Проаналізовано функціональні взаємозв'язки між структурними елементами базових конструкцій роликових підшипників. На основі побудованої структурно-функціональної моделі підшипників удосконалено функції сепараторів щодо усування перекосу їх конструкцій, зменшення сил взаємодії з роликами і базуючим кільцем підшипників, зменшення проковзування роликів. Це дозволило обґрунтувати зміни конструкції сепаратора – збільшити кількість вікон, змінити форму бокових поверхонь перемичок і перерізу кілець сепаратора, що сприятиме підвищенню технічного рівня підшипників.

Ключові слова: технічний рівень, роликові підшипники, структурно-функціональна модель підшипника, функції сепараторів підшипників, конструкція сепаратора

Проанализированы функциональные взаимосвязи между структурными элементами базовых конструкций роликовых подшипников. На основе построенной функционально-структурной модели подшипников усовершенствованы функции сепараторов по устранению перекоса их конструкций, снижения сил взаимодействия с роликами и базирующим кольцом подшипника, уменьшения проскальзывания роликов. Это позволило обосновать изменения конструкции сепаратора – увеличить количество окон, изменить форму боковых поверхностей перемычек и сечения колец сепаратора, что способствует повышению технического уровня подшипников.

Ключевые слова: технический уровень, роликовые подшипники, функционально-структурная модель подшипников, функции сепараторов подшипников, конструкция сепаратора

UDC 621. 822
DOI: 10.15587/1729-4061.2016.85849

IMPROVING THE DESIGN OF CAGES FOR BEARINGS OF HIGH TECHNICAL LEVEL

A. Gaydamaka
PhD, Associate Professor
Department of machine parts and applied mechanics
National technical University «Kharkiv Polytechnic Institute»
Bagaliya str., 21, Kharkiv, Ukraine, 61002
E-mail: gaydamaka_av@mail.ua

1. Introduction

In the present system «production market-consumer», the main role belongs to the latter. The manufacture of products that meet consumer requirements is a prerequisite for their competitiveness. This fully applies to roller bearings for railway vehicle axleboxes (RBRVA), in particular, freight and passenger cars. However, according to the Ukrzaliznytsia (Ukrainian Railways), failure of the most common conventional cylindrical roller bearings of cars between 2000...2010 caused by contact-fatigue damage of rings and fatigue cracks of cages reached 10...12 % of the total number of failures that has negatively affected transport safety and frequency of maintenance [1]. So, finding ways of system improvement of the technical level of Ukrainian RBRVA in the design and modernization is urgent and is of great practical importance for many branches of mechanical engineering.

2. Literature review and problem statement

Increase in the technical level of roller bearings in terms of the rolling surface contact endurance within the specified dimensions is achieved by improving the distribution of load among rollers, optimizing the rollers geometry, increasing the number of rollers. A better distribution of radial load among rollers is due to improvement of bearing units [2]. Improvement of bearing units for RBRVA is limited because of significant cost of introduction. The face radius optimization of cylindrical bearing rollers was considered in [3], tapered ones – in [4]. Rather fundamental research [3, 4] and earlier works have provided reliable operation of roller end faces and sides of rings. However, [3, 4] disregard wear-related changes in the contact. The impact of increasing the number of rollers as one of the most promising ways to raise the technical level within the specified dimensions was investigated in [5] for cylindrical bearings and in [6] for tapered bearings. Still, [5, 6] do not answer many important questions, such as how the increase in the number of rollers will affect the cage design and performance, are there any new useful functions after the cage redesign, how to change the cage design with the effect of improving as much technical level indices of the bearing as possible.

The most effective way to improve the technical level of axle roller bearings of Ukrainian passenger and freight cars is the use of case bearings with tapered (BRENCO – USA, TBU 1520 HARP – Ukraine) and cylindrical (CRU Duplex HARP – Ukraine) rollers [7], which also have an increased number of rollers. BRENCO bearings, which make up about 1 % of conventional cylindrical roller bearings 30-232726E2M and 30-42726E2M have been used in Ukraine since 2008. According to the Ukrzaliznytsia, they increase the technical level by eliminating damage of ring collars and roller end faces. Thus, the results of studies [8] show that heating of BRENCO bearings has increased by 60...100 % within acceptable lubricant values. CRU Duplex HARP bearings, which are less than 0.3 % of Ukrainian conventional cylindrical roller bearings, have been commissioned in 2012 and are characterized by a 5 % increase in the estimated service life and therefore lower maintenance costs compared with conventional bearings, but need further increase in radial and axial load capacity [9]. So, the proposed [7] technical solutions of RBRVA do not fully meet consumer requirements as improving one or more quality indicators degrades other or is not effective enough.

Uncertainty of the impact of the functional relationships among structural roller bearing elements on the cage redesign effectiveness and performance when increasing the number of rollers necessitated research in a direction that provides the technical level improvement.

3. Aims and objectives

The aim of the study is to determine relationships among structural elements and their functions in roller bearing designs and validate the cage design changes when increasing the number of rollers to increase the technical level.

To achieve this goal it is necessary to solve the following problems:

– to build a structural-functional model of the basic design of roller bearings;

– to validate the cage design changes when increasing the number of rollers in the bearing of increased technical level.

4. Selection of the basic design and method of research

The structure and functional relationships of parts of the most common conventional cylindrical roller bearings (almost 99 % of the total number of bearings) of axle boxes of freight and passenger cars of Ukrainian trains are shown in Fig. 1. External radial load $2F_r$ on RBRVA is taken as evenly distributed among bearings, and axial F_a acts along the wheelset axis. The designs of these bearings are chosen as basic for modernization.

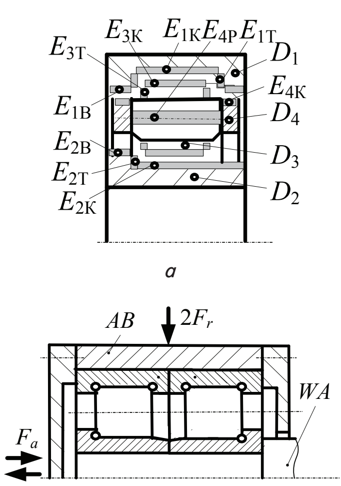

Fig. 1. The basic roller bearing design: *a* – structure; *b* – bearings in axleboxes (WA – wheel axle, AB – axlebox body; F_r, F_a – radial and axial load)

Each bearing consists of outer rings D_1, for example with two collars, and inner rings D_2, for example with one collar, rollers D_3, cage D_4. Elements of rings are raceways E_{1K}, E_{2K}, collar face E_{1T}, E_{2T} and reference face E_{1B}, E_{2B}, roller elements – rolling surfaces E_{3K} (cylindrical, tapered, spherical) and end face E_{3T} (flat, convex), frame cage elements – surfaces of the ring E_{4K} and jumper E_{4P} of the appropriate shape. The outer ring D_1 may be common to both bearings.

Radial load F_r in bearing is transferred through a raceway E_{1K} of the outer ring D_1 on the radial surfaces E_{3K} of rollers D_3 and raceway E_{2K} of the inner ring D_2; axial load F_a, acting for example, from left to right, is transferred from the end face E_{2T} of the inner ring side D_2 on the end faces E_{3T} of a roller D_3 and the end faces E_{1T} of the outer ring sides D_1.

During bearing rotation, rollers D_3, through the rolling surface E_{3K}, enter into the force interaction with surfaces E_{4P} of jumpers of the cage D_4 and move it. The jumpers are rigidly connected with the cage rings, which in turn are based on the guide paths E_{1B} of the outer ring sides D_1 by external friction surfaces E_{4K} (cage basing on a two-side outer ring) or guide paths E_{2B} of the inner ring sides D_2 (cage basing on a two-side inner ring).

With a given bearing structure, specification of known and identification of new relationships of elements of parts with functions are performed based on a structural-functional method that allows adjusting their designs. Therefore, the structural-functional method of system analysis is chosen to increase the technical level of roller bearings for railway vehicle axleboxes [10]. Improvement of RBRVA basic design functions to increase the technical level is made on the example of wheelset bearings of railway cars. The structural-functional method of system analysis of bearings includes building structure and functioning models, as well as a structural-functional model, determining weight coefficients of functions, improving basic design functions.

5. Basic design model

RBRVA basic design as an assembly unit includes inner and outer rings, rollers (cylindrical, tapered, spherical), cage. RBRVA structural model is shown in Fig. 2.

The function of the bearing rings is to ensure the movement of rolling elements and shaft and housing fits of the bearing units. The most important element of rings are raceways corresponding to the shape of rolling elements. The bearing rings with cylindrical and tapered rollers can be no-collar, one-collar, two-collar. Sometimes the function of the collar can be performed by thrust planar or shaped side ring. Friction surfaces of collars in contact with the roller end faces are made so that there was no point contact. Raceways are in contact with the convex rolling surfaces of rollers for even pressure distribution.

The function of rolling elements of bearings is the maximum possible reduction of friction between rings. Rolling elements can be of ball and roller shape. The design functions of railway roller bearings, which can be cylindrical, tapered, spherical are considered below.

Railway bearings with cylindrical, tapered, spherical rollers operate in conditions of off-center radial and axial loads that cause misalignment of rings. To reduce the load concentration effect of rollers, the shape of the latter is changed by performing tapered and spherical bevels on the edges, one-radius or two-radius bombina, end face hollows of various shapes. The roller end faces are made convex with a rather irregular geometric shape to reduce wear.

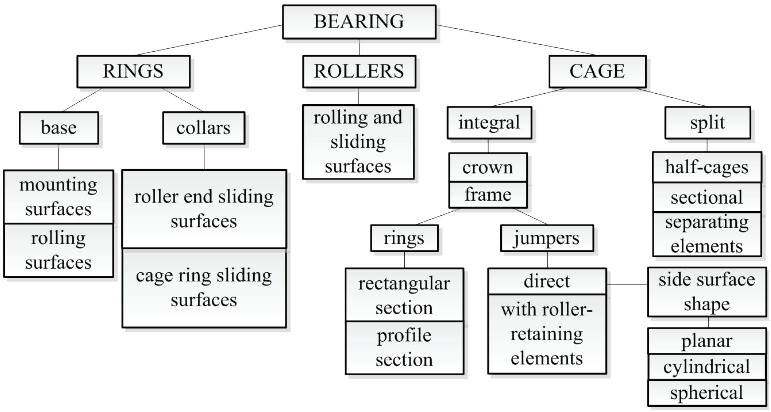

Fig. 2. Structural model of roller bearings

The function of bearing cages is to eliminate contact of rolling elements among themselves and keep them at a certain distance. Sometimes cages have components that fix rolling elements in the bearing to prevent falling out from windows when removed inner or outer rings. Polymer cages additionally solve the problems of improving lubrication conditions of bearing parts, damping dynamic loads, reducing slippage of rolling elements, vibration and noise.

The frame (massive) design of cages is the most common. The concept of massive design has been introduced for metal cages made of rods, pipes or blanks and production of which required a certain stiffness for machining. Some designs of metal and polymer cages are called frame. However, in the latter case, the stiffness requirement is not associated with machining. Unlike crown designs, the frame one covers rolling elements on all sides. The choice of frame or crown design is determined by the bearing type, assembly and operation conditions.

The design elements of the cage (frame half-cages, frame sectional, separating elements) are useful for large size bearings with d≥100 mm provided that the replacement of an integral cage design with a component does not limit the speed parameter of the bearing.

The friction surfaces of the cage are surfaces of windows (windows are formed by jumpers and rings) in contact with rolling elements, and bearer surfaces of rings in contact with surfaces that are based on the sides of outer or inner bearing rings. If a cage is based on rollers, the friction surfaces of jumpers are made of appropriate shape (cylindrical, tapered, spherical). Flat side surfaces of straight jumpers are used for perception of loads from cylindrical rollers when a cage is based on the sides of one of the bearing rings. The cage basing on the sides of the outer ring provides a better lubrication of the contact surfaces, but the friction torque in the bearing is somewhat higher due to increased «arm» of friction forces.

Rings of polymer cages are made with the profile section for a better quality of casting and placement of oil pockets. Oil pockets and various elements facilitating the oil flow to friction surfaces of parts can be located on jumpers.

The shape of the cage window is often different from the shape of the rolling element. For example, a slight staggered arrangement of the cage windows is provided to improve the operation smoothness, reduce vibration and noise of some high-speed bearings. The impact of the windows shape was often studied for high-speed ($n_v \geq n_{hr}$) and preferably ball bearings. Concerning RBRVA, the impact of the cage design elements (windows and rings) is under-investigated.

It was found that it is possible to significantly reduce or even eliminate the phenomenon of the cage misalignment in the running roller bearing by changing the rectangular geometry of windows by the curved with the convexity of sides towards the center that meets the new function of the cage. Another new function of the cage is associated with a decrease in the forces of the cage interaction with rollers and bearing locator ring, depending on the stiffness of jumpers and rings. Stiffness reduction of the first ones is achieved by increasing the number of windows, and stiffness of rings – by replacing the rectangular section with the profile one. Additional stiffness reduction of the cage elements is achieved by the cage material replacement – metal with polymer. The factor of the cage design stiffness is related to a third new function – a function of slippage reduction of rollers on the raceways.

6. The functional model of the basic design

The function of roller bearings is to fix the moving parts of mechanisms, perceive loads and reduce rotation resistance. RBRVA, as a heavily loaded structure, is characterized by two basic functions – wheelset parts fixing (F_1) and load perception (F_2) and one auxiliary – rotation resistance reduction (F_3), which are the first level of the functional model (Fig. 3). The second level of the model is determined by the basic functions involving the use of bearings – inner ring fitting on the axis (F_{11}), outer ring fitting in the axle box (F_{12}), perception of external radial load (F_{21}) perception of external axial load (F_{22}), separation of rollers (F_{31}), perception of loads from the cage (F_{32}).

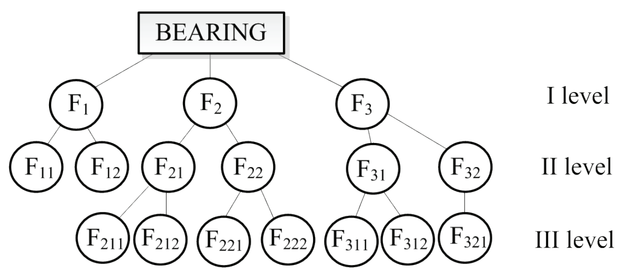

Fig. 3. The functional model of roller bearings

Differentiation of the second-level functions is represented by the auxiliary third-level functions that constitute the basic functions – ensuring minimum friction of rolling (F_{211}) and slippage (F_{212}) on the radial rolling surfaces of rings, ensuring minimum sliding friction on the end faces of the ring sides (F_{221}), ensuring minimum slippage friction on the basing surfaces of the ring sides (F_{222}), keeping rollers at equal distances in the bearing (F_{311}), keeping rollers from falling out when the removed ring (F_{312}), ensuring minimum sliding friction on radial surfaces of the ring collars (F_{321}). Basic functions F_{11} and F_{12} are not analyzed in the present paper.

7. Structural-functional model of the basic design of RBRVA

Structural and functional models reflect stable static links between elements and their functions. Actual properties are manifested through dynamic links that appear in the operation of parts. In the bearing operation, new functions of the cage occur - the function of eliminating the design misalignment, the function of reducing the forces of interaction with rollers and locator ring, the function of reducing slippage of rollers. Therefore, to determine the functionality and assess the performance quality of functions, for example of RBRVA with the most promising integral frame design of the cage, it is necessary to combine the structural and functional models (with new functions) and build a structural-functional model (Fig. 4).

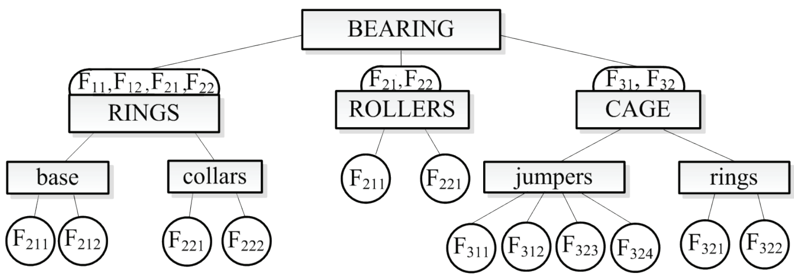

Fig. 4. Structural-functional model of roller bearings

Unlike the models of the bearing structure and functioning, the structural-functional model includes additionally new useful functions of the cage - the function of eliminating the design misalignment F_{322}, the function of reducing the forces of interaction with rollers and locator ring F_{323}, the function of reducing slippage of rollers F_{324}.

8. Contribution of material object

The contribution of a material object (MO) – a part or element of RBRVA to their functions in bearings was determined based on the proposed structural-functional model (Table 1) by peer review [10].

Table 1

The weighting factors of the functions of RBRVA parts

MO of the function	Costs of MO, rel. un.	Index of the function	Contribution of MO to the function, rel. un.
Outer ring	0.4	F_{21} F_{22} F_{211} F_{212} F_{221}	0.2 0.2 0.25 0.1 0.25
Inner ring	0.4	F_{21} F_{22} F_{211} F_{212} F_{221}	0.2 0.2 0.25 0.1 0.25
Cage	0.15	F_{31} F_{32} F_{311} F_{312} F_{321} F_{322} F_{323} F_{324}	0.1 0.3 0.05 0.05 0.2 0.1 0.1 0.1
Rollers	0.05	F_{21} F_{22} F_{211} F_{221}	0.2 0.2 0.3 0.3

Further, according to Table 1, the weighting factors of functions that are associated with the cage are taken into account since they determine the changes in its design due to increasing the number of bearing rollers within the specified dimensions.

9. Discussion of the research results

The analysis of the basic functions of perception of radial F_{21} and axial F_{22} loads by rings and rollers shows that their implementation is ensured by different reliable designs – two-collar, one-collar, no-collar. Efficiency improvement of the functions F_{21}, F_{22} is carried out by optimizing the surface geometry of rollers and rings when solving relevant contact problems [11, 12]. Further improvement of the functions F_{21}, F_{22} requires increasing the number of rollers. Auxiliary functions provide minimum friction of rolling (F_{211}) and slippage (F_{212}) on radial surfaces of rings, minimum sliding friction on the end faces of the ring sides (F_{221}) at constant dimensions, geometrical parameters, manufacturing technologies depend on the number of rollers in the bearing and lubrication conditions of parts. Provision of minimum sliding friction on basing surfaces of the ring sides (F_{222}) is determined by the material, stiffness and functions (property to accumulate oil and give to the friction surfaces) of the cage design. The basic function F_{31} is not analyzed in the present paper. Efficiency of the bearing function F_{32} can be improved through optimizing the geometry of the working surfaces of rollers, rings and cages, as well as retaining, by the cage elements (jumpers and rings), additional oil in special pockets, channels, openings, contributing to its submission to the parts. The operating experience of roller bearings shows that the polymer cages allow involving more rolling elements, increasing the bearing capacity and reducing power consumption while reducing the cost.

A study of relations among structural elements and their functions in the roller bearing designs revealed new useful functions of the cage that can reduce friction and wear of all parts. Implementation of the new functions of the cage is possible after the design changes of jumpers and rings. The specified results were achieved on the basis of peer review that needs clarification. However, today there is no other method of assessing the design quality of bearings, which can be checked by long-term operation. Thus, the development of new or upgrading the known bearing designs require the development of a modern design methodology of bearings.

The study of relations among structural elements and their functions in the roller bearing designs is a continuation of the author's theoretical works on kinematics and dynamics of bearing parts [13], which were the basis for selecting the number and geometry of windows, as well as stiffness of the cage rings.

The research has allowed offering an improved design of the cage with the greatest possible number of windows [14]. The maximum number of windows of the frame design of the cage is chosen provided that the bearing mounting and dismantling operations are performed. The corresponding cylindrical roller bearing 2726 for axle boxes of Ukrainian cars with 16 rollers (instead of 14) and improved frame design of the cage has the maximum possible carrying capacity within the specified dimensions [15]. Estimated life of the bearing with improved frame design of the cage in terms of the contact endurance of rolling surfaces only due to increasing the number of rollers according to the expression [15]

$$\frac{L_{10}^{(15)}}{L_{10}^{(14)}}=\left(\frac{C^{(16)}}{C^{(14)}}\right)^{10/3}=\left(\frac{16^{3/4}}{14^{3/4}}\right)^{10/3}=1.396303...$$

has increased by almost 39,6 %. Misalignment elimination of improved cage design, reduction of forces of the cage interaction with rollers and locator ring additionally will reduce friction and wear of the bearing parts. Final conclusions on the effectiveness of the proposed design improvements of the cage are possible after a special study of efficiency of upgraded bearings, planned by the author.

10. Conclusions

1. For the constructed structural-functional model of bearings, functional relationships between the parts and their elements were analyzed, and new useful functions of the cage – elimination of misalignment of its design, reduction of forces of interaction with rollers and locator ring, slippage reduction of rollers were revealed.

2. Elimination of misalignment of the cage design, reduction of forces of interaction with rollers and locator ring, slippage reduction of rollers on the rings are fully implemented in the bearing after design changes of the cage elements, namely when the ring section has a profile geometry to reduce stiffness, and jumpers have a reduced thickness due to increased number of windows. Jumpers of the cage are also made oval with a convexity arrow towards the middle of the window.

3. Estimated life of the roller bearing with improved frame design of the cage has increased by almost 19 % in terms of contact endurance of rolling surfaces. Efficiency of the cage design improvements that will contribute to design misalignment elimination, reduction of forces of interaction with rollers and locator ring, slippage reduction of rollers can be evaluated after special studies of efficiency of upgraded bearings.

References

1. Gaydamaka, A. Rolikovi pidshipniki byks vagonov i lokomotivov: modelirovanie i sovershenstvovanie [Text] / A. Gaydamaka. – Kharkiv: Cursor, 2011. – 320 p.
2. Morchikadge, I. Soverchenstvovanie i modernizatsija byksovich yzlov gruzovich vagonov [Text] / I. Morchikadge, A. Sokolov // Zeleznie dorogi mira. – 2006. – Vol. 10. – P. 59–64.
3. Simson, E. A. Modelirovanie i optimizatsij iznosa v zone tortzevogo kontakta skolzhenij rolikovich podshipnikov [Text] / E. A. Simson, V. V. Ovcharenko, M. V. Trohman // International scientific conference MicroCAD, 2009. – P. 35–36.
4. Fujiwara, H. Optimized Radius of Roller Large End Face in Tapered Roller Bearings [Text] / H. Fujiwara, T. Tsujimoto, K. Yamauchi // NTN Technical review. – 2009. – Vol. 77. – P. 96–104.
5. Ozu, T. High Load Capacity Cylindrical Roller Bearings [Text] / T. Ozu // NTN Technical review. – 2006. – Vol. 74. – P. 90–95.
6. Ueno, T. Extremely High Load Capacity Tapered Roller Bearings [Text] / T. Ueno, T. Matsushita // NTN Technical review. – 2009. – Vol. 77. – P. 73–80.
7. Melnichuk, V. K voprosy povyshenja nadioznosti byksovich yzlov s podchipnikami kachenija [Text] / V. Melnichuk, A. Demchenko, I. Martynov // Zaliznichny transport Ukraine. – 2006. – Vol. 2. – P. 17–19.
8. Mironov, A. Optimizazij nastroyki sredstv teplovogo kontrolj tipa KTSM i ASK MS v uslovijch expluatazii raznotipnuch podshipnikov [Text] / A. Mironov, A. Pavlyuk, V. Mityushev // Vagonu i vagonnoe chozjystvo. – 2013. – Vol. 4, Issue 36. – P. 35–39.
9. Martinov, I. Putannj rozrahunku dovgovichnosti byksovich rolikopidshipnikiv [Text] / I. Martinov // UkrDAZT. – 2000. – Vol. 44. – P. 76–79.
10. Antonov, A. Systemnuy analis [Text] / A. Antonov. – Moscow: Visha shkola, 2004. – 454 p.
11. Chermensky, O. Rolikovie podshipniki [Text] / O. Chermensky. – Moscow: Mashinostroenie, 2003. – 576 p.
12. Harris, T. Rolling bearing analysis [Text] / T. Harris. – New York, 2006. – 481 p.
13. Gaydamaka, A. Modeli kinematiki i dinamiki tsilindrichnih rolikopodshipnikov zaliznichnogo transporta [Text] / A. Gaydamaka // Visnyk Dnipropetrovskogo natsional'nogo universitetu zaliznychnogo transportu. – 2014. – Vol. 3. – P. 100–108.
14. Patent 50093 Ukrayina, MPK F 16S 33/46. Separator rolykopidshypnyka [Text] / Haydamaka A., Alefirenko V. – Zayavnyk i patentovlasnyk Natsional'nyy tekhnichnyy univesytet «Kharkivs'kyy politekhnichnyy instytut». – u200912229; declarated: 27.11.2009; published: 25.05.2010. – Bul. 10. – 2 p.
15. Patent 91168 Ukrayina, MPK F 16S 33/58. Tsylindrychnyy rolykopidshypnyk maksymal'noyi vantazhnosti v mezhakh zadanoho habarytu z polimernym separatorom tsil'noyi konstruktsiyi [Text] / A. Haydamaka. – Zayavnyk i patentovlasnyk Natsional'nyy tekhnichnyy univesytet «Kharkivs'kyy politekhnichnyy instytut». – u201400214; declarated: 13.01.2014; published: 25.06.2014. – Bul. 12. – 3 p.