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System Model of a Technical Level of Rolling Bearings

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Authors' contributions

This work was performed in cooperation between all authors. Author SG directed researches, offered and proved universal system model of an indicator of a technical level of products of machine building. Author VY offered and proved application of system model to rolling bearings. Author AG executed necessary researches and developed formulas for single indicators of quality of roller cylindrical bearings. All authors read and approved the final manuscript.

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ABSTRACT

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 links between rolling bearing elements as mechanical system is established; quality indicators are offered; 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 at 10,5%, the power efficiency at 59%, a resource at 19%, decrease at 11% of level of internal dynamic loadings, nominal temperature condition of operation at speeds of train movement up to 300 km/h are proved. As a result the indicator of a technical level of the upgraded bearings is raised at 47%.
Conclusion: Further development was gained by a system method of estimation and management of a technical level of machine-building production at stages design and modernization.

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Keywords: Roller cylindrical bearing; operational characteristics; settlement models; quality indicators.

1. INTRODUCTION

In practice of modern machine-building 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 decision becomes complicated due to the absence of complex researches of influence of bodies of rolling quantity, material of a separator, temperature condition, and other factors of the characteristic of their quality [2−4]. As the most perspective directions of modernization of axle boxes of wheel axes are considered: Use of bearings of cassette type with conic rollers (the producer - BRENCO, USA) [5] or cylindrical roller bearings with the increased quantity of rollers (SKF, Sweden, and NSK, Japan) [3].

Maintenance of conic bearings in axle boxes of railway transport of Ukraine was shown more considerable heating at operation, than for cylindrical bearings [6]. Replacement of conic bearings by the cylindrical bearings limits absence of information about influence of the increased quantity of rollers on other service characteristics of axle boxes.

Therefore, development of the system model of a technical level of rolling bearings providing a scientific basis for a choice of effective 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 machine-building production in relation to gears, to restrictive couplings, mechanisms of parallel structure, machines-robots etc., is presented in works [7−9]. 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 high-technology products of machine-building in uniform system of 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 $\{q_i \Leftrightarrow q_j\}$ 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 system 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 and schematized on settlement models (Fig. 1).

At block diagram (Fig. 1, *a*) it is presented two rings − external P_1 with two boards and internal P_2 with one board, rollers P_3 and a separator 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 to the case of axle box and shaft, rollers – kinematics of friction of rolling, a separator – reduction of losses of friction. Elements of rings – the racetracks M_{1K}, M_{2K}, 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 rollers – surfaces of rolling M_{3K} and face M_{3T}, provide perception of radial and axial loadings. Separator elements – rings M_{4K} and the jumper M_{4C}, provide basing of a separator on rings or on rollers.

Radial loading F_r (see Fig. 1, *b*) is transferred from an external ring P_1 by a race path M_{1K} through roller P_3 surfaces M_{3K} to the racetrack M_{2K} of an internal ring P_2. Axial loading F_a is transmitted from an internal ring P_2 by surface M_{2T} through roller P_3 surfaces M_{3T} on a surface M_{1T} of an external ring P_1. At rotation of the rollers P_3 the surfaces of rolling M_{3K} press on a surface of sliding M_{4C} of jumper of a separator P_4 and press it surfaces M_{4K} to surfaces M_{1B} or M_{2B} of external P_1 or internal P_2 rings [10].

Differentiation of single and complex indicators of functional properties of roller cylindrical bearings is executed by results of theoretical studies and experiments. The specified analytical dependences of distribution of radial and axial forces in the bearing are received [10,11], models of a kinematics and dynamics which allowed defining frequency of action and size of forces, attached to a separator are developed [12].

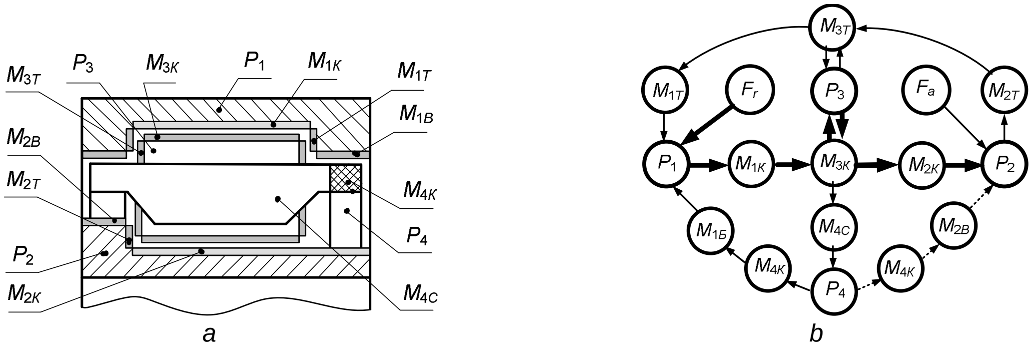

Fig. 1. Models of the bearing: a – block diagram; b – structurally functional graph

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}). Change of the geometry of elements theoretically has to influence their power interaction.

The structure of settlement formulas for simple and complex indexes of quality is proved and approved by authors earlier [7]. Some formulas is offered for the first time (in Table 1 are noted *).

Calculation of an indicator of a technical level $U(Q)$ of standard and advanced designs is executed on a basis of next system of the non-uniform linear equations [7].

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

where q_i = 0,1 + 1,18th $[(y_i - y_i^-)/(y_i^+ + y_i^-)]$ − at a positive gradient of an indicator; q_i =1,0 – 1,18th $[(y_i - y_i^-)/(y_i^+ + y_i^-)]$ − 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.

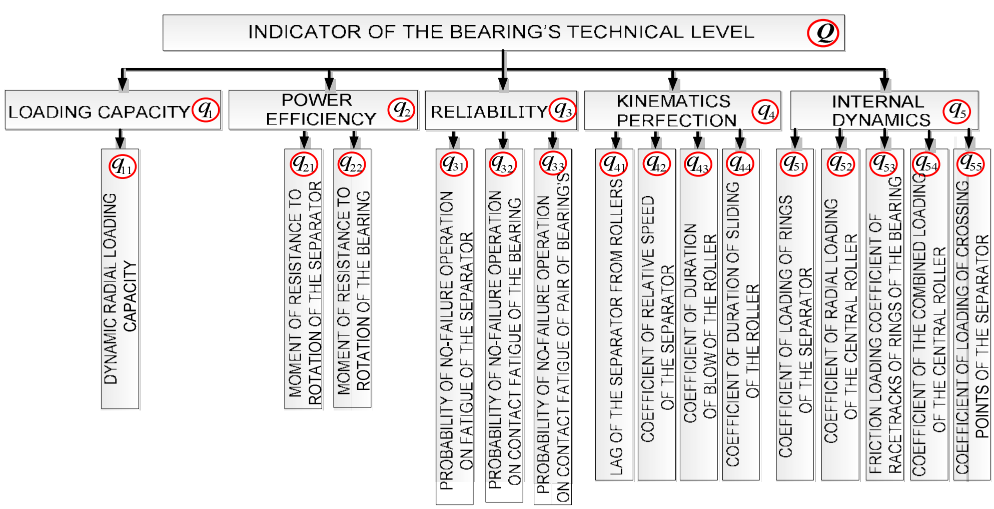

Fig. 2. Hierarchical model of an indicator *Q* of the bearing's technical level

Table 1. Indicators of quality of roller cylindrical bearing

Properties	Indicators	Settlement formulas		References
1. Loading capacity	1.1. Dynamic radial loading capacity of the bearing, *N*	$C = \mu\,(il_w\cos\alpha)^{7/9} z^{3/4} D_w^{29/27}$	(2)	[1]
2. Power efficiency	2.1. Moment of resistance to rotation of a separator, *N·m*	$M_S = 0{,}5 d_b f_b [F_s(\psi) + F'_s(\psi)]\cos\psi - 0{,}5 D_w f_s [F_s(\psi) + F'_s(\psi)]$.	(3)	*
	2.2. Moment of resistance to rotation of the bearing, *N·m*	$M_n = 0{,}5 d_r [(F_{fi} + F'_{fi}) + z_{lk} \cdot F_{ki}]$	(4)	*
3. Reliability	3.1. Probability of no-failure operation on fatigue of separator	$u_{PF} = -(n_F - 1) / (n^2_F \nu^2_{\sigma 0} - \nu^2_{\sigma})^{1/2} \Rightarrow P_F$	(5)	[13]
	3.2. Probability of no-failure operation on contact fatigue of rings and rollers	$u_{PL} = -(n_L - 1) / (n^2_L \nu^2_c - \nu^2_P)^{1/2} \Rightarrow P_L$	(6)	[14]
	3.3. Probability of no-failure operation on contact fatigue of pair of bearings	$P_{2L} = 1 - (1 - P_L)^2$	(7)	[1]
4. Kinematics perfection	4.1. Relative lag of a separator from rollers	$\Delta = 200 S_0 z / (d_0 \pi)$	(8)	[15]
	4.2. Coefficient of relative speed of a separator	$k_\omega = \omega_s z_{lk} / \omega_c$	(9)	*
	4.3. Coefficient of duration of blow of a roller	$k_\omega = t_s / t_c$	(10)	*
	4.4. Coefficient of duration of sliding of a roller	$k_\psi = (\psi_F - \psi_e)/\psi_F$	(11)	*
5. Internal dynamics	5.1. Coefficient of loading of rings of a separator	$k_{FR} = F_R / F_{f0}$	(12)	*
	5.2. Coefficient of radial loading of the central roller	$k_{Fr} = F_r / F_{r0}$	(13)	*
	5.3. Coefficient of a friction loading of racetracks of rings	$k_{Ff} = F_{f0} / F_{fi}$	(14)	*
	5.4. Coefficient of the combined loading of the central roller	$k_F = F_{r0} / F_{a0}$	(15)	*
	5.5. Coefficient of loading of jumpers of separator	$k_{Fs} = F_s / F_{f0}$	(16)	*

Rated values of indicators of a technical level for models of standard (z=14) and upgraded (z=16) bearing 2726 are given in Table 2. In brackets – indicators of advanced bearing in which the separator is made of polyamide with the changed geometry of windows [4].

Designations: μ − coefficient of the accounting of geometry of details of the bearing, accuracy of their production and materials; i − quantity of ranks of bodies of rolling; l_w − length of a roller, *m*; α − nominal corner of contact; z − quantity of rollers; z_{lk} – quantity of rollers in the loading zone; D_w − diameter of a roller, *m*; d_r, d_b − diameters of fit of an internal ring and boards of an external ring, *m*; f_s, f_b − coefficients of friction of a jumper with a roller and separator rings with boards of the basing ring; F_r − radial load of the bearing, *N*; F_s, F_s' − forces of interaction of the separator conducted rollers with jumper in a zone of radial loading, *N*; F_{fo}, F_{fi} − friction forces of rollers on running paths of external and internal rings, *N*; F_{fi}, F'_{fi} – friction forces of sliding of rollers, *N*; F_{ki} – friction force of rolling of rollers on an internal ring, *N*; S_0 − a clearance in a window of a separator, *m*; d_0 − diameter of the centers of rollers, *m*; ω_w, ω_s, ω_c − angular speeds of rollers, 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*.

For example, the moment of resistance to rotation caused by a separator decides by friction of jumpers 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) [10], analyzed on a formula (3) as the sum of the moments of every effort applied for a separator (see Table 1):

$$M_S=0{,}5d_bf_b[F_s(\psi)+F'_s(\psi)]\cos\psi-$$
$$-0{,}5D_wf_s[F_s(\psi)+F'_s(\psi)].$$

Force $F_s(\psi)$ of interaction of the leading roller decides on a jumper of a separator at the time of the beginning of slipping of a roller in a zone of radial loading 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 jumper of a separator on the basis of the theorem of change of kinetic energy of a separator for one cycle of its loading [10].

As 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 jumper of standard and advanced separators M_S=(1,018…1,363)10^{-3} $N\cdot m$ and M'_S=(0,521…0,692)10^{-3} $N\cdot m$; resistance moments taking into account experimentally certain forces of interaction of a roller with a jumper of standard and advanced separators M_{Se}=(1,190)10^{-3} $N\cdot m$ and M'_{Se}=(0,680)10^{-3} $N\cdot m$.

The normalized values of the moments M_s and M'_s of resistance to rotation caused by standard and advanced separators:

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

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

On the basis of normative conditions of production and operation of bearings as a part of axle boxes, results of theoretical and test studies of authors and other researchers, numerical values of indexes of quality are determined (see Table 2). Results of calculation of a system indicator of a technical level *U* for standard and advanced designs are presented in the form of the chart called by a "quality web" (Fig. 4), where settlement corner $\varphi_i = \lambda_i \cdot 2\pi$.

Value of a system indicator of a technical level is received *U*=0,53 at 47% 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 at 10,5%

Table 2. Matrixes $[\lambda]$ and [*Q*] for models of standard and upgraded bearing 2726

Loading capacity	Power efficiency	Reliability	Kinematics perfection	Internal dynamics	Model's level
0,24	0,19	0,021	0,057	0,49	λ_i = const for all levels
(0,21)	(0,19)	(0,032)	(0,034)	(0,54)	
0,39	0,25	0,59	0,55	0,39	1 – system "bearing"
(0,65)	(0,61)	(0,82)	(0,55)	(0,55)	
	0,64	0,60	0,72	0,61	2 – subsystem
	(0,96)	(0,85)	(0,72)	(0,88)	"separator – rollers"
		0,74	0,76	0,64	3 – subsystem "separator"
		(0,88)	(0,76)	(0,93)	
			0,79	0,64	4 – subsystem "ring"
			(0,79)	(0,93)	
				0,73	5 – "weak element"
				(0,98)	(race path)

****** All calculations of indicators of quality are executed by the authors* and 19%, decrease in loads of a separator at 11% by improvement of internal dynamics, possibility of stabilization of temperature condition of operation of the bearing at increase of speed of the train to 200…300 *km*/*h* thanks to separator material replacement is as a result confirmed.

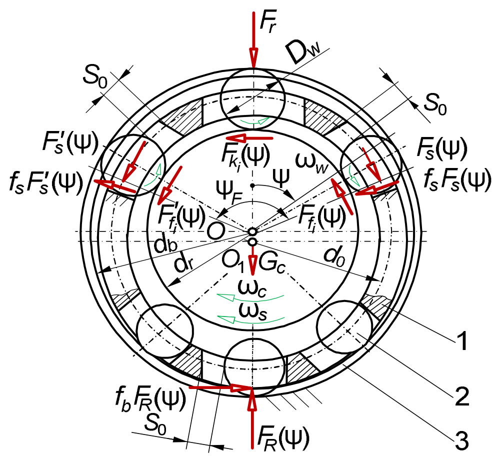

Fig. 3. Model of loading of a separator: 1 – separator; 2 – roller; 3 – ring

Dynamic load-carrying capacity and resource of bearings are calculated according to standards of ISO [1]. Increase of power effectiveness of the upgraded bearings is reached due to application for a separator of polymeric material with a smaller friction coefficient.

The decrease in loads of a separator is explained by the following:

- at increasing of quantity of rollers in the bearing their quantity in a loading zone ψ_F increases (see Fig. 3);
- as a result each roller is affected by smaller radial and axial forces, loads of a separator from rollers at edges of a zone of a radial loading also decrease.

Improvement of internal dynamics of the bearing is promoted decrease of loading at contact of a roller with the middle of a jumper of a separator and decrease of thickness of jumpers.

Theoretical and test studies of a heat generation in bearings of axle boxes are actually for high-speed passenger trains [16,17].

For the studied range of loadings (radial 30 … 50 *kN* and axial 5 … 20 *kN*) and speeds of an forced air cooling (28 … 83 *m/s* at speeds of trains 100 … 300 *km/h*) the calculated gradient of temperatures for the upgraded bearings is than 0,4 … 1,4°*C* less in comparison with standard.

Results of the executed researches confirmed the increased load ability and reliability of roller cylindrical bearings with the increased quantity of rollers that coincides with the published results of resource tests and statistics of operational supervision [2, 3 and 14].

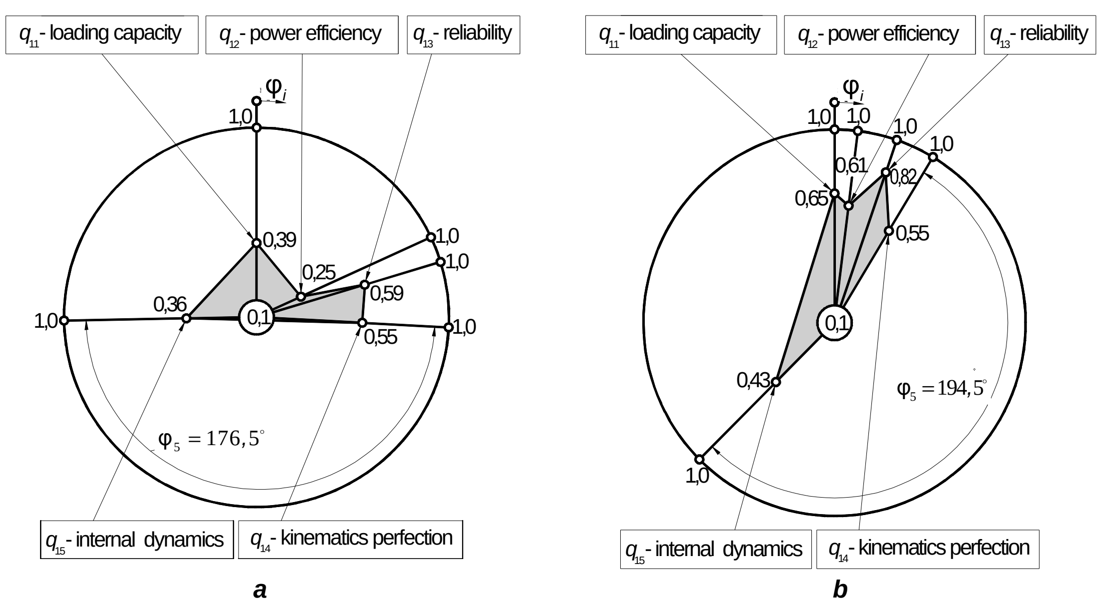

Fig. 4. "Quality webs" for bearing 2726: a – standard design; b – upgraded

Tolerance of the accepted indicators of kinematics perfection of the bearing to the made changes in a design of a separator is explained by the following:

- characteristics of the movement of a separator with the rotating internal and motionless external ring don't depend on errors of production, contact and assembly deformations of details;
- indicators of quality of kinematics are defined only by separator dimensions, clearances in windows and the angular size of loading zone [12]. Therefore, at an assessment of a technological level of similar bearings indicators of kinematics perfection can be excluded from system (1). Efficiency of modernization of axle boxes of wheel axes of modern railway transport on the basis of the offered system of single and complex indicators of quality of roller rolling bearings is for the first time comprehensively analyzed and proved.

4. CONCLUSION

The system method of the analysis and management of the technical level of the high-technology products of machine-building at stages of their design and modernization gained further development and application. On the example of roller cylindrical bearings as a part of allowing considering known and new structures, axle boxes of railway transport efficiency of numerical display of quality indicators of the main structural and functional properties of bearings, designs, details and elements etc. as the uniform universal system of models which is based on the uniform principles, axioms, and hypotheses is confirmed.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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