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RELIABILITY ANALYSIS OF THE HOUSING-COVER CONNECTIONS OF PARALLEL-SHAFT REDUCERS

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Abstract: Violation of the density between the housing and the cover of gear reducers can lead to gaps, noise and impacts from gear engagement, an increase in the load on the teeth, and in many cases, to their failure. Therefore, the presented report assessed the reliability of bolted connection connecting the housing and the cover of parallel-shaft reducers according to various failure criteria. It was found that the probability of a violation of the density between the parts is many times higher than the probability of loss of bolt strength.
Keywords: *parallel-shaft reducers, reliability, threaded connections, endurance, joint density*

Introduction.

Gear reducers are one of the main components of modern machines and equipment, and the correct assessment of their reliability, increasing their durability and maintainability are of great importance. Bolted or screw connections connecting the casing and the cover of gear reducers belong to the elements, the risk of failure of which is not too great. The failure of the elements of the connection with the loss of its strength is rare. But deformation of the connecting elements, spontaneous unscrewing of the nut and, as a result, a violation of the tightness between the casing and the cover can lead to disruption of the normal operation of the gearbox as a whole. A violation of the tightness between the casing and the gearbox cover can lead to errors, noise and shocks in the engagement of the wheels, an increase in the load on the gears, and in many cases, to their total failure.

In the presented work, as the main criteria for the functionality of the casing-cover connection of parallel-shaft reducers, the tensile strength condition of the threaded part of the bolt, the condition of tightness between the casing and the cover and the condition of non-slip between the casing and the cover were taken as a basis.

In the existing literature [1 - 5], the calculation of bolted connections that attach the gear housing with its cover is performed mainly by empirical formulas.

In [6] by applying the finite element method to analyse a gear reducer housing, were studied the influence of the retaining bolts tightening force magnitude on the stress state and nodal displacements of the housing, for the specified input parameters.

In [7], the problem of optimizing the gearbox housing using numerical analysis is considered.

In [8-10], the question of increasing the service life of spur gearboxes by activating the non-working flank was considered.

An analysis of the literature on bolted connection connecting the housing and the cover reducers has shown that a comparative analysis of their reliability for various failure criteria has not yet been considered. Such an analysis can be of great practical significance, and therefore, this paper is devoted to this important task.

Determination of bolt loads.

To assess the reliability of the connection, it is necessary to determine the load on the most loaded bolt. Using the example of a single-stage cylindrical gearbox, we will consider the problem of determining the loads on the housing-cover connections. The reactions of the support F_n' and F_n'' arise in the bearing supports of the shaft from the action of the full normal force F_n arising in the parallel-shaft reducer (Fig. 1). These forces are transmitted directly to the bolts connecting the housing and the gearbox cover. We can also divide the force F_n acting on a more loaded bolt into two components. Firstly, the sliding force F_q is transmitted not only to the bolts, but also to the outer ring of the bearing. Therefore, this force does not significantly affect the reliability of the connection. Another component of the F_a is transmitted directly to the bolts and tries to detach the gearbox housing from the cover. The gaping force acting on the most loaded bolt, based on the figure, can be determined as follows:

$$F_b = F_{1a} = \frac{F_a(0{,}5a+e)}{a} = \frac{F_a(a+D\sin\alpha_w)}{2a}. \quad (1)$$

where a - the distance between the bolts; D - outer diameter of the bearing; e - the distance between the axis of the shaft and the line of action of the force F_a; α_w - engagement angle.

For standard gears, $\alpha_w=20^0$ is accepted [2]. Taking $\mu_a=D/a$, we can write expression (1) as follows:

$$F_b = \frac{1}{2}F_a(1+\mu_a \cdot \sin\alpha_w). \quad (2)$$

Structurally, it is possible to accept $\mu_a=0{,}65\div0{,}7$ for existing gearboxes of cylindrical gears.

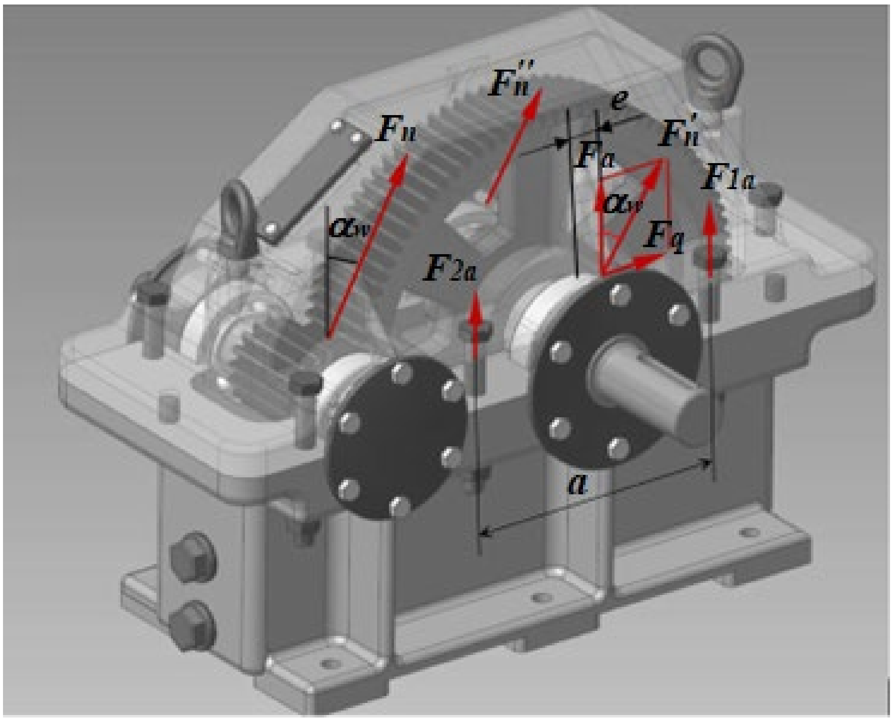

Figure1. Design scheme of the housing-cover connection of a parallel-shaft reducers

Given the equal load on the supports (i.e. $F_n'=F_n''=0.5\ F_n$) in a single-stage cylindrical gearbox and the dependence of the normal force generated by the engagement on the torque transmitted by the driven shaft ($F_n=F_t/\cos\alpha_w=2T_2/d_2\cdot\cos\alpha_w$, [1]), we can determine the force F_a, which tries to break the connection of the housing and cover, as follows:

$$F_a = F_n' \cdot cos\alpha_w = \frac{1}{2} F_n \cdot cos\alpha_w = \frac{F_t}{2} = \frac{T_2}{d_2}.$$

where F_t - circumferential force arising from cylindrical straight-tooth transmission; T_2 - torque on the driven shaft of the gearbox; d_2 - dividing diameter of the driven wheel.

Considering the last expression in the formula (2), we can write:

$$F_b = \frac{T_2}{2d_2}(1 + \mu_a \cdot sin\alpha_w). \quad (3)$$

As can be seen from the last expression, the external dividing force falling on the bolt directly depends on the torque on the driven shaft of the gearbox, inversely proportional to the diameter of the dividing circle of the driven wheel. First, let's consider the issue of assessing reliability by the condition of bolt strength. To ensure the density between the parts of the housing-cover connection of the gearbox, the bolt is tightened by a certain initial tension force F_0, and thus the force $F_и$ is not transferred to the bolt completely (Fig. 2, a). Part of the load is perceived by the deformed housing and the flanges of the cover. In this case, the calculated force acting on the bolt in the direction of its axis should be calculated according to the following formula (Иосилевич Г.Б., 1988):

$$F_h = F_0 + \chi F_b. \quad (4)$$

Where is F_0 - preliminary bolt tightening force; χ - external load factor.

The external load factor takes into account which part of the external force is perceived by the bolt. This coefficient becomes dependent on the geometric dimensions and elastic modulus of the materials of the connected parts and the bolt. Calculations show that when metal elements are connected, it receives values in the range χ=0.2÷0.4 [3].

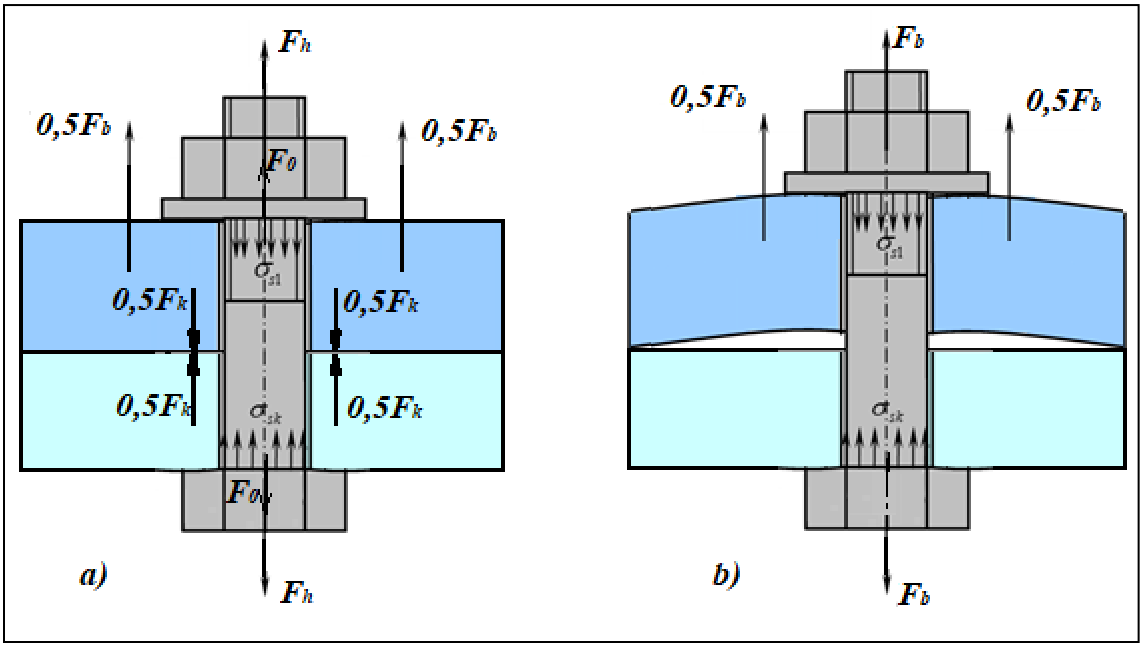

Figure 2. Design scheme of the bolted connection of the parallel-shaft reducers

Reliability analysis.

In practical calculations, it can be assumed that the load and bearing capacity of the connection parts obey the normal distribution (Fig. 3). Then for the case under consideration, the survival probability of the connection according to the condition of bolt strength can be calculated by the following formula [11]:

$$R_b^* = \Phi\left(\frac{\overline{W}_b - \overline{F}_h}{\sqrt{\sigma_{Wb}^2 + \sigma_{Fh}^2}}\right) \quad \text{or} \quad R_b^* = \Phi\left(\frac{\overline{W}_b - \overline{F}_h}{\sqrt{\left(V_{Wb} \cdot \overline{W}_b\right)^2 + \left(V_{Fh} \cdot \overline{F}_h\right)^2}}\right) \qquad (5)$$

Where $\overline{W}_b$ - Mathematical expectation of the bearing capacity of the bolt;
$\overline{F}_h$ - Mathematical expectation of the calculated load on the bolt;
σ_{Wb} - Standard deviation of the bearing capacity of the bolt
σ_{Fh} - Standard deviation of the calculated load on the bolt;
V_{Wb} - Coefficient of variation of the bearing capacity of the bolt;
V_{Fh}- Coefficient of variation of the calculated load on the bolt.

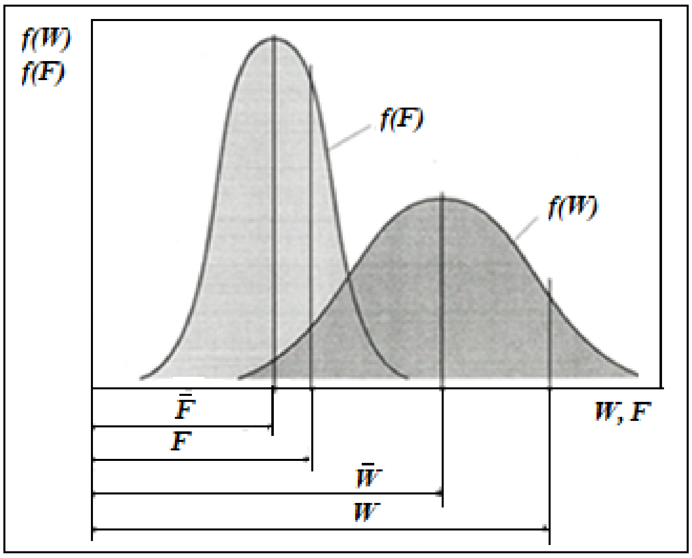

Figure 3. Normal distribution of load values and load-bearing capacity of the elements of the housing-cover connection of gearbox

When the joint is opened for some reason in the housing-cover connection (for example, as a result of an increase in external force or self-unscrewing of the thread), F_0=0 and χ=1 occur, so that the bolt is only under the action of force F_b (Fig. 3, b). In this case, the probability of trouble-free operation of the housing-cover connection of the gearbox according to the condition of bolt strength can be calculated as follows:

$$R_b^{**} = \Phi\left(\frac{\overline{W}_b - \overline{F}_b}{\sqrt{\sigma_{Wb}^2 + \sigma_{Fb}^2}}\right) \quad \text{or} \quad R_b^{**} = \Phi\left(\frac{\overline{W}_b - \overline{F}_b}{\sqrt{\left(V_{Wb} \cdot \overline{W}_b\right)^2 + \left(V_{Fb} \cdot \overline{F}_b\right)^2}}\right). \qquad (6)$$

where $\overline{F}_b$ - mathematical expectation of the force acting on the bolt when the density is violated;
σ_{Fb} - Standard deviation of the force acting on the bolt when the density is violated;
V_{Fb}- Coefficient of variation of the force acting on the bolt when the density is violated.

To ensure the condition of density in the housing-cover connection of the gearbox, the residual force arising at the contact of the connected parts must satisfy the condition F_k=F_0-F_d>0 [3]. Where

F_d is the part of the force acting on the connection perceived by the details, which can be defined by the following expression:

$$F_d = (1 - \chi)F_b. \tag{7}$$

Thus, in the housing-cover connection, the density condition can be written as $F_0 > F_d$, and the probability that the connection will work without failure in accordance with this condition can be determined by the following expression:

$$R_k = \Phi\left(\frac{\overline{F}_0 - \overline{F}_d}{\sqrt{\sigma_{F0}^2 + \sigma_{Fd}^2}}\right) \text{ or } R_k = \Phi\left(\frac{\overline{F}_0 - \overline{F}_d}{\sqrt{\left(V_{F0}\cdot \overline{F}_0\right)^2 + \left(V_{Fd}\cdot \overline{F}_d\right)^2}}\right). \tag{8}$$

Where $\bar{F}_0$ is the mathematical expectation of the preliminary tightening force;
$\bar{F}_d$ is the mathematical expectation of the force perceived by the connected parts;
σ_{F0} is the mean square deviation of the preliminary tightening force;
σ_{Fd} is the mean square deviation of the force perceived by the connected parts;
V_{F0} is the coefficient of variation of the preliminary tightening force;
V_{Fd} is the coefficient of variation of the force perceived by the connected parts.

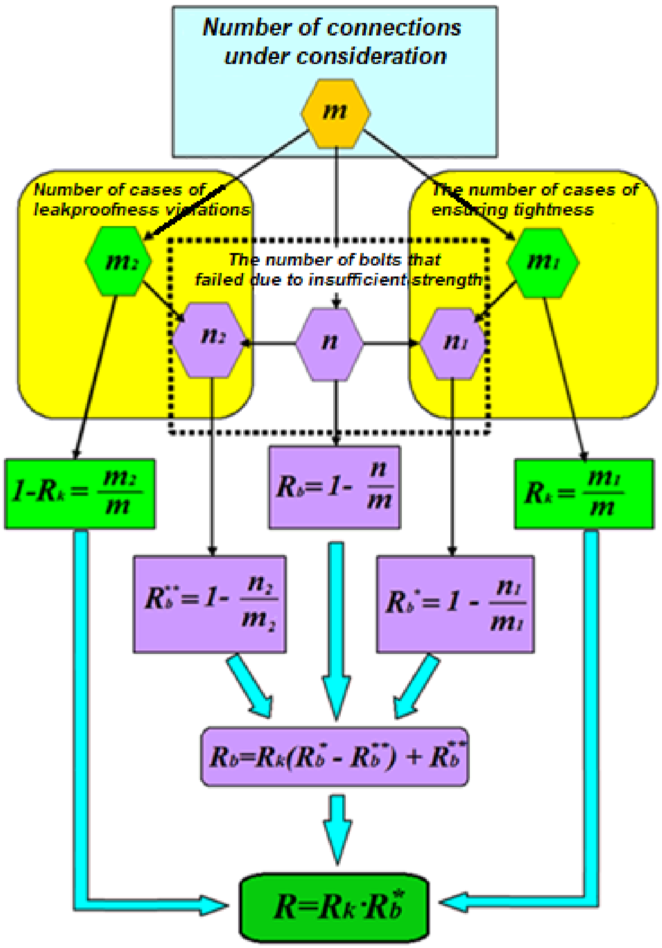

Figure 4. Scheme for the reliability analysis of the connection between the casing and the cover of reducer

Let's use the classical methods of probability theory to determine the ratio between reliability indexes according to various criteria for the survival probability of the housing-cover gearbox connection. Suppose that a test was carried out on the housing-cover connection with the number m, and after a certain period of operation, the bolt with the number n failed, losing strength. Of these, the bolt n_1 of the number failed, provided there is no breach of tightness, and the bolt n_2 of the number failed as a result of loss of tightness. Suppose that with the number of bolts m as a whole, there was no density violation on the number of bolts m_1, and with the number of bolts m_2, density violations occurred. The probabilities of uptime or failure according to various criteria can be described schematically in accordance with Fig. 4.

The survival probability of the bolt according to the strength condition can be determined by the following expression:

$$R_b = 1 - \frac{n}{m}. \quad (9)$$

Similarly, we can determine the survival probability by the density condition (R_k) and the probability of density violation (P_k) by the following formulas:

$$R_k = \frac{m_1}{m}; \qquad P_k = 1 - R_k = \frac{m_2}{m}. \quad (10)$$

The survival probabilities of the bolt according to the strength condition in cases of absence and presence of density, respectively, can be determined by the following expressions:

$$R_b^* = 1 - \frac{n_1}{m_1}; \qquad R_b^{**} = 1 - \frac{n_2}{m_2}. \quad (11)$$

By solving expressions (9-11) together, we can obtain the following expression to determine the probability that the bolt will work without failure due to the strength condition:

$$R_b = R_k(R_b^* - R_b^{**}) + R_b^{**}. \quad (12)$$

As already mentioned, a breach of tightness in the housing-cover connection of the gear reducer should also be considered as a transmission failure. Because the violation of tightness also leads to the fact that the gearbox loses its function. Given this, the probability that the housing-cover gearbox connection will work according to both criteria without failure can be determined as follows:

$$R = 1 - \frac{n_1 + m_2}{m}. \quad (13)$$

Having made some simplifications in the last expression, given expressions (10) and (11), we can write the following expression:

$$R = R_k \cdot R_b^*. \quad (14)$$

An assessment of the reliability of the casing-cover connection of a cylindrical gearbox with a gear ratio u=4, an axial distance a_w=224 mm, a diameter of the division of the bearing wheel d_2=360 mm at the location of the bearings is considered. Standard M12 bolts with a thread pitch of P=1,5 mm and an internal diameter of d_1=10,16 mm were selected for connecting the housing-cover gearbox. Since there were no special requirements for the design, the bolt material was selected steel 20, which corresponds to strength class 4.6. The yield strength of the bolt material was adopted as the bearing capacity. The yield strength of the selected material is assumed to be σ_y=240 N/mm2. Depending on the magnitude and fluctuation of the torque acting on the bearing shaft of the gearbox, as well as on the bearing capacity of the bolt material, the survival probability of the housing-cover connection was calculated.

Since the connection of the housing and the gear reducer cover is designed with a large margin factor according to all failure criteria, it is practically impossible for the connection to fail at rated load. The loss of operability of this connection occurs due to accidental overloads or shocks that occur during operation. Therefore, it is important to assess the reliability of the housing-cover connection depending on the load according to various performance criteria. To this end, on the basis of the methodology described above, an assessment of reliability indicators was carried out according to various criteria for the operability of the connection in question. In these calculations, the coefficient of variation of the bearing capacity V_{Wb}=0,05, the coefficients of variation of the calculated and external forces acting on the bolt, V_{Fh}=V_{Fb}= 0,07, the coefficients of variation of the initial tightening force and compression forces created on the part, V_{F0}=V_{Fd}=0,1 are adopted. The results are graphically shown in Fig. 5.

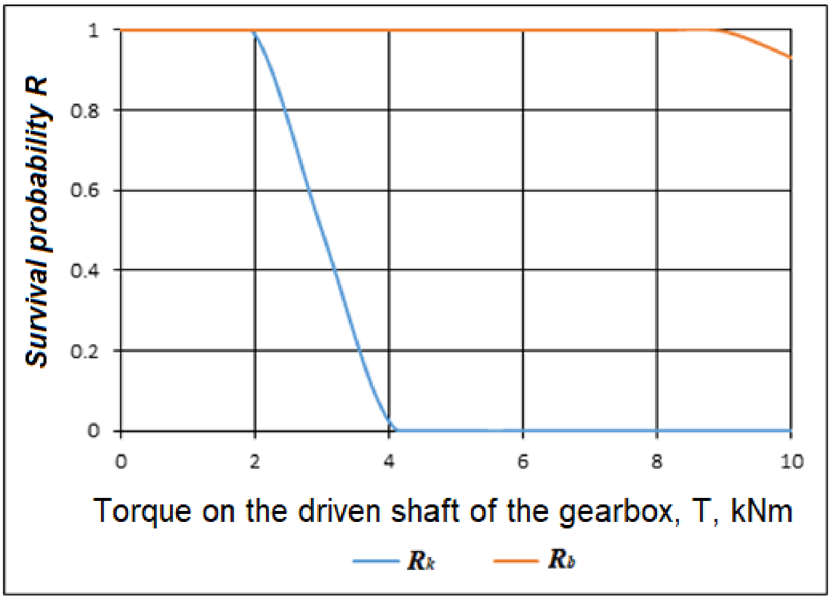

Figure 5. Dependence of the reliability indicators of the housing-cover gearbox connection on the transmitted torque

Conclusions.

As can be seen from the graph in Fig. 5, the reliability of the casing-cover connection of a parallel-shaft reducer is mainly determined by the condition of joint density. Since the bolts are designed with a large margin factor, even with a load many times higher than the nominal one, the indicator of their reliability gets the maximum value. And with a load exceeding the nominal by about two times, the probability of trouble-free operation drops sharply due to the tightness condition. And violation of the tightness condition can lead, as already mentioned above, to the occurrence of gaps in the engagement and shaft supports. This can eventually lead to the appearance of sound and vibration, as well as to increased impacts during engagement. Therefore, it is very important to control the initial tension force created on the bolts in order to increase the tightening in the housing-cover connection.

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