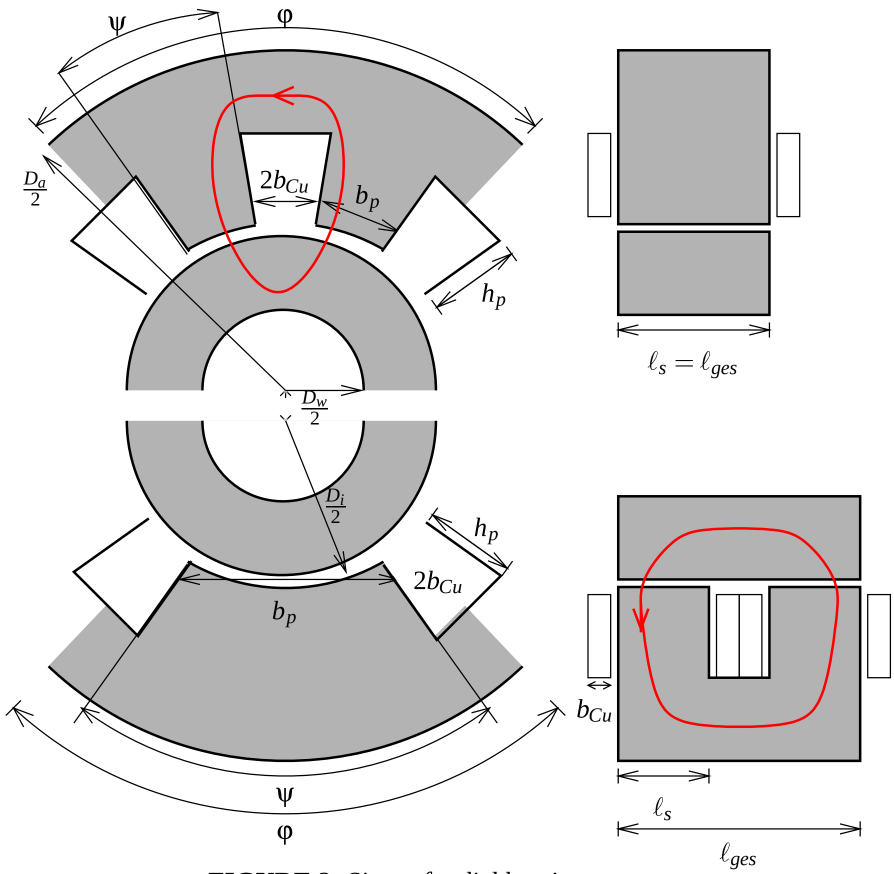

***FIGURE** 2: Sizes of radial bearings*

This leads with $\psi \approx \varphi$ to

$$F_u \approx \frac{F_{mag}}{\varphi} \int_{-\frac{\varphi}{2}}^{\frac{\varphi}{2}} \cos(\theta)\, d\theta = \begin{cases} 0.97F_{mag} & \text{4 pole-pairs} \\ 0.95F_{mag} & \text{3 pole-pairs} \end{cases} \quad (6)$$

Now, starting with F_{min} and F_{max} the usable force F_u can be calculated and from F_u the force F_{mag} of an ideal pole-pair can be derived.

Calculation of the pole-face area

As we use the iron until saturation, no pole-shoe is necessary to get the maximum force[4]. Therefore the pole-face and also the cross-section of the whole flux path can be calculated by

$$A = F_{mag} \frac{\mu_0}{B_{max}^2} \quad . \quad (7)$$

Calculation of the other sizes

As the surface

$$A = b_p \cdot \ell_s \quad (8)$$

is the product of the pole width b_p and the pole length ℓ_s the only decision has to be done choosing both values.

The first idea is choosing

$$b_p = \ell_s = \sqrt{A} \quad (9)$$

which leads to the minimal length of one winding and therefore to minimal resistance of the coil. Although this choices leads to good results for heteropolar bearings, it leads to very large homopolar bearings.

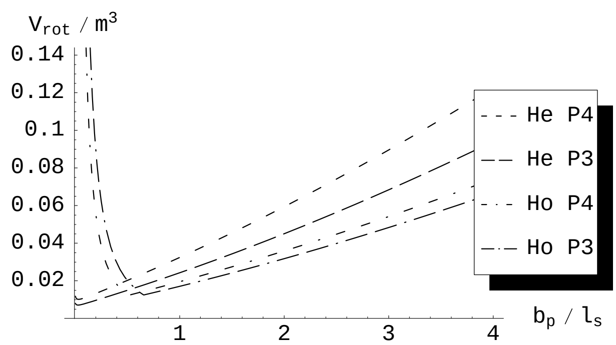

***FIGURE** 3: Rotor volume of a 3 kN radial bearing*

Figure 3 shows how the size of the rotor depends on the ratio of b_p/ℓ_s. With respect to this figure and assuming that a homopolar bearing has half of the poles per revolution comparing to a heteropolar bearing, we chose

$$\frac{b_p}{\ell_s} = 1 \text{ (heteropolar)}, \quad \frac{b_p}{\ell_s} = 2 \text{ (homopolar)}. \qquad (10)$$

These are only heuristic values which reduces the number of free parameters. They are introduced to compare the different bearings types. Nevertheless it can be subject of an optimization.

To get the same cross-section the height of the rotor- and stator-back are chosen to b_p for the heteropolar bearing and to ℓ_s for the homopolar bearing.

The inner diameter can be calculated by

$$D_i = D_w + 2h_r \quad \text{with} \qquad (11)$$

$$h_r = \begin{cases} b_p & \text{heteropolar} \\ \ell_s & \text{homopolar} \end{cases} \qquad (12)$$

and D_w the axis-diameter.

To place the coils, a minimum distance $2b_{Cu}$ between the pole-faces must be left. To assure this, the inner diameter must fulfill

$$D_i \geq \frac{b_{Cu} + b_p}{\sin(\psi/2)} \quad . \qquad (13)$$

With a maximum current density

$$j_{max} = \frac{\Theta}{\varphi_w h_p b_{Cu}} \qquad (14)$$

the pole height is calculated by

$$h_p = \frac{\Theta}{\varphi_w j_{max} b_{Cu}} \quad . \qquad (15)$$

With the height of the stator back

$$h_s = \begin{cases} b_p & \text{heteropolar} \\ \ell_s & \text{homopolar} \end{cases} \qquad (16)$$

the diameter of the bearing is

$$D_a = D_i + 2s_0 + 2h_p + 2h_s \quad . \qquad (17)$$

Recalculation

At the last step the designed bearing can be calculated e. g. with a FEM system. This is necessary to respect parameters like the finite permeability of the iron or leakage.

As these calculations produce the extra-mass of the rotor part of the bearing, too, the design decisions of step one also have to be reviewed.

COMPARISON

Table 4 shows the conditions of the design. The main goal of the design is a small rotor mass and a small moment of inertia. The first leads to a small weight and to higher natural frequencies of the rotor. The second affects the dynamic behaviour of the drive.

TABLE 4: *Values of the design*

Maximum Induction	B_{max}	0.8 T
Maximum current density	j_{max}	$4{\cdot}10^6$ A/mm²
Nominal air gap	s_0	0.5 mm
Winding factor	φ_w	0.4
Gap between poles	b_{Cu}	1 cm

The figures on the next pages are built of four pictures. The first always shows the curve for neglected axis diameter. The next focuses to small size bearings also with $D_w = 0$. The pictures in the 2nd row assume an axis-diameter of 100 mm for larger bearings and 30 mm for the smaller ones on the right side.

If we neglect the axis diameter, the diameter of the rotating part (D_i) of the homopolar bearings is smaller but they are longer. Therefore the volume is more or less the same. But if we respect a large axis diameter ($D_w = 100$ mm) the range of the volumes spreads. The reason can be found in figure 4 which shows that these bearings are quite long. This is reasoned by the design-scheme which leads to short poles with wide coils.

The same happens for 3- (shorter but higher diameter) compared to 4-pole-pair-bearing.

As homopolar bearings only have half of the poles on the circumference we can state the the inner diameter grows with the number of poles per circumference while the length shrinks.

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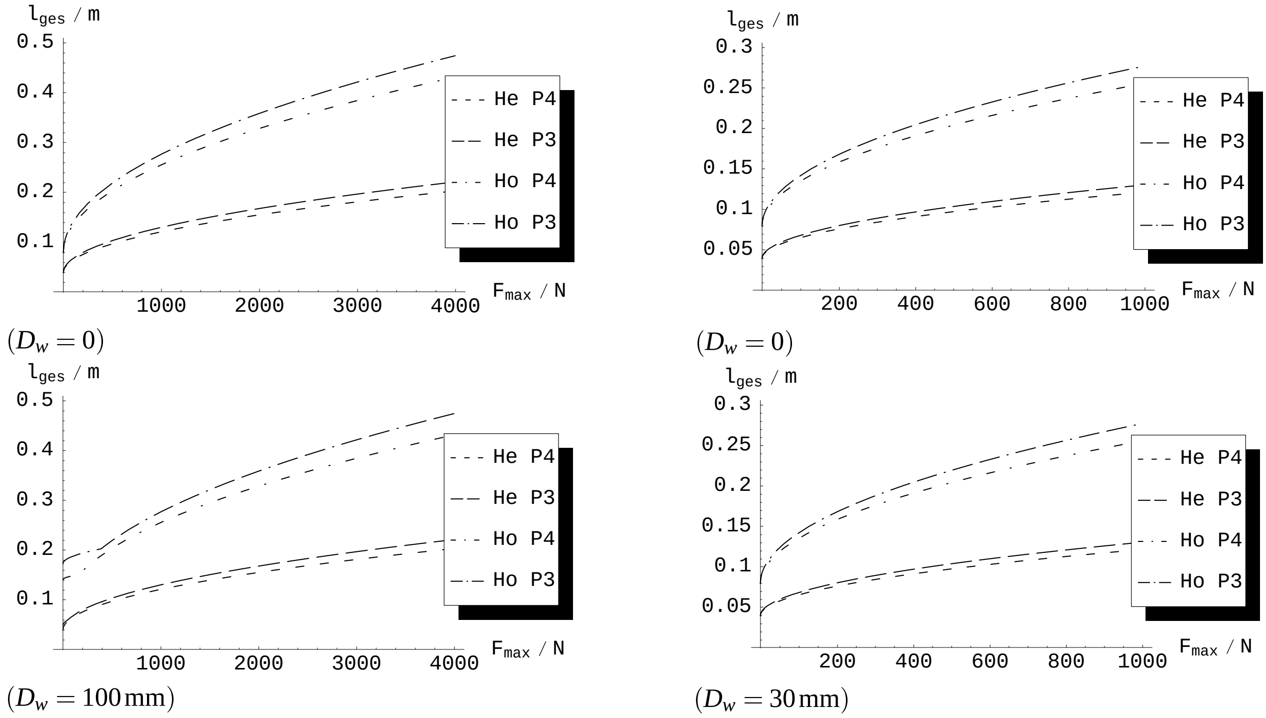

***FIGURE** 4: Length of the bearing rotor*

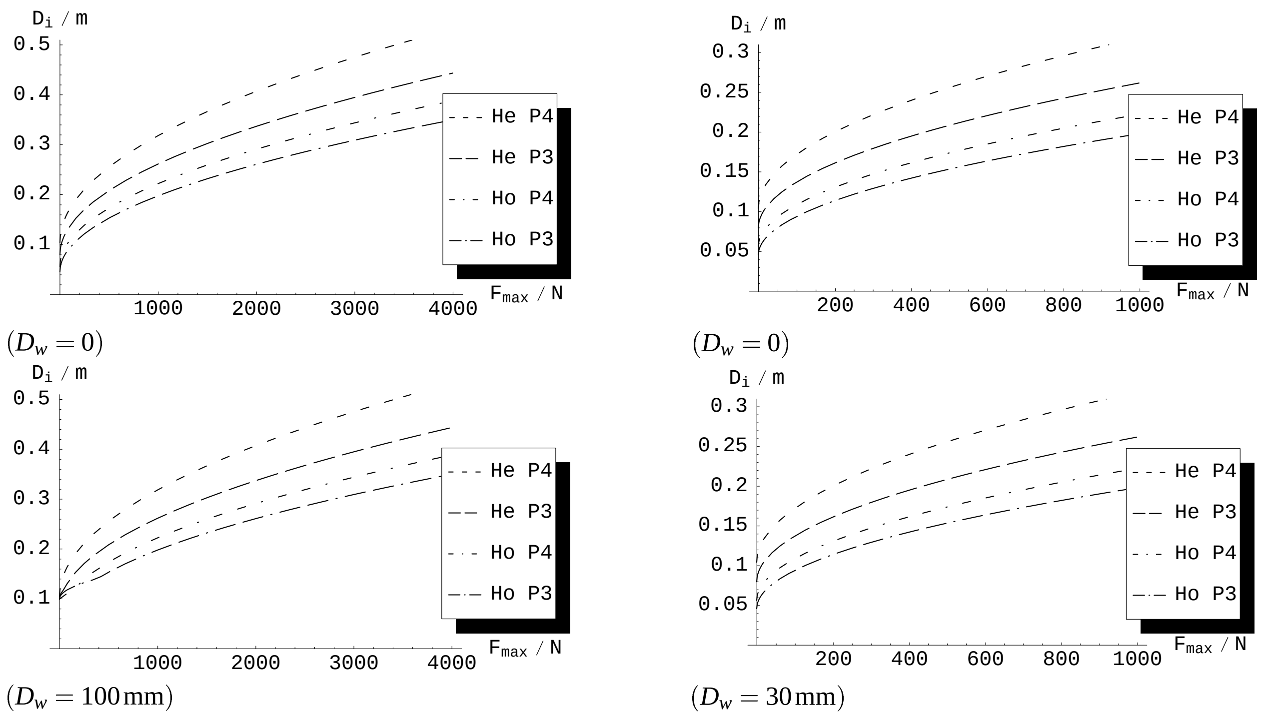

***FIGURE** 5: Diameter of the bearing rotor*

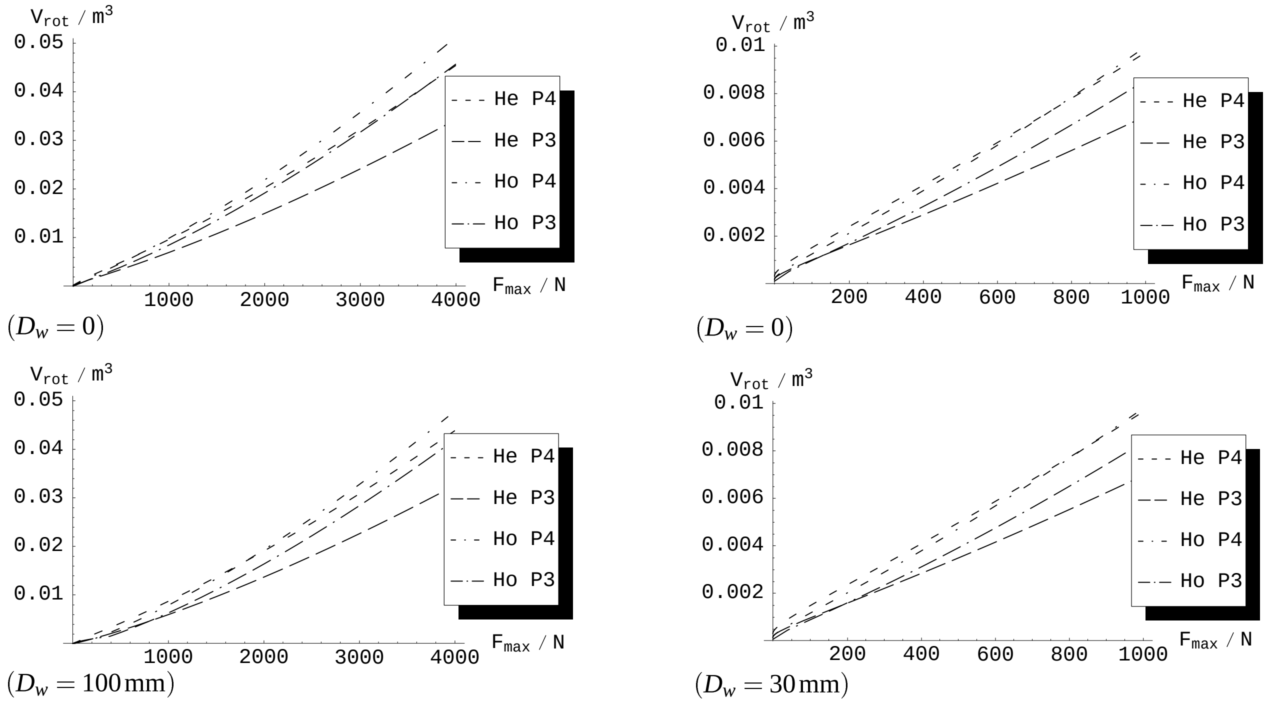

***FIGURE** 6: Rotor volume (without axis)*

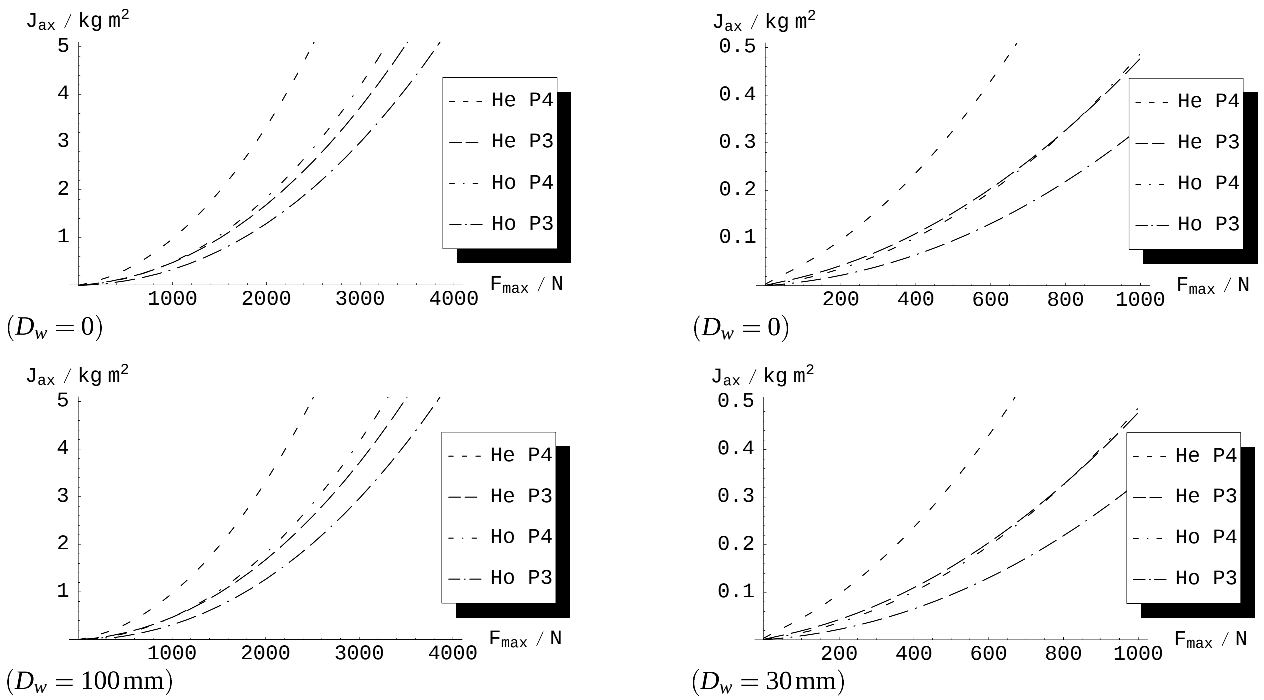

***FIGURE** 7: Moment of Intertia*