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Impact of exploitation conditions on the types of wear of the excavator slew bearing toothed race

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Abstract. Excavators as operating machines or equipment are exposed to diversetypes of undesired conditions, such as variable workloads, exposure to various environment conditions, unprofessional or imperfect maintenance and others. This paper demonstrates a case of anexcavator slewing ring failure which is investigated. The study suggests the failure to be caused by improper control and inadequate maintenance. The example is illustrated by photodocumentation with description of damage and probable causes in details. In conclusion, distinctive types of conditions are listed for consideration while selecting the appropriate bearing for certain type of load. Further, we outline the necessary conditions needed for maintenance and monitoring the slew ring during normal operations.

1. Introduction

During their exploitation, excavators are exposed to diverse types of loads that adversely affect the machine mechanisms and cause their wear and damage. In addition to the components that directly come in contact with the material and the base they work with (bucket, track chain and drive wheels), there are also components and mechanisms in the machine that are not in direct contact with materials but are also subject to wear and early failures. In such components and mechanisms, damages or failures occur due to the transfer of various loads in the form of variable forces and torques. The equipment manufacturers use modern automation systems and adequate engineering design to ensure maximum load control and monitoring of all the operating parameters that can affect the exploitation life of excavators. However, the improper use and handling of the excavator is often found in practice to be a significant cause of failure. Consequently, due to the frequent overloads of the machine, operators use methods which they find convenient, for instance simply turn off or even disable the signalling or warning devices to eliminate their interference during the work or operation. Consequently, the machine operates in an incorrect mode and becomes overloaded, resulting in early failures of some or most of the excavator mechanisms. Another critical factor noted is the quality of the maintenance of excavator components. Quality expected maintenance involves regular lubrication, monitoring of the wear condition, and appropriate replacement or repair of components or mechanisms, so that they can achieve their maximum useful lifetime in operations. While operating excavators and other machines, the quality of maintenance greatly affects the lifetime of certain components or mechanisms, which relates to any machine, especially excavators. Here in this study, an example from the practice is presented, where inaccurate maintenance and improper handling caused one of the vital components of the excavator - the slew bearing to fail. Additionally, we illustrate how the toothed race got worn and broken from the interior of the bearing, whose purpose is to enable the rotation of the work mechanism of the excavator (the cab, the engine, the work part of the arm with the bucket) in relation to the drive mechanism (track chain).

2. Main causes of wear of the slew bearing and the toothed race

In the design of machines, such as excavators, the choice of the slew bearing is not only based on the values of the bearing the static and dynamic load capacity in relation to the actual loads to which they will be exposed, but also on the requirements regarding the reliability and expected useful lifetimeexploitation of the bearing. Normally, the bearing static and dynamic load values are adopted from the manufacturer's specification tables for respective bearings. The real loads to which the excavator will be exposed must be considered in a distinctive way, where the following essential factors should be observed:

- Type of application
- Loads acting on the bearing
- Torque applied to the gear.
- Frequency of oscillating movements
- Bearing size most suitable for the application

Figure 1 shows the load distribution diagram for the excavator with the essential parameters necessary for the basic calculation of the real loads, which are used for the proper selection of bearings.

2.1. Determining bearing loads

Excavator manufacturers give certain load diagrams which indicate the bearing load / excavator arm load ratio, where the forces and torque that the excavator can withstand are defined. This is essential to avoid the overload of the critical components of the excavator (work arm, bucket or pick-up arm, slew bearing). In order to avoid the overload, it is indispensable to determine possible loads in terms of forces and torques, which result from the weight of the work components of the excavator (bucket, work arm, the cab and engine parts of the excavator, counterweight), as well as from the inertial forces that are either known or can be calculated, depending on the specific use of the excavator (type of use, frequency of oscillatory motion).

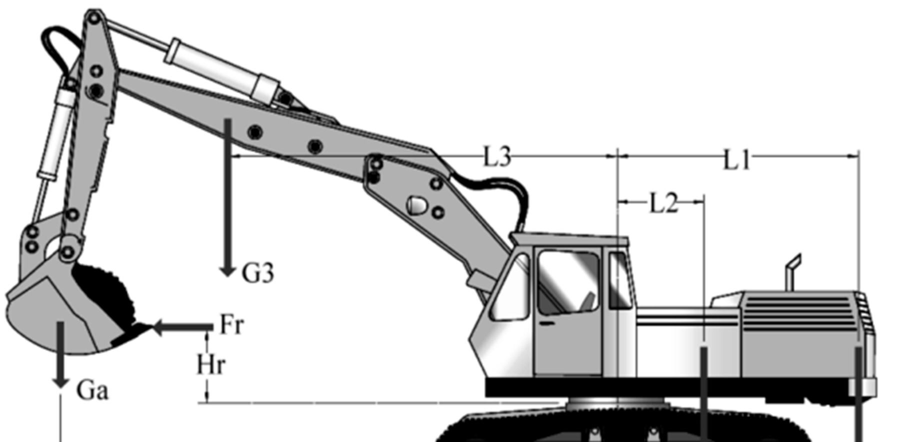

Figure 1. Load distribution on excavator.

According to Figure 1, the calculation of the resulting loads and torque acting on the excavator bearing can be performed by the following equations [1]:

$$F_a = G_a + G_1 + G_2 + G_3 \quad \text{– for the resulting force} \tag{1}$$

$$M_t = G_a \cdot L + F_r \cdot H_r + G_3 \cdot L_3 - G_1 \cdot L_1 - G_2 \cdot L_2 \quad \text{– for the resulting torque} \tag{2}$$

Where are:

F_a – resulting axial load applied to the slewbearing,	[kN];
F_r – external radial load applied to the slewbearing, e.g. work/wind force,	[kN];
G_a – liftingload,	[kN];
G_1 – weightfraction 1, e.g the counterweight	[kN];
G_2 –weight fraction 2, e.g. the weight of the cabin	[kN];
G_3 –weight fraction 3, e.g. the weight of the boom,	[kN];
H_r– distancefrom the bearing centre point to the line of action of the radial force Fr,	[m];
L –distancefrom the centre of rotation to the centre of the lifting load,	[m];
L_1– distancefrom the centre of rotation to the centre of gravity of the weight fraction 1,	[m];
L_2– distancefrom the centre of rotation to the centre of gravity of the weight fraction 2	[m];
L_3– distancefrom the centre of rotation to the centre of gravity of the weight fraction 3	[m];
M_t– resultingtilting moment acting on the bearing	[kNm].

When doing the calculation, the variation of the distances L, H_r and L_3 should be taken into account, and if the variations are found to be drastic in relation to the calculation, it will be mandatory to take the maximum values of the distances so that the maximum value of the torque M_t can be calculated.

Radial load F_r is not taken into account for values ≤ 5% in relation to axial load F_a. In case of maximum loads F_a / F_r = 0.6, the calculation of the support angle must be taken into account and a specific calculation must be performed. In standard use of excavators, radial forces are limited exactly by these relationships in order to avoid overloads of the slew bearing as well as of other work components of the excavator.

2.2. Determining bearing load in relation to the type of use

After determining the static load values in terms of forces and torque, it is essential, when selecting a particular type and size of the bearing, to carry out a certain correction of the force and torque values to which the bearing will be exposed in exploitation. Anticipation of certain types of loads, to which the excavator and the bearing will be exposed, depends on the type and mode of operation of the machine, as well as on the relationship of the lifetime and reliability of the bearing. Based on their deep experimental experience, the bearings manufacturers have compiled the tables with the load correction factors k_L in relation to the use of bearings in certain types of machines - Table 1.Based on the correction factors, the values of the resulting load force F_a and the heeling moment M_t are corrected.

Table1. Correction factor of loadk_L [1, 2].

Application	Load factor k_L	Service time in full load revolutions
Mini excavators	1.33	150.000
*Main slewing gear of bucket wheel excavator	2.15	300.000

*In these applications, the operating conditions, particularly the operating time and the loads during the slewing process, vary considerably. Infrequent slewing motions, e.g. occasional positioning for certain jobs, may permit a rating on static criteria alone. On the other hand, continuous rotation or oscillating motions will require a rating on the basis of service time criteria. Selections based on service time may also be required if the bearing carries out relative movements, which is often the case with the discharge boom conveyors in bucket wheel units.

$$F_{ar} = k_L \cdot F_a \tag{3}$$

$$M_{tr} = k_L \cdot M_t \tag{4}$$

Where are:

F_{ar}– maximumrated axial load,	[kN];
F_a– resultingaxial load applied to the bearing,	[kN];
M_{tr}– maximumrated tilting moment,	[kNm];
M_t– resultingtilting moment acting on the bearing	[kNm];
k_L – load factor (see Table 1)	[–].

Based on the calculated maximum load values of the axial force and torque, the slew bearing is selected from the respective diagrams of the bearings manufacturer, taking into account that the bearing load curves and screw load curves meet the calculated values.

2.3. Improper operation of the machine

In case the purpose of the machine is changed, that is, if it is exploited under different conditions in relation to the normal conditions of exploitation, certain problems will occur, mostly in the form of wear and later even the failure of the worn components. Regarding excavators, it is necessary to observe the load diagrams recommended by the manufacturer. Figures 2 and 3 show a diagram of the load capacity of the excavators designed to be used at railway construction sites, with arms equipped with clamps. The excavator main drive is on wheels, with the attached auxiliary wheels for movement and work on the railway.

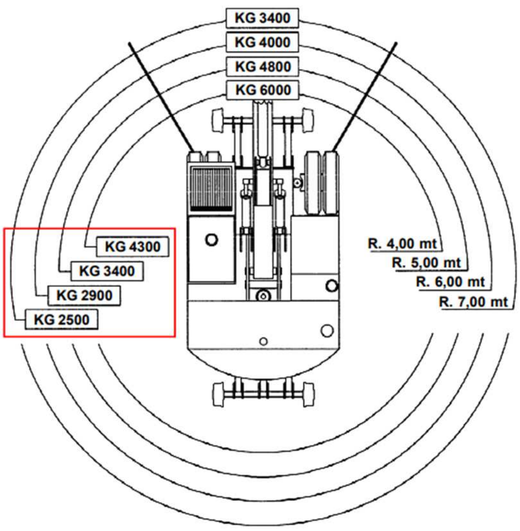

Figure 2. Maximum loading capacity diagrams – on wheels [3].

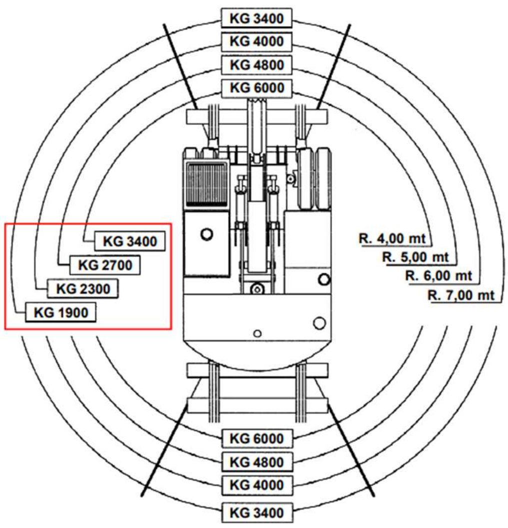

Figure 3. Maximum loading capacity diagrams – on rails [3].

The loads shown in Figures 2 and 3 are more related to the problem of stability, which is best illustrated in Figure 3, where the load capacity of the excavator, when working on the railway, is drastically reduced when the load is being lifted along the sides of the excavator.

Figures 4 and 5 show an overview of the dimensions and the maximum arm capacity of the excavator on which the slew bearing has been disassembled and the problems of the wear of the raceway and gears detected. Table 2 shows the basic technical characteristics of the excavator related to the loads.

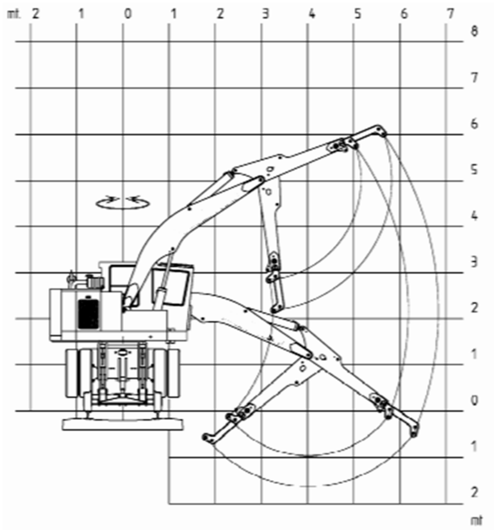

Figure 4. Maximal hand grip excavator [4].

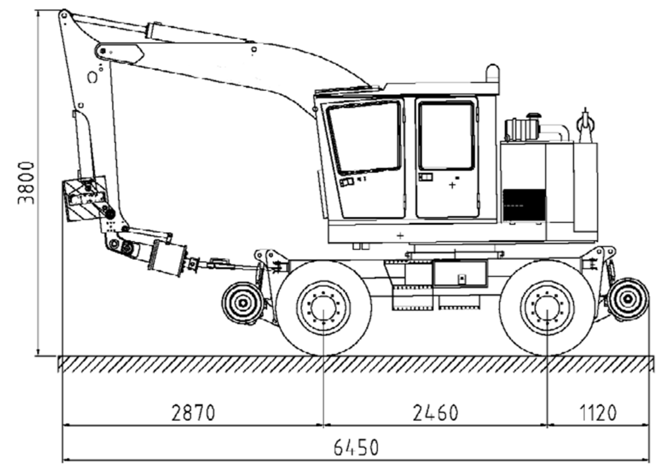

Figure 5. Dimensions of excavators [4].

Table 2. Technical characteristics of excavators [5].

Performances	Unit	Quantity
Max. capacity on plain road	kg	4.300
Max. capacity on plain railway	kg	3.400
Max. surmountable slope on road	%	62
Max. surmountable slope on railway	%	40
Max. tractive effort on road	N	129.600
Max. tractive effort on railway	N	81.000
Total machine weight in work configuration	kg	16.500
Maximum range radius of the boom	m	6.9

Figure 6 shows the slew bearing mounted on the excavator, while Figure 7 shows the cross-section of the bearing. After the slew bearing was been disassembled, as shown in Figures 8 and 9, numerous damages to the teeth of the toothed race, located on the interior of the slew bearing, were identified.

Figure 6. Mounted slewing bearing.

Figure 7. Cross-section double row ball slewing bearing with an internal gear.

Figure 8. Damaged teeth on a toothed ring of a slewing bearing.

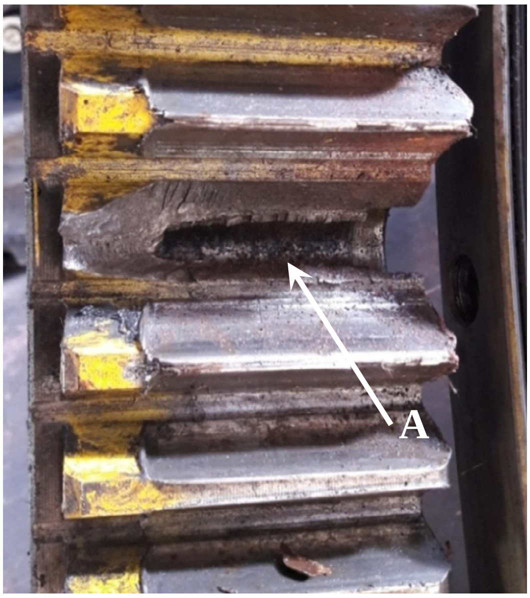

Figure 9. Broken tooth of slew bearing – section A.

The visible damages shown in Figures 8 and 9 are the consequence of the action of two basic forms of wear:

- abrasive wear - the exposure of the gears to the abrasive action of solid particles from the environment in which the excavator operates (dust, sand);
- fatigue wear of the material - teeth exposure to very high and variable cyclic loads that caused the wear of the teeth and fatigue of the tooth material.

It was also found the process of wear was additionally propagated by the small - insufficient quantity of grease, which indicates that the toothed race was inadequately lubricated and maintained. Figures 10 and 11 show the base of the broken tooth and the worn surrounding teeth, which confirms the progressive action of the abrasive wear along with the fatigue wear of the material. Based on the Figures shown, it can be concluded that improper handling of the excavator (operation with frequent overloads) and inadequate maintenance, resulted in an advanced wear and breakage of the teeth of a toothed race.

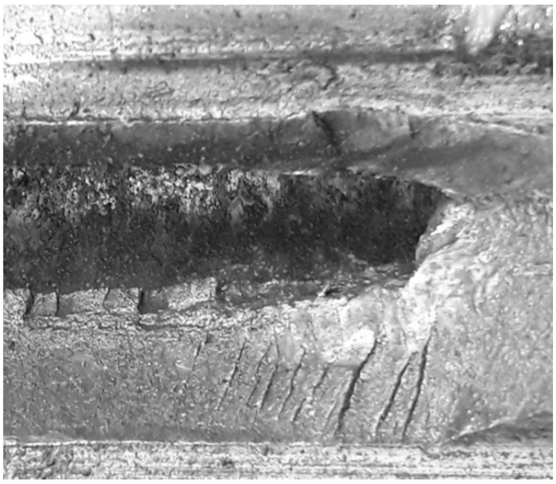

Figure 10. Fracture point - fatigue wear.

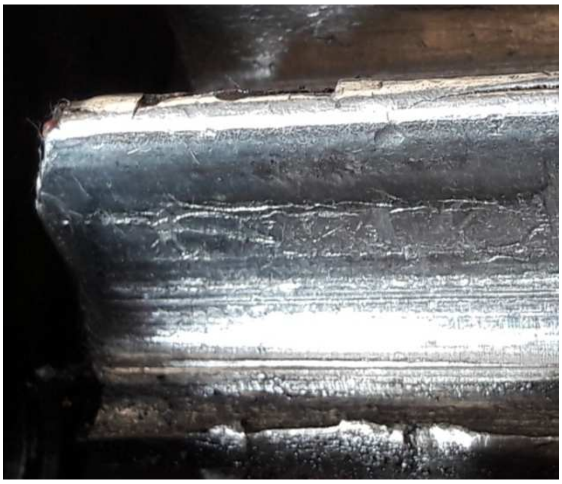

Figure 11. Surface of the tooth - abrasive and fatigue wear.

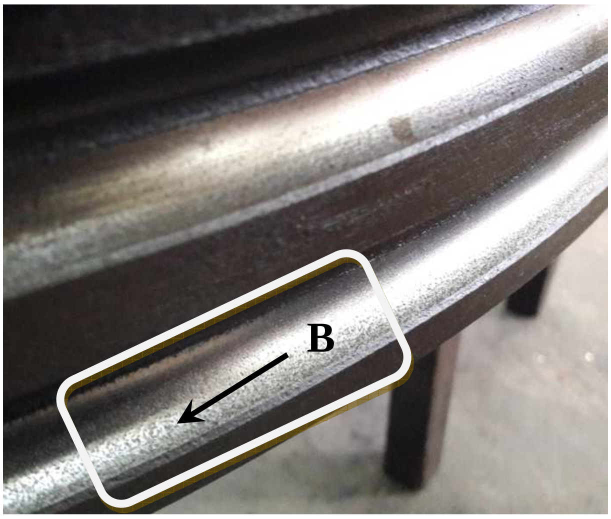

Figure 12. Fatigue wear – pitting.

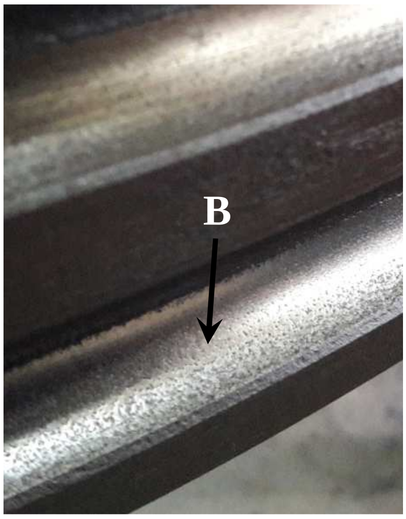

Figure 13. Surface of the rolling trail – pitting.

On the other hand, investigation of the bearing interior that is the raceway as shown in Figures 12 and 13, it depicts the consequences of the surface fatigue of the material or pitting are seen. Pitting is known to be the consequence of action of excessive pressures in contacts between the surfaces, as it was the case here - the contact of the balls – the raceway in the slew bearing. Additionally, pitting is the result of action of higher shear loads, i.e., cyclic loads, which often occurs in the contact of the tooth pairs, in this case, the contact between the toothed race and the drive gear. Tooth pairs with flat teeth are especially prone to pitting due to cyclic overload and poor lubrication, creating conditions for the occurrence of all three types of pitting: initial, medium and advanced. As far as the raceway is concerned - Figures 12 and 13, the emergence of pitting is a consequence of the operation of high pressure loads, with the reduced presence of grease, that is, insufficient bearing lubrication. If the bearing had been properly lubricated, the impact of high contact loads and pressures, which cause the change in the surface structure of the material and its wear in the form of small flakes, i.e. pitting, would have been reduced.

3. Reducing potential damage of the slew bearing and toothed race

To avoid possible damage and failure of these components, it is imperative to provide adequate maintenance. The maintenance of the critical components of the excavator, which requires the involvement of the excavator operator, can be reduced by simple automation of the lubrication system, not only for this slew bearing, but also for other critical components in the excavator. There are solutions that ensure lubrication is performed on the bearings at the right time and right quantity. One of the solutions is to employ a centralized lubrication system (CLS) for grease lubrication - a progressive lubrication system consisting of a pump, a primary grease divider and secondary grease divider that are connected to the lubrication points, see Figure 14. These systems provide the possibility of injection of the precisely calculated amount of grease required to respective bearings of journal requiring lubrication. In this way, lubrication is achieved at certain time intervals and exact quantity of grease dispensed in to the bearing.

The second solution is a single-line lubrication system (Figure 15), which, in contrast to the progressive system, considers the possibility of more precise dosing, where each lubricant-metering device serves only one lubrication point. The disadvantage is that the metering valves - injectors can block due to elevated temperatures and impurities, so their lubrication function fails. By using modern diagnostic systems, however, this disadvantage can be avoided because diagnostic devices are able to indicate whether the lubrication has been performed well on the component by the valve.

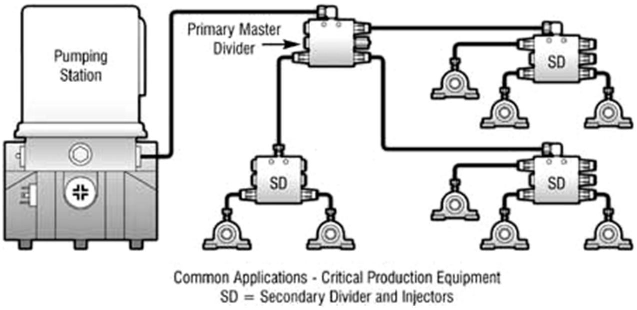

Figure 14. Progressive lubricant system.

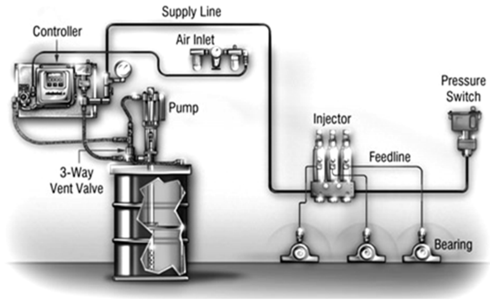

Figure 15. Single-Line lubricant system.

The solution for the toothed race lubrication is based on the use of polyurethane gear which is installed on the excavator structure and coupled with the toothed race. It performs the lubrication with grease by dosing the grease through a single-line of the above-mentioned systems – Figure 16.

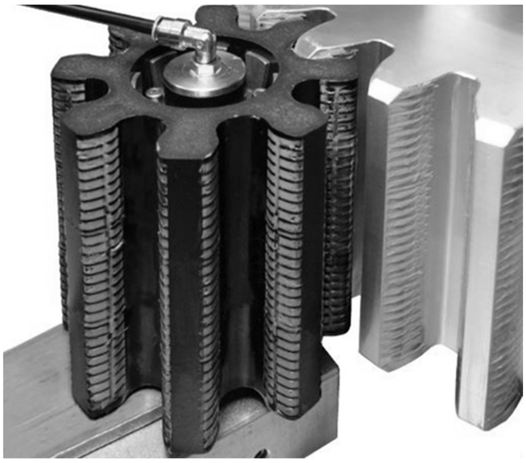

Figure 16. Polyurethane (PU) lubrication pinion [6, 7].

Taking into account that the price of a new slew bearing with a toothed race for the shown excavator ranges from EUR 2,000 to EUR 9,000, depending on the quality and the manufacturer, the investment of EUR 1,500 ÷ EUR 2,000 for simple lubrication systems is not a considerable investment and it provides a quality and long-lasting solution in terms of maintenance. In this way, the occurrence of certain types of wear, such as fatigue, will be minimized, provided that the maximum permissible load of the excavator for the specific use is respected. In addition to lubrication, the effects of abrasive wear on the gears of the toothed race can be reduced by periodic cleaning and washing of the gears to remove impurities, which requires the involvement of manual work of an operator or a person involved in the machine maintenance. Moreover, use of the CLS will reduce the human interface with the bearing which min most of the times introduces dirt and dust hence considerable reduction of abrasive wear can be achieved.

4. Conclusion

In this paper, an example of the impact of the exploitation conditions on the wear of the toothed race and the slew bearing of an excavator has been presented. In addition to exploitation conditions, the wear may also be caused by other factors that occur during the excavator operation, depending on the design of the excavator, the type of use, potential occurrence of vibration loads (excavator operation with a hydraulic hammer, etc.), types of loads and torques acting on the excavator, slew bearings, gears, etc. Obviously, this paper has only touched the problematic of the excavator exploitation depending on certain exploration conditions. In respect of the presented example of the excavator, intended for use on railway construction sites, the problem of the occurrence of certain types of wear of the slew bearing and the toothed race of the excavator has been studied. Additionally, certain solutions have been proposed for the observed types of wearing that are cost-effective compared to the replacement of the whole set of the slew bearing and toothed race, whose implementation provides longer operation lifetime of the slew bearing and the toothed race.

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