Heavy Bearings Exploitation Energy and Reduction Methods

V G Szekely and R Cioară
Transilvania University of Brasov, Eroilor 29, 500039 Brasov, Romania

E-mail szekely.valentin.gabriel@unitbv.ro

Abstract. The global trend of resource conservation so as “not to compromise the ability of future generation’s development” is the fundamental basis of the concept of sustainable development. Concordant with this, the energy efficiency of products is increasingly discussed and frequently taken into account in the design stage. In more cases a product is more appreciated and more attractive as the energy consumption and its associated materials are lower. In the production stage, said consumption advantages primarily the manufacturer, particularly through low consumption thereof. In the operational phase, low energy and materials consumption represents an user advantage and it’s a major argument in the decision to purchase and use a particular product. Heavy bearings are frequent products used in wind turbines that are producing non-conventional “clean” energy, as windmills. An enhanced energy efficiency bearing contributes to the enhancement of the overall efficiency of the wind turbines. Based on a suitable mathematical model, this paper identifies and recommends courses of action to reduce the operating energy of heavy bearing through the “cage” - which is the subject of a much larger research - with the highest priority. The identified actions may constitute from a set of requirements for the design stage of the heavy bearing predominantly oriented towards innovation-invention.

1. Introduction
In more cases a product is more appreciated and more attractive as the energy consumption and its associated materials are lower. In the production phase, reduced consumption advantages primarily the producer and it contributes to the reductions of costs. In the operational phase, low energy and materials consumption represents an user advantage and it’s a major argument in the decision to purchase and use a particular product.

The energy efficiency of products is increasingly discussed and frequently taken into account at the design stage. Moreover, improving the energy efficiency of products can represent an objective to redesign a product, for its eco-design. The global trend of resource conservation so as not to compromise the ability of future generation’s development [1] is the fundamental basis of the concept of sustainable development. Energy efficiency is part of the sustainable development concept [2], and eco-design is one of the specific means. In this context it’s necessary to specify that the mission of Transilvania University of Brasov (institution within which the authors of this paper are activating), stated in the first article of the Charter of the University [3], is “to produce and transfer knowledge to society through: (1) Advanced scientific research, development, innovation and technology transfer in the field of Sustainable Development ...” . Not incidentally the research institute of the university is called “Pro-DD” (in English “Pro-SD”) and gives priority to research for sustainable development.

The quality of the bearings presented in many technical systems largely depends on their energy efficiency. Bearings are effective solutions used from a long time, already of old tradition. Scientific
literature regarding bearings is particularly rich: hundreds or even thousands of books, thousands of patents, (tens of) thousands of articles published in specialized magazines and bulletins of professional conferences. Relatively few of them [4] [5] [6] [7] addresses to mathematical models to study bearings either in their entirety or on certain issues. Special mention must be given to doctoral theses in the field; major scientific papers have a higher consistency and originality. Only in Romania have been developed dozens of such work. It seems that everything has been studied until now and that something new can hardly be added.

Heavy bearings are frequent products used in wind turbines which produce unconventional “clean” energy [8]. A bearing with higher energy efficiency contributes to the overall efficiency of the wind turbines, contributing to the increase of the wind turbines efficiency and performance. This paper aims to identify courses of action to reduce the operating energy for heavy bearing, influence of the “cage” – which is the subject of a much larger research – which has higher priority. The identified actions may constitute a set of requirements for the design phase of the heavy bearings, predominantly oriented towards innovation-invention.

2. Movements of the bearing components

Representative components of a bearing are the two rings, inner and outer, intermediate rolling bodies (balls, rollers or needles) and the cage. In heavy bearings are used as rolling elements balls or rollers and the cage is often massive. At many heavy bearings, and not only, the cage is made of brass, a deficient and expensive material.

The model which describes the movements of the bearing components can be simple or complex depending on the multitude of details taken into account. In this case is sufficient a simple model, the purpose of this study is to identify courses of action - especially to redesign and/or develop new constructive solutions - that will contribute to reduce the necessary operating energy of heavy bearings. For this purpose it is sufficient that the model allows the expression of the bearing components revolutions depending on the rotary motion of the moving ring under ideal conditions of contact between the rings and the intermediate rolling bodies.

It is assumed that the components of the bearing do not have dimensional and shape deviations and all intermediate rolling bodies have identical dimensions and that none of the bearing components don’t present elastic deformations.

According to the assembly into which a bearing is integrated the outer ring could be fixed and the inner ring would be into a rotary motion, rolling elements and the cage (figure 1a), or the inner ring could be fixed and the outer ring would be into a rotary motion, rolling elements and the cage (figure 1b).

![Figure 1. Mobile components of a radial bearing and their speed / revolution.](image-url)
The following measurements are of interest:

\( n_{ii}, n_{ie} \) – the revolutions of the inner ring and outer ring;

\( n_c \) – the revolution of the cage which is identical with the revolution of the rolling element (ball or roller) around the rotation axis of the bearing;

\( R_{i-ii} \) – the inner radius of the bearing inner ring;

\( R_{e-ii} \) – the outer radius of the bearing inner ring, expressed for the theoretical point of contact with the rolling elements (balls or rollers);

\( R_{i-ie} \) – the inner radius of the bearing outer ring, expressed for the theoretical point of contact with the rolling elements (balls or rollers);

\( R_{e-ie} \) – the outer radius of the outer ring;

\( R_{cr} \) – radius of the rolling elements (balls or rollers);

\( R_{mc} \) – the average radius of the cage;

\( R_{i-c}, R_{e-c} \) – the inner radius of the cage, respectively the outer radius thereof;

\( B_{ii}, B_{ie} \) – width of the bearing inner ring and outer ring;

\( B_c \) – width of bearing cage.

Obvious,

\[ R_{e-ii} + 2R_{cr} = R_{i-ie}. \] (1)

**Case A.** The inner ring of the bearing is in revolution \( (n_{ii} > 0) \), while the outer ring is fixed \( (n_{ie} = 0) \), figure 1a. It is assumed that all intermediate rolling bodies are simultaneously in contact with both rings of the bearing, contact which are considered theoretically ideal and as a result the peripheral speeds of the balls and rings in the contact points are equal.

The following notations are (to review figure 1a):

\( v_{A1} \) – the peripheral speed of the inner ring 1 at the point A, point of contact with the rolling element 2;

\( v_{A2} \) – cumulated peripheral speed of the body 2 at the point A, point of contact with the inner ring 1;

\( v_{trc} \) – peripheral speed of the rolling element 2 exclusively due to its revolution \( n_{cr} \);

\( v_C \) – velocity of the center C of the rolling element 2 due to the rotation of the cage 3 with the revolution \( n_c \);

\( n_B \) – the apparent speed of the rolling element 2 in regard to point B, instantaneous point of rotation of the body 2 in regard to the outer ring 4 which is fixed,

the next relations are obvious:

\[ v_{A1} = 2\pi R_{e-ii} n_{ii}; \] (2)

\[ v_{A2} = 2\pi(2R_{cr}) n_B = 2v_{trc} = v_{trc} + v_C; \] (3)

\[ v_{trc} = 2\pi R_{cr} n_{cr}; \] (4)

\[ v_C = 2\pi R_{mc} n_c. \] (5)

Using the previous relationships and imposing the condition \( v_{A1} = v_{A2} \) the next expressions for revolutions \( n_{cr} \) and \( n_c \) are obtained:

\[ n_{cr} = \frac{1}{2} \frac{R_{e-ii}}{R_{cr}} n_{ii}; \] (6)

\[ n_c = \frac{1}{2} \frac{R_{e-ii}}{R_{e-ii} + R_{cr}} n_{ii}. \] (7)

**Case B.** The inner ring of the bearing is fixed \( (n_{ii} = 0) \), while the outer ring is in revolution \( (n_{ie} > 0) \), figure 1b. Using also the next notations:

\( v_{B4} \) – the peripheral speed of the outer ring 4 at the point B, point of contact with the rolling element 2;
\(v_B2\) – cumulated peripheral speed of the body 2 at the point B, point of contact with the outer ring 4;
\(n_A\) – the apparent speed of the body 2 in regard to point A, instantaneous point of rotation of the body 2 in regard to the inner ring 1 which is fixed,
the next relations are obvious:

\[
v_{B4} = 2\pi R_{i-ie} n_{ie};
\]

\[
v_{B2} = 2\pi(2R_c) n_A = 2v_{tcr} = v_{tcr} + v_C;
\]

Using the relations (4) (5) (which remain valid for the specified case), (8) and (9), and imposing the condition \(v_{B4} = v_{B2}\) the next expressions for revolutions \(n_{cr}\) and \(n_c\) corresponding to case B are obtained:

\[
n_{cr} = \frac{1}{2} \frac{R_{i-ie}}{R_{cr}} n_{ie};
\]

\[
n_c = \frac{1}{2} \frac{R_{i-ie}}{R_{cr}} n_{ie}.
\]

3. Heavy bearing operating/exploitation energy

At any time \(t\), the kinetic energy \(E_{c,i} = E_{c}(t)\) of the bearing is the sum of the kinetic energies of its components in motion of rotation: \(E_{c,i} \) or \(E_{c,c} \) – the kinetic energy of the inner ring, respectively of the outer ring, as the case may be; \(E_{c,cr} \) – cumulated kinetic energy of the \(q\) rolling elements (balls or rollers); \(E_{c,c} \) – the kinetic energy of the cage. Most often the inner ring of the bearing is the ring which is in motion of rotation, hereafter this case is approached. Taking into account the relations (6), (7), (10) and (11) the referred kinetic energies have the next expressions [9]:

\[
E_{c-i} = \frac{1}{2} J_{ii} \omega_{ii}^2 = \pi^2 \rho_{ii} B_i \left(R_{e-i}^4 - R_{i-i}^4\right) k_{ii} n_{ii}^2;
\]

\[
E_{c-c} = \frac{1}{2} J_{c} \omega_{c}^2 = \pi^3 \rho_c B_c \left(R_{e-c}^4 - R_{i-c}^4\right) k_c n_c^2 = \frac{1}{4} \pi^3 \rho_c B_c \left(R_{e-c}^4 - R_{i-c}^4\right) k_c \frac{R_{e-i}^2}{(R_{e-i} + R_{cr})^2} n_{ii}^2;
\]

\[
E_{c-cr} = q \left(\frac{1}{2} J_{cr} \omega_{cr}^2 + \frac{1}{2} m_{cr} v_C^2\right) = q \frac{\pi^2}{2} \frac{R_{e-i}^2}{R_{cr}^2} \left(\frac{J_{cr}}{R_{cr}^2} + m_{cr} \right) n_{ii}^2;
\]

where \(k_{ii}\) and \(k_c\) are coefficients that take into account the particularities of the inner ring geometry and that of the cage in relation to the idealized rectangular section thereof; \(J_{ii}, J_{c},\) and \(J_{cr}\) are the moments of inertia in relation to their own rotation axes of the inner ring, cage and respectively of an rolling element, \(m_{cr}\) is the mass of an rolling element, \(\rho_{ii}, \rho_c\) and \(\rho_{cr}\) are the materials densities of the inner ring, cage and rolling elements.

The \(k_c\) coefficient takes into account the presence of the \(q\) pockets in the cage which are for the rolling elements.

If the rolling element is a full ball, then:

\[
m_{cr} = \frac{4}{3} \pi \rho_{cr} R_{cr}^3,
\]

\[
J_{cr} = \frac{2}{5} m_{cr} R_{cr}^2 = \frac{8}{15} \pi \rho_{cr} R_{cr}^5,
\]

and therefore the relation (14) becomes

\[
E_{c-cr} = q \frac{14}{15} \pi^3 \rho_{cr} R_{e-i}^2 R_{cr}^3 n_{ii}^2.
\]
If the rolling element is a full roller, then:

\[ m_{cr} = \rho_{cr} \pi R_{cr}^2 B_{cr}, \quad (18) \]

\[ J_{cr} = \frac{1}{2} m_{cr} R_{cr}^2 = \frac{1}{2} \rho_{cr} R_{cr}^4 B_{cr}, \quad (19) \]

and relation (14) becomes

\[ E_{c-cr} = q \frac{3}{4} \pi^3 \rho_{cr} R_{cr}^2 R_{i}^2 B_{cr} n_{ii}^2. \quad (20) \]

At any time \( t_j \) revolution of the driven ring (the inner ring in the studied case) is \( n_{ii} = n_j = n(t_j) \), and the kinetic energy of the bearing is

\[ E_c(t_j) = E_c(n_j) = E_{c-ii}(n_j) + E_{c-cr}(n_j) + E_{c-\omega}(n_j) = K \cdot n_j^2. \quad (21) \]

During its operation, the driven ring of the bearing has a variable speed; very evident in the case of wind turbine where the speed of the port-blade shaft is variable depending on the wind speed, figure 2. The main consequence is that all components of the bearing which are rotating have variable speed.

![Figure 2](image)

**Figure 2.** Graph of the time variation of a port-blade shaft speed at a wind power plant.

The operating energy of the bearing is given by the amount of energy required to accelerate the moving parts thereof.

Either \((n_j)_{\text{min}}\) and \((n_j)_{\text{max}}\) two consecutive extreme local values from the port-blade shaft speed chart, corresponding to different moments of time: \((n_j)_{\text{min}} = n(t_1); (n_j)_{\text{max}} = n(t_2), t_1 < t_2\).

Obviously the \( n_j \) port-blade shaft speed becomes the speed of the engaged bearing ring. The typical case addressed in the paper is the one with the outer ring fixed and the inner ring rotating, so \( n_j = (n_{ii})_j \).

\[ E_{c-exp} = \sum_j \left( E_c(t_{j2}) - E_c(t_{j1}) \right) = \sum_j \left( E_c \left( n_j \right)_{\text{max}} - E_c \left( n_j \right)_{\text{min}} \right) = K \cdot \sum_j \left( n_j^2_{\text{max}} - n_j^2_{\text{min}} \right). \quad (22) \]

Reducing the operating energy of the bearing assumes the necessity to decrease the value of the \( K \) factor, the instantaneous \( n_j \) speed of the ring engaged depends strictly by the external conditions.

The possibility to reduce the value of the \( K \) factor associated to the engaged ring, inner or outer ring, as the case may be, it is quite low.

It is possible to reduce the value of the \( K \) factor associated to the rolling elements either by reducing the radius \( R_{cr} \) either by using hallow rolling elements [10] [11]. Reducing the radius \( R_{cr} \) entail the necessity to increase the number of rolling elements and, to a large extent, this action causes a decrease of the bearing loading capacity. The use of hollow rollers or balls is possible only if their
stiffness is not affected, radius $R_{cr}$ must be large enough. Hollow rolling elements have an important influence on the decrease of the $K$ factor due to the subtraction of the mass thereof, and by decreasing the moment of inertia to their own axis of rotation.

The $K$ factor can be reduced by reducing the value which corresponds to the cage. There are two possible courses of action: using a material with low density [12] (the effect would determine a simultaneous reduction, in the same proportions, of the cage mass as well as its moment of inertia) and the development of new constructive solutions with lower masses and/or inertia exclusively due to the cage geometry and not due to their realization of materials with low densities.

Obviously, it is possible to gain cumulative benefits/effects due to the use of less dense material and due to the adoption of favorable constructive solutions.

4. Conclusions

Heavy bearings constitute a frequent product often used in unconventional "clean" energy plants as wind turbines. A higher energy efficacy of the bearing increases the overall wind turbine efficiency.

At any time the kinetic energy of the bearing is the sum of the kinetic energies of its components in motion of rotation: inner or outer ring, as the case may be, the $q$ rolling elements (balls or rollers) and the cage. At wind turbines, but not only, the engaged bearing ring has a variable speed; in consequence all components of the bearing which are engaged have variable speed. Operating energy of the bearing is given at least by the amount of energy required to accelerate the moving parts thereof.

It is unlikely to reduce the kinetic energy by changing the constructive solution of the bearing ring which is rotating.

One way to reduce the kinetic energy, which is evidenced, is to use hollow rolling elements, balls and rollers.

Reducing the kinetic energy of the bearing by reducing the kinetic energy of the cage is rarely addressed. The current paper demonstrates this possibility and identifies, with arguments, two courses of actions: using a material with low density and the development of new constructive solutions whit significantly lower masses and/or inertia compared with those of a reference cage.

References

[1] Harris J M, Wise T A, Gallagher K P and Goodwin N R (eds) 2001 A survey of sustainable development. Social and Economic Dimensions (Washington, Covelo, London: Island Press)

[2] Tureac I, Mărușcu-Klein V, Popescu M, Cioară R 2006 Dezvoltare durabilă a produselor în construcția de mașini (Brasov: Transilvania University Press)

[3] Carta Universității Transilvania din Brașov. Available at: http://www2.unitbv.ro/LinkClick.aspx?fileticket=hm8HJPZxM2M%3d&tabid=61

[4] Bostan V 2014 Modele matematice în inginerie: probleme de contact. Modelări și simulări numerice în aero-hidrodinamică (Chișinău: Technical University of Moldavia Press)

[5] Lazovic T, Ristivojevic M and Mitrovic R 2008 Mathematical model of load distribution in roller bearings FME Trans vol 36 no 4 p 189-196

[6] Zivkovic A, Zeljkovic M and Tabakovic S 2010 Mathematical model for the roller bearing life determination AJME vol 8 no 3 p 108-115

[7] Fritzson D, Fritzson P, Viklund L and Herber J 1994 Object-oriented mathematical modelling – Applied to machine elements Computer and Structures vol. 51 no. 3 p 241-253 (Pergamon Press)

[8] Wälzlagerotechnik Industrietechnik 1990 (FAG) 501

[9] Deliu Gh 2003 Mecanica (Cluj-Napoca: Albastră Publishing House)

[10] Barabaș S A 2010 Cercetări privind ingineria rulmenților de mari dimensiuni cu scopul reducerek maselor înerețiale și a sporirii eficienței în exploatare PhD thesis Transilvania University of Brașov

[11] Cioară R et al. 2015 Bilă pentru rulmenți grei Patent RO 125679

[12] Csaki I 1999 Cercetări privind fabricarea colivilor de rulmenții din materiale compozite ușoare cu parametrii tribologici optimizați, solicitate de industriile de aeronautică și ușoară PNCD 45 grant C 5076