Ensuring Reliability of The Gearbox during Operation Stage

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Keywords: Operational Reliability, Gearbox, failure.

Abstract: A significant proportion of the costs and downtime for repairs are attributed to transmission units, including the gearbox. One of the main reasons for such high transmission costs is the existing structure of the operating and repair cycle, which uses a strategy of waiting for failure, as a result operability is ensured mainly through overhaul and comprehensive maintenance with high consumption of spare parts. spare parts and repair downtime. This article is devoted to one of the most expensive repairs for ZF gearboxes, associated with the destruction of the front bearing of the output shaft. When inspecting gearboxes delivered with a similar defect, the condition of the gearbox parts does not allow making an unambiguous decision on the cause of the defect due to critical destruction of the mating parts. Based on the available research and scientific literature in the field of gearbox operation, an analysis was carried out and the root causes of gearbox failure in operation were identified.

1 INTRODUCTION

Today automakers are investing in smart and energy efficient vehicles because of the fierce competition they want to make smart and efficient mobility options. In the context of raising urbanization and inclusiveness of modern society, autonomous vehicles are designed to ensure an increase in the mobility of population all categories, while reducing the accident rate on the roads (Makarova, Mukhametdinov, Tsybunov, 2018). Numerous studies are devoted to the problems of the autonomous vehicles operation: the advantages, prospects and features of the transportation process organization. Despite technological advances in design, autonomous vehicles are still classic vehicles but with smart abilities. Each mechanical or electrical component of such vehicle has a limited life cycle. Therefore, the greater the mileage of an autonomous vehicle, the greater the mechanical parts wear. The higher the difficulty degree, the higher the risk of technical problems. Until the autonomous vehicle fleet becomes sufficient to obtain large statistical datasets of all failure kinds, there is a significant probability of failures during operation.

Although the vehicles produced today are reliable and maintainable, there is still a need to further improve their performance and fault tolerance (Makarova, Khabibullin, Belyaev, 2012). As the author of the paper (Bertsche, 2008) noted in his study, the number of returns due to critical failures and defects in automotive components and systems has increased. This increased the manufacturer's costs by eight times and led to the fact that warranty costs amounted to 8-12% of the company's turnover. The increase in the defects number can be explained by

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Makarova, I., Mukhametdinov, E., Gabsalikhova, L., Shepelev, V., Galiev, S., Buyvol, P. and Drakaki, M.
Ensuring Reliability of the Gearbox during Operation Stage.
DOI: 10.5220/0010530707680774
In *Proceedings of the 7th International Conference on Vehicle Technology and Intelligent Transport Systems (VEHITS 2021)*, pages 768-774
ISBN: 978-989-758-513-5

the increasing complexity of modern vehicles design. Considering that the system for ensuring the units operability is based on the regularities of changes in the technical state during operation, due to the action of various factors of a constructive, technological, operational and organizational and technical nature (Khabibullin et. al, 2013), the issue of researching the vehicle components and assemblies reliability remains relevant (Makarova, Pashkevich, Buyvol, Mukhametdinov, 2019.).

2 METHODS FOR DEFINING RELIABILITY: STATE OF THE PROBLEM

A vehicle is a complex mechanical system with several levels of hierarchy, consisting of various subsystems and components. Ensuring the reliability of the system can be carried out by design and analytical methods. Design methods include defining accurate design data, manufacturing instructions, followed by early and extensive testing procedures to ensure reliability. Analytical methods for ensuring reliability include determining and / or predicting reliability using quantitative and qualitative methods. They are applied during the conceptual design phase and during vehicle operation.

Faults diagnostics to identify the root cause of a vehicle's loss of performance is the main task when servicing a vehicle (Gritsenko, Shepelev, Zadorozhnaya, Shubenkova, 2020, Tsybunov, Shubenkova, Buyvol, Mukhametdinov, 2018). Correctly and timely detected defective unit allows not only to reduce the load on the mating parts, but also to neutralize such negative environmental consequences as excessive oil consumption, an increase in pollutants in the exhaust gases (Makarova, Shubenkova, Mavrin, Gabsalikhova, Sadygova, Bakibayev, 2019). The use of a fault tree analysis (FTA) as a tool for diagnosing problems with vehicle performance has been widely used by many researchers (James, Gandhi, Deshmukh 2018, Makarova, Shubenkova, Mukhametdinov, Giniyatullin, 2020). The Fishbone diagram is also used to help identify and pinpoint the causes of maintenance errors that can lead to failures in automotive systems (Murugan, Ramasamy, 2015).

It is also effective to use a combination of methods. For example, the authors of the work (Stefana, Marciano, Alberti, 2016) used such tools as reliability block diagram, bow-tie analysis, FTA, Failure Mode and Effects Analysis (FMEA) and likelihood and consequences analysis.

As one of the promising methods for troubleshooting, many authors suggest using vibration diagnostics, which allows to determine the degree of parts wear in a non-disassembly way (Makarova, Mukhametdinov, Gabsalikhova, Garipov, Pashkevich, Shubenkova, 2019, Gritsenko, Shepelev, Zadorozhnaya, Almetova, Burzev, 2020)

In the era of big data, the availability of information has increased significantly, as a result of which more sophisticated tools can be used to determine the hidden relationships in investigated variables. To determine the vehicle mean operating time between failures, in addition to the classical predictive models, the methods of intellectual analysis are currently used. In particular, in the work (Chong, Liu, Sun, Gilfedder, Titmus, 2019), the authors applied the concept of deep learning in neural networks, using data on the mileage between vehicle faults from a geographic information system. Most of the components in automotive systems are mechanical, the failure time of which corresponds to the Weibull distribution. Therefore, in their work (Kumar, Jain, Soni, 2019), the authors proposed a semi-Markov model suitable for repairable mechanical systems.

The development of methods to improve the transmission elements reliability is an urgent task, since it affects the efficiency and driving comfort (Roshdy, Abdelazi, 2020).

The papers (Liang, Walker, Ruan, Yang, Wu, Zhang, 2019, Deryusheva, Kosenko, Zagutin, Arakelyan, Krymsky, 2019, Ilyuchyk, Basalai, 2019) are devoted to researching of changes in the technical state and their design during transmission units' work. As a result of using the recommendations of these studies in production and operation, the reliability of vehicles and other machines transmission units has significantly increased, and the costs of ensuring their working capacity in operation stage have been reduced.

Within the framework of the indicated problems, this study will analyze the defects' causes, establish the distribution law for the failures' number from the mileage, and then propose measures to improve the reliability of this unit.

3 RESULTS AND DISCUSSION

3.1 Identifying the Most Common Gear Box Defects

Since the beginning of the use of ZF gearboxes on KAMAZ vehicles, the main reason for the failure was the vehicle towing in neutral gear, without disconnecting the propeller shaft. In this case, there is no rotation of the intermediate shaft, the oil pump is stopped, so the bearing operates under oil starvation conditions. The most serious damage to a part occurs if gearbox demultiplicator remains included in the reduced range.

The classification of the ZF gearbox main faults and failures at the initial stage of operation is shown in Fig. 1.

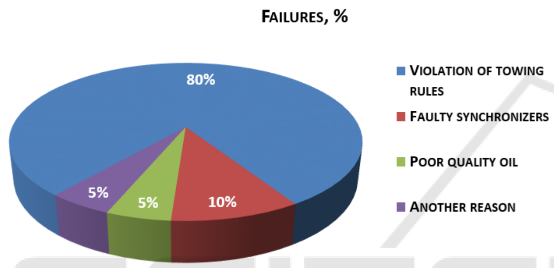

Figure 1: Distribution of claims by defects' type.

The problem under study is associated with the destruction of the output shaft bearing, which is a tapered roller radial thrust bearing with a size of 42.07 x 82.904 x 40.386, cm. (Fig. 2)

The bearing is installed on the output shaft pin, fixed with two split half rings of different thickness, depending on the clearance of the locating groove. The bearing outer cage is the tapered surface of the input shaft cavity, lubrication is carried out from a centralized lubrication system, oil is supplied through an opening in the oil bypass throttle.

As the main information source, we used the analysis of claims for failures of the gearbox with the defect "destruction of the output shaft bearing" due to calls from vehicles' owners. The analysis was carried out for gearboxes manufactured in Brazil, China, Russia and Germany. Fig. 3 shows photographs of the types of bearing destruction during operation stage. Defect analysis was carried out at the service center of the ZF KAMA company.

One of the failure classification signs is the defect cause, which is divided into three main types: structural, production and operational.

Structural failure occurs due to imperfections and structure defects, the reasons are errors in the unit's development and design, underestimation of safety margins, violation of standards established by state official standardization bodies.

A production failure is a failure due to a production violation or human error. The reasons for production failures are non-observance of documentation technical standards, use of low-quality components, insufficient level of production quality control. In the process of analyzing the output shaft bearing failure, the following factors are identified: incorrect selection of the adjusting half rings, damage to the bearing or its parts during installation, incorrect/ non-installation of the oil retaining ring (the consequence is oil starvation at the time of start-up), bearing damage during storage and transportation, installation of a poor-quality bearing, damage when connection with the power unit, the use of a shaft with deviations from the required dimensions (landing with excessive or weakened interference).

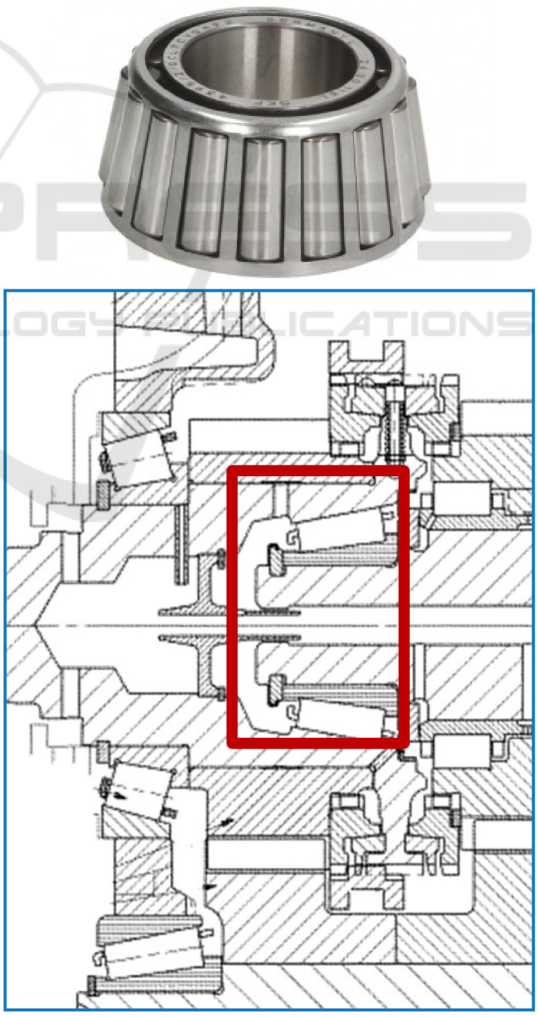

Figure 2: Output shaft bearing.

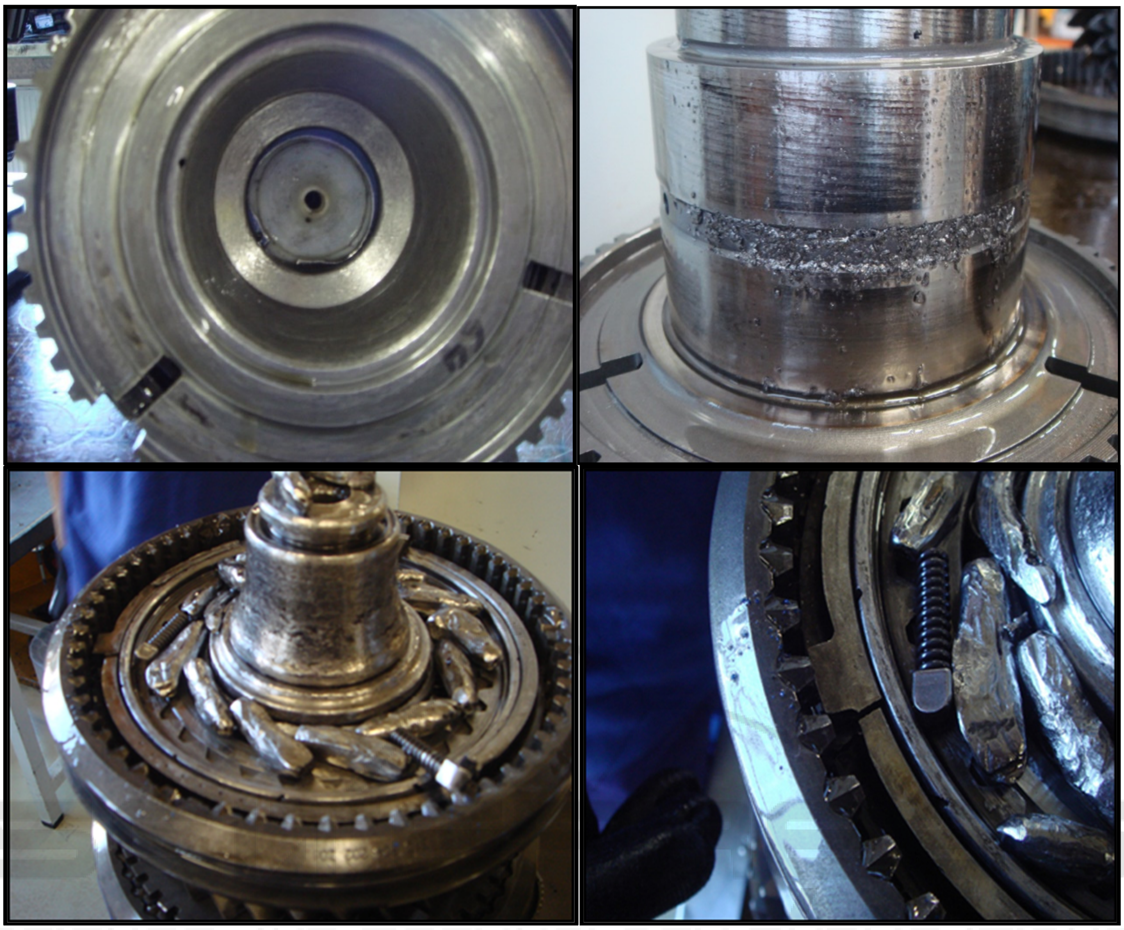

Figure 3: Types of the output shaft bearing destruction

An operational failure is a failure caused by a violation of established rules and/or operating conditions. Operational failures arise due to the use of facilities in conditions for which they were not intended, violations of operating rules (overloading, missing maintenance and repair, the use of non-compliant greasing substances, non-compliance with transportation and storage rules). For example, in case of maintenance violations, the gear box mean operating time between failures can be reduced by more than 3 times as a result of air with abrasive dust or moisture from the external environment entering the crankcase.

The operational reasons for the failure of the gearbox are the following factors: rolling, incorrect load orientation (engine braking), high-speed operation of the vehicle with low speed, violation of towing conditions, the use of non-recommended greasing substance.

The gearbox failure due to the bearing fault is a grouping feature. To compile a statistical series, the information was divided into n equal intervals. The number of statistical series intervals was determined by the formula of G.A. Sturgess:

$$n = 1 + 1{,}44\ln(N), \quad (1)$$

where N = 30 – number of elements in the statistical series.

$$n = 1 + 1{,}44\ln(30)=5{,}94=6$$

Interval length:

$$A = (t_{max} - t_{min})/n \quad (2)$$

where t_{max} and t_{min} — the highest and lowest reliability index values in the summary information table.

$$A = (91302 - 11206)/6=15029 \text{ km}$$

At the beginning of the first interval, the minimum mileage was taken, the results of the calculations are shown in Table 1.

Table 1: Calculation results.

Interval number, i	Lower bound, t_i	Upper bound, t_{i+1}	Middle of interval, t^*	Frequencies, m_i	Cumulative frequencies
1	1126,00	16155,34	8640,67	17	17
2	16155,34	31184,68	23670,01	8	25
3	31184,68	46214,02	38699,35	3	28
4	46214,02	61243,36	53728,69	0	28
5	61243,36	76272,70	68758,03	1	29
6	76272,70	91302,04	83787,37	1	30
Amount:				30	

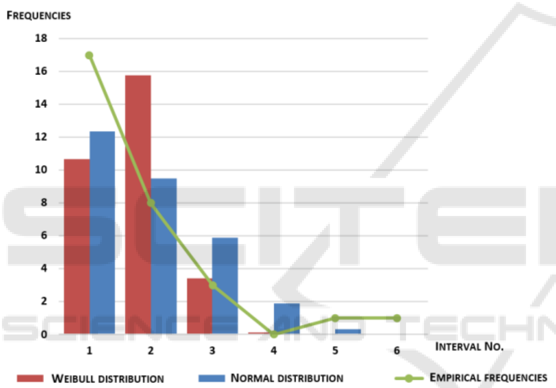

Figure 4: Theoretical and empirical fault distribution functions.

Based on the results of reliability analysis during the warranty period of operation and calculations on the output shaft bearing failure, it was established that the sample is subject to the normal distribution law.

3.2 Proposed Events to Improve Gearbox Reliability

3.2.1 A Design Modify

The bearing strength calculation showed that the durability and statistical carrying capacity of the output shaft front bearing are ensured. In the gearbox highest transmission, the gear ratio is equal to "1," i.e., the input and output shafts are locked by the fourth transmission synchronizer and rotate at the same angular speed, respectively, the bearing is at rest and in the absence of vibration, impact on the bearing is minimal. A different pattern is created during operation on the lower gears, namely when moving on the descent, at the moment when braking occurs, including due to the engine, the output shaft bearing takes maximum loads, taking into account the features of the distribution of forces in the oblique gear, at certain moments the loads on the bearing can be critical.

The Ecosplit gearbox lubrication system is designed in such a way that oil is supplied to the input shaft niche and the sliding surface of the divider gear through a hole in the oil bypass throttle, located offset from the output shaft rotation axis. Factors such as exceeding the maximum permissible engine speed, incorrect strategy for selecting gears of the main gearbox of the gearbox, erroneous shift of the demultiplicator gears can lead to oil starvation and bearing overload, and, as a result, to destruction and failure of the gearbox as a whole.

For this type of failure, researches were carried out and it was found that one of the reasons for the failure is a lubrication lack and high axial loads. According to the results, a change was introduced in the gearbox design: the diameter of the oil crossing hole in the throttle was increased from 2.0 to 2.5 mm, the purpose of which is to supply a larger volume of oil.

The expansion of the oil crossing hole diameter ensures the supply of more quantity oil, thereby ensuring the removal of heat from the friction parts and improving the lubrication process.

3.2.2 Replacement of Roller Radial Thrust Bearing

Based on the analysis carried out, it can be argued that the failure cause is operational factors, one of them is short-term dynamic overloads arising from a change in the direction of the power flow loading the roller cone bearing, for example, during engine braking. For vehicles operating in mountainous terrain, there is a variant of the gearbox with an intarder (hydrodynamic brake-retarder), which has proven itself as an auxiliary braking system, but the cost of vehicles with additional units is high and carriers, as a rule, prefer standard vehicles. For long-term operation in mountainous terrain with maximum load, drivers use engine braking at high speeds at the lower gears of the gearbox to unload the main braking system. As noted earlier, this process is accompanied by a maximum load of the gear box front bearings.

Vibration plays an important role in the failure occurrence. In the highest gear, the speed of the input and output shafts rotation is the same, that means the bearing does not rotate relative to the rolling elements, and in the presence of even slight vibration (for example, the effect of adhesion), small relative movements between the bearing rolling elements are generated and, under the influence of such a process, grooves are formed on the raceways over time. Considering the fact that the vehicle maximum operating time is carried out in the highest gear, the vibration effect can be critical. When the speed decreases, switching to lower gears occurs, the angular speeds of the input and output shafts rotation change, the bearing starts to rotate, and the presence of even a small depletion on the rolling elements can lead to rolling elements' sliding relative to the bearing rings without rotating the rollers, which leads to bearing seizure. As one of the solutions, to change the output and input shafts design, by analogy with the gearbox of the ZF Astronic and Traxon models, where this unit has a different design solution, and use two bearings: a cylindrical roller bearing for taking only radial loads and a support bearing for axial forces.

Such a design entails a change in the input and output shafts, the introduction of new parts and additional adjustment operations during assembly, an increase in the labor intensity and assembly operations time, therefore, will also lead to a significant increase in the gearbox cost.

3.2.3 Change of Lubrication System

For bearing failure-free operation, it is necessary to provide a bearing lubricating layer, which cannot occur if the greasing substance amount of is insufficient or the greasing substance has lost its lubricating properties. Under such conditions, metal contact occurs between the bodies and the raceways. At the initial stage, wear implements the lapping process: microscopic small roughness vertices formed during machining are cut and the rolling effect is achieved and the surface looks mirror smooth. With a lack of greasing substance, a significant increase in temperature occurs, which in certain situations can lead to bearing wedging. Additionally, with the lack of a lubricating layer, small cracks may appear on the rolling bodies surfaces, which increase rapidly during operation, preventing smooth rotation of the bearing. Such cracks accelerate the process of fatigue cracks formation under the raceways surface, reducing the bearing durability.

To ensure sufficient lubrication, it is proposed to change the lubrication system using a output shaft with minimal design changes: introduce two additional radial holes at the installation site of the internal bearing race, which will also prevent fretting corrosion.

The hydrodynamic mode disruption and the peak loads presence, possibly also a combination of both factors, can cause the loss of bearing and gearbox operability as a whole.

4 CONCLUSIONS

1. Based on the results of reliability analysis during the warranty period of operation and calculations on the output shaft bearing failure, it was established that failures are subject to the normal distribution law.
2. It was found that the most likely cause of the failure is short-term peak loads arising during operation, taking into account the peculiarity of the forces distribution in the oblique engagement.
3. An analysis of the bearing lubrication system showed that the existing lubrication system does not fully provide lubrication at peak loads and heat removal from the bearing rolling bodies. Two solutions are proposed: to change the assembly - to use two different bearing assignments, or to change the lubrication system in order to provide the necessary lubrication.

ACKNOWLEDGEMENTS

The reported study was funded by RFBR, project number 19-29-06008\19.

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