Original Research Article
System model of a technical level rolling bearings

SUMMARY:

Purpose: to develop system hierarchical model of a technical level of rolling bearings, to prove efficiency of the modernization of standard designs providing increase of operational characteristics of axle boxes of railway transport.

Methodology: the hierarchy of structure and functional communications between rolling bearing elements as mechanical system is established; quality indicators are proved; dependences for calculation of elements of a matrix of quality for the standard and modernized design are offered; results of solutions of system model are presented in the form of "a quality web"; efficiency of the proposed constructive solutions is confirmed.

Results: The directions of modernization of a design of roller cylindrical bearings as a part of axle boxes of railway transport providing increase of their dynamic loading capacity for 10,5%, a resource for 19%, decrease by 11% of level of internal dynamic loadings, nominal temperature condition of operation at speeds of train service up to 300 km/h are proved. As a result the indicator of a technical level of the upgraded bearings is raised for 17%.

Conclusion: further development was gained by a system method of estimation and management of a technical level of production of mechanical engineering at stages design and modernization.

1. INTRODUCTION

In practice of modern mechanical engineering there is no the universal method of the analysis of quality of design of bearings providing an objective choice and scientific justification of optimum versions of constructive and technological decisions [1]. In relation to roller cylindrical bearings as a part of axle boxes of high-speed railway transport the solution becomes complicated lack of complex researches of influence of number of bodies of swing, material of a separator, temperature condition, etc. factors of the characteristic of their quality [2 – 4]. Therefore, development of the system model of a technical level of rolling bearings providing a scientific basis for a choice of effective design decisions at early stages of design and modernization should be considered an actual problem of engineering science.

2. METHODOLOGY

The system method of an assessment of technical level of production of mechanical engineering in relation to transfers by gearing, to restrictive couplings, mechanisms of parallel structure, etc., is presented in works [5 – 7]. The universal method of display of a technical level provides functional-structural integrity, objectivity of display and physical informational content of indicators of quality of the knowledge-intensive products of mechanical engineering in uniform system basis their internal and external (structural and functional) functional properties. Adequacy of modeling of a set of indicators of quality $\{Q\} = \{q_1, q_2, \ldots, q_n\}$ and the relations $\{q_{i\to}^{\leftarrow}q_j\}$ as uniform information system is axiomatically proved. At each level application of subjective expert methods for establishment of weight coefficients isn't required, extension of the list of the functional properties inherent in system in general, and also the analysis of designs analogs and selection of options on the basis of a uniform complex indicator of $U(Q)$ of a technical level is provided.

In this article the assessment of a technical level of rolling bearings is also executed on the basis of system hierarchical model. The bearing is considered as the mechanical system providing decrease in the moment of friction of axle boxes. The device, elements of details, sequence of transfer of loading, for example in the single-row roller cylindrical bearing, are schematized on settlement models (fig. 1).
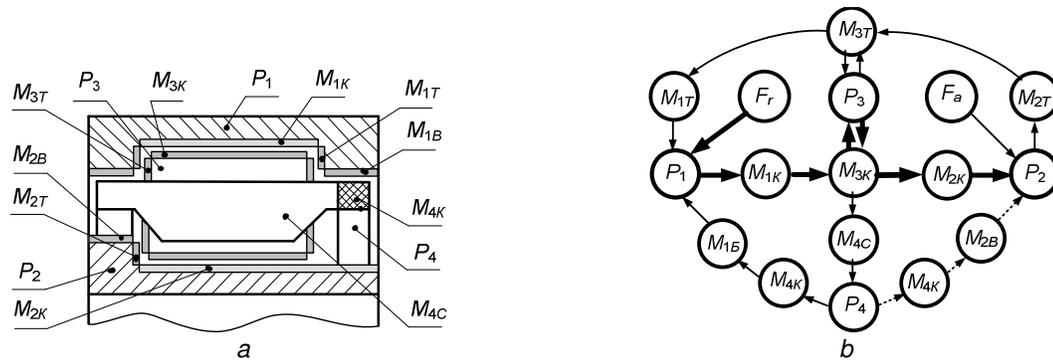
Fig. 1. Settlement models of the bearing: *a* - block diagram; *b* – structurally functional graph

Block diagram of the bearing (fig. 1, *a*) it is presented in the form of two rings – external P_1 with two boards and internal P_2 with one board, rollers of P_3 and a separator of P_4.

Each of details of the bearing is considered as the subsystem which is carrying out certain functions (fig. 1, *b*). External and internal rings provide connections according to the case of an a surface of boards provide perception of loadings and centering of a separator. Elements of rollers – surfaces of swing of M_{3K} and face M_{3T}, provide perception according to radial and axial loadings. Separator elements – rings of M_{4K} and the crossing point M_{4C}, provide basing of a separator on rings or on rollers.

Radial loading of F_r (see fig. 1, *b*) it is transferred from an external ring of P_1 by a race path of M_{1K} through P_3 roller M_{3K} surfaces to the M_{2K} racetrack of an internal ring of P_2. Axial loading of F_a is transmitted from an internal ring of P_2 by M_{2T} surface through P_3 roller M_{3T} surfaces on a surface of M_{1T} of an external ring of P_1. At rotation of the bearing P_3 rollers the surfaces of swing of M_{3K} press on a surface of sliding of M_{4C} of crossing points of a separator of P_4 [8] and press it surfaces of rings of M_{4K} to surfaces of M_{1B} or M_{2B} of external P_1 or internal P_2 of rings.

On the basis of the analysis of requirements of consumers and conclusions of experts, technical documentation of producers and results of scientific researches, standard quality indicators

axle box and with shaft, rollers – kinematics of friction of swing, a separator – reduction of losses by friction. Elements of rings – the M_{1K}, M_{2K} racetracks, face M_{1T}, M_{2T} and the basing M_{1B}, M_{2B} of a surface of boards provide perception of loadings and centering of a separator. Elements of rings – the M_{1K}, M_{2K} racetracks, face M_{1T}, M_{2T} and the basing M_{1B}, M_{2B} of of bearings as a part of axle boxes of railway transport (fig. 1, *b*).

Differentiation of single and complex indicators of functional properties of roller cylindrical bearings is executed by results of theoretical and pilot studies [8 – 10].

3. RESULTS AND DISCUSSION

Main functional properties of bearings (loading capacity, power efficiency, reliability, kinematics perfection, internal dynamics) (fig. 2) and the corresponding indicators of quality (table 1) systemically depend on parameters of the interacting details of the bearing (P_1, P_2, P_3, P_4) and their elements (M_{1K}, M_{2K}, M_{1T}, M_{2T}, M_{1B}, M_{2B}, M_{3K}, M_{3T}, M_{4K}, M_{4C}).

Rated values of indicators of a technical level for models of standard (z=14) and advanced (z=16) bearings 2726 are given in table 2.

In brackets – indicators of advanced bearings in the form of a matrix [Q] (1).
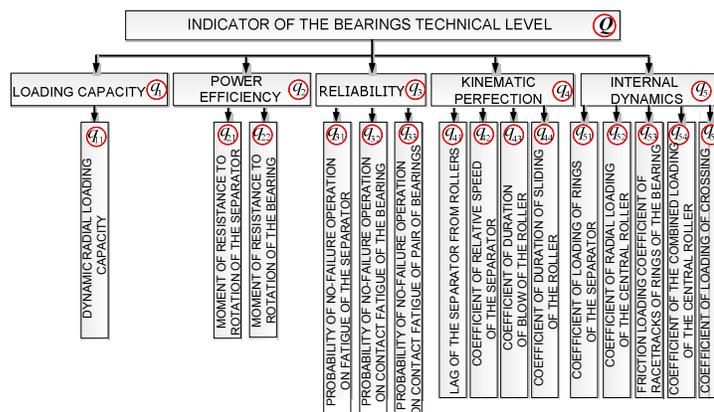

Fig. 2. Model of an indicator of a technical level of the roller cylindrical bearing

Table 1. Indicators of quality of roller cylindrical bearings

Characteristic	Indicator	Settlement formula
1. Loading capacity	1.1. Dynamic radial loading capacity of the bearing, N	$C = f(il_w cos\alpha)^{7/9} z^{3/4} D_w^{29/27}$
2 Power efficiency	2.1. Moment of resistance to rotation of a separator, $N{\cdot}m$	$M_S = 0{,}5d_b f_b[F_s(\psi) + F'_s(\psi)]cos\psi - 0{,}5D_w f_s[F_s(\psi)+F'_s(\psi)].$
	2.2. Moment of resistance to rotation of the bearing, $N{\cdot}m$	$M_n = 0{,}5d f_n F_r$
3. Reliability	3.1. Probability of no-failure operation on fatigue of a separator	$u_{PF} = - (n_F - 1) / (n^2_F v^2_{\sigma 0} - v^2_\sigma)^{1/2} \Rightarrow P_F$
	3.2. Probability of no-failure operation on contact fatigue of rings and rollers of the bearing	$u_{PL} = - (n_L - 1) / (n^2_L v^2_c - v^2_P)^{1/2} \Rightarrow P_L$
	3.3. Probability of no-failure operation on contact fatigue of rings and rollers of pair of bearings	$P_{2L} = 1 - (1 - P_L)^2$
4. Kinematics perfection	4.1. Relative lag of a separator from rollers	$\Delta = (2S_0 z/d_0 \pi)100\%$
	4.2. Coefficient of relative speed of a separator	$k_\omega = (\omega_s z_z)/\omega_c$
	4.3. Coefficient of duration of blow of a roller	$k_\omega = t_s/t_c$
	4.4. Coefficient of duration of sliding of a roller	$k_\psi = (\psi_F - \psi_e)/\psi_F$
5. Internal dynamics	5.1. Coefficient of loading of rings of a separator	$k_{FR} = F_R/F_{f0}$
	5.2. Coefficient of radial loading of the central roller	$k_{Fr} = F_r/F_{r0}$
	5.3. Coefficient of a friction loading of racetracks of rings of the bearing	$k_{Ff} = F_{f0}/F_{fi}$
	5.4. Coefficient of the combined loading of the central roller	$k_F = F_{r0}/F_{a0}$
	5.5. Coefficient of loading of crossing points of a separator	$k_{Fs} = F_s/F_{f0}$

Designations: f – coefficient of the accounting of geometry of details of the bearing, accuracy of their production and materials; i – quantity of ranks of bodies of swing; l_w – length of a roller, m; α − nominal corner of contact; z – quantity of rollers; D_w – diameter of a roller, m; d, d_b – diameters of openings of an internal ring and boards of an external ring, m; f_s, f_b – coefficients of friction of a crossing point with a roller and separator rings with boards of the basing ring; f_n – the provided coefficient of friction of the bearing; F_r – radial load of the bearing, N; Z_z – quantity of rollers in a zone of radial loading; F_s, F_s' – forces of interaction of the leader and the separator conducted rollers with crossing points in a zone of radial loading, N; $F_{f0},$ F_{fi} – friction forces of rollers on running paths of external and internal rings, N; S_0 – a clearance in a window of a separator, m; d_0 – diameter of the centers of rollers, m; ω_s, ω_c – angular speeds of a separator and internal ring, s^{-1}; t_s, t_c – duration of contact of a roller with a separator and a cycle of loading of a separator, s; ψ_F, ψ_e – settlement corner of a zone of radial loading of the bearing and experimentally certain corner of sliding of a roller, rad; F_{r0}, F_{a0} – the radial and axial forces operating on the central roller, N; F_R – force of interaction of a separator with the basing ring of the bearing, N.

**Table 2. Matrix [*Q*] of rated values of indicators of quality
for standard and advanced designs of the bearing 2726**

Loading capacity	The power efficiency	Reliability	The kinematics perfection	The internal dynamics	Models level
0,39 (0,65)	0,61 (0,61)	0,59 (0,82)	0,55 (0,55)	0,36 (0,43)	1 – system "bearing"
	0,64 (0,96)	0,60 (0,85)	0,72 (0,72)	0,39 (0,55)	2 – subsystem "a separator – rollers"
		0,74 (0,88)	0,76 (0,76)	0,61 (0,88)	3 – subsystem "separator"
			0,79 (0,79)	0,64 (0,93)	4 – subsystem "ring"
				0,73 (0,98)	5 – "the weak element" (race path)

Calculation of an indicator of a technical level of $U(Q)$ of standard and advanced designs is executed on a basis follow – Russian cabbage soup of next system of the non-uniform linear equations [5]

$$\begin{bmatrix} q_{11} & q_{12} & q_{13} & q_{14} & q_{15} & -1 \\ 0 & q_{22} & q_{23} & q_{24} & q_{25} & -1 \\ 0 & 0 & q_{33} & q_{34} & q_{35} & -1 \\ 0 & 0 & 0 & q_{44} & q_{45} & -1 \\ 0 & 0 & 0 & 0 & q_{55} & -1 \\ 1 & 1 & 1 & 1 & 1 & 0 \end{bmatrix} \cdot \begin{bmatrix} \lambda_1 \\ \lambda_2 \\ \lambda_3 \\ \lambda_4 \\ \lambda_5 \\ U \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 1 \end{bmatrix} \quad (1)$$

where $q_i = 0{,}1 + 1{,}18$th $[(y_i - y_i^-)/(y_i^+ + y_i^-)]$ – at a positive gradient of an indicator;
$q_i = 1{,}0 - 1{,}18$th $[(y_i - y_i^-)/(y_i^+ + y_i^-)]$ – at a negative gradient; y_i^-, y_i^+ – lower and top borders of statistically average range of change of an indicator of a certain property; $\lambda = \{\lambda_1, \lambda_2, ..., \lambda_5\}$ – a column of the weight coefficients determined by the decision of system.

For example, the moment of resistance to rotation caused by a separator decides by friction of crossing points on rollers and friction of rings with boards of basing bearing ring, hydrodynamic losses in greasing and in seals. Disregarding losses on friction of the rollers which are out of a zone, and also losses in greasing and in seals, the moment of resistance to rotation caused by a separator according to model of loading of a separator (fig. 3) [8], analyzed on a formula:

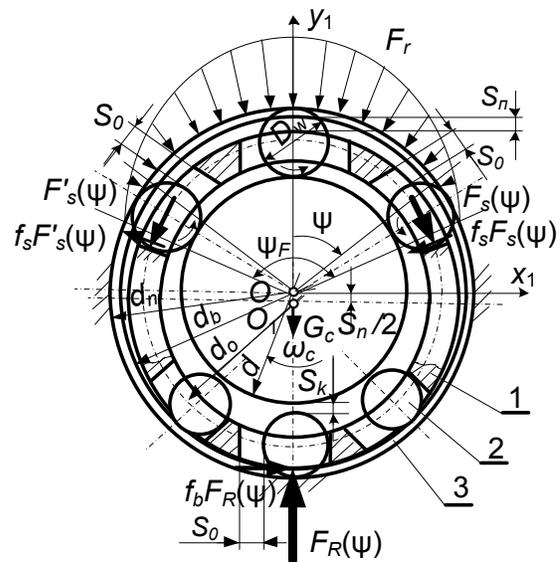$$M_S = 0{,}5 d_b f_b [F_s(\psi) + F'_s(\psi)]\cos\psi - 0{,}5 D_w f_s [F_s(\psi) + F'_s(\psi)]. \quad (2)$$

**Fig. 3. Model of loading of a separator:
1 – separator; *2* – roller; *3* – ring**

Force $F_s(\psi)$ of interaction of the leading roller decides on a crossing point of a separator at the time of the beginning of slipping of a roller in a zone of radial loading of the bearing by a solution of system of the equations of the movement of a roller, and force $F'_s(\psi)$ of interaction of the conducted roller decides on a crossing point of a separator on the basis of the theorem of change of kinetic energy of a separator for a cycle of its loading [8].

Below the example of calculation of rated value of the moment of resistance to rotation caused by a separator for the following basic data is given: resistance moments taking into account settlement forces of interaction of a roller with a crossing point of standard and advanced separators $M_S = (1{,}018...1{,}363)10^{-3}$ N m and $M'_S = (0{,}521...0{,}692)10^{-3}$ N m; resistance moments taking into account experimentally certain forces of interaction of a roller with a crossing point of standard and advanced separators – $M_{Se} = (1{,}190)10^{-3}$ N·m and $M'_{Se} = (0{,}680)10^{-3}$ N·m.

The normalized value of the M_s moment of resistance to rotation caused by a standard separator

$q_M = 0,1+1,18\text{th}[(M_{Se} - M_{S(min)})/(M_{S(max)} - M_{S(min)})] =$
$= 0,1+1,18\text{th}[(1,190 - 1,018)/(1,363 - 1,018)] =$
$= 0,1+1,18\text{th}(0,499) = 0,64.$

The normalized value of the M'_s moment of resistance to rotation caused by an advanced separator

$q'_M = 0,1+1,18\text{th}[(M'_{Se} - M'_{S(min)})/(M'_{S(max)} - M'_{S(min)})] =$
$= 0,1+1,18\text{th}[(0,680 - 0,521)/(0,692 - 0,521)] =$
$= 0,1+1,18\text{th}(0,93) = 0,96.$

Results of calculation of an integrated indicator of a technical level of U for standard and advanced designs are presented in the form of the chart called by "a quality web" (fig. 4).

Value of a system indicator of a technical level is received 17% more in comparison with a standard design. Efficiency of performance of the offered modernization providing at the expense of increase in quantity of rollers increase of dynamic loading capacity and a resource of the bearing respectively for 10,5% and 19%, decrease in loads of a separator by 11% by improvement of internal dynamics of the bearing, possibility of stabilization of temperature condition of operation of the bearing at increase of speed of the train to 300 km/h thanks to separator material replacement is as a result confirmed.
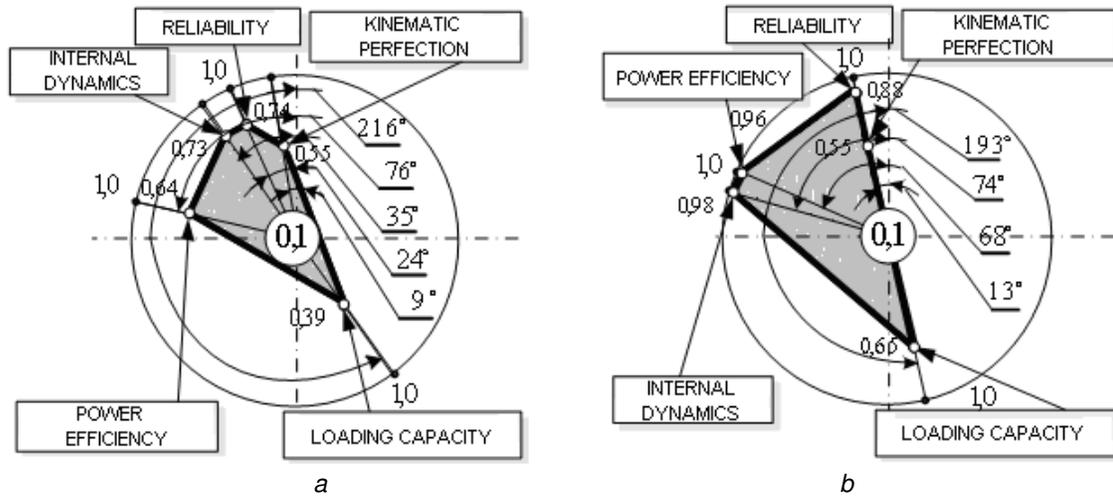

a   *b*

Fig. 4. "Quality webs" for standard (*a*) and modernized (*b*) bearing 2726

4. CONCLUSION

In the presented article the system method of the analysis and management of the technical level of the science-intensive products of mechanical engineering at stages of their design and modernization gained further development and application. On the example of roller cylindrical bearings as a part of axle boxes of railway transport efficiency is confirmed numerical display of quality indicators of the main structural and functional properties of bearings, allowing to consider known and new structures, designs, details, elements of details as the uniform universal system of models which is based on the uniform principles, axioms, hypotheses.

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