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## INTEGRITY OF GEAR TRANSMISSION UNITS INDICATED BY RELIABILITY FOR DESIGN INTEGRITET ZUPČASTIH PRENOŠNIKA SNAGE PRIKAZAN KROZ POUZDANOST ZA DIZAJN

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### Keywords

- planetary gear transmission units
- reliability for design
- bucket wheel excavator
- property based design

### Ključne reči

- planetarni zupčasti prenosnici
- pouzdanost za dizajn
- rotorni bager
- dizajn zasnovan na svojstvima

### Abstract

*Reliability for design is defined in the form suitable for design parameters definition and it can also be a specific indicator of component integrity in exploitation conditions. Service life of gear unit component is limited by failure of function indicated by minimal elementary reliability for design. This reliability presents a feature of gear unit component and design constraint. Integrating the elementary reliabilities of components into the gear unit reliability structure provides overall unit reliability which is the indicator of gear transmission units quality and integrity.*

*The aim of the study is to present the integrity of planetary gear transmission unit using it in the case of bucket wheel excavator traction group. We will also explain and promote the new term Reliability for Design in the form of the indicator of gear unit integrity.*

### Izvod

*Pouzdanost za dizajn definisana je u formi koja je pogodna za definiciju parametara i takođe može biti specifičan pokazatelj integriteta komponenata tokom eksploatacije. Radni vek komponenata zupčastih prenosnika ograničen je razaranjima za koja je elementarna pouzdanost za dizajn najmanja. Ova pouzdanost predstavlja osobinu komponente zupčastog prenosnika i konstrukciono. Integrisanje elemenarnih pouzdanosti komponenata u strukturu pouzdanosti zupčastog prenosnika obezbeđuje ukupnu pouzdanost koja je pokazatelj kvaliteta i integriteta zupčastog prenosnika.*

*Cilj rada je prikaz integriteta planetarnog prenosnika na primeru planetarnog zupčastog prenosnika za pogon rotora rotornog bagera. Novi termin „Pouzdanost za dizajn“ takođe će biti objašnjen i promovisan u obliku pokazatela integriteta zupčastog prenosnika.*

components will use almost all their resources. Benefits of replacing components at the same time reflects on the reduction of maintenance cost of machines and the production failure costs.

As consequences of negative effects and transmission unit integrity limitation is the result of possible failure of transmission unit components: gears, bearings, shafts and shaft joints, gaskets, etc. Possible failures of gear teeth are numerous and they may be micropitting, pitting, spalling, scuffing and the combination of these effects [4-7]. The gear tooth failure process is usually a combination of these effects. Bearings can fail in function of various forms, predominantly in contact with surface wear. Shafts can fail in function by fretting at contacts, worn-out gaskets, etc. All of the mentioned possible failures are the result of stochastic exploitation conditions and also of stochastic failure process. These are the main reasons that gear drive units fail. Integrity is the result of complex combination of the mentioned effects.

Integrity of the gear transmission unit has to be defined by the probabilistic indicator such as the reliability with specific features and with a specific way of foundation. This is the *Reliability for Design* based on the *Elementary Reliability* in relation to a certain failure of the design

### INTRODUCTION

Many advantages are connected to gear traction units, especially to gear units based on planetary transmission principle. Some of the advantages are the reliable transmission ratio, the very high load capacity per unit volume, the applicability in wide range of load power and the fields of use. But also they have some disadvantages such as the permanent transmission ratio, the limited service life, the decrease of reliability and the increase of noise and vibrations in the course of service life and similar disadvantages. These negative effects can be reduced by a selection of suitable design parameters [1]. Selection of appropriate oil characteristic can improve gear durability by achieving proper film thickness [2], which will have a positive effect in reducing gear wear. Researchers constantly work on improving solutions of vibro-diagnostic monitoring systems for rotary equipment in order to prevent failures [3]. There are many other ways to reduce negative effects or prevent failure accidents of gear's surface-to-surface contact, but it is not possible to completely eliminate the negative effects. Similar situation is with other components of gear units. A suitable solution for this problem is to purposefully adjust all components to fail at the same time. That way all of the

component. Elementary reliability in this sense is the result of impact relation between the service load probability and the component failure probability.

In the case of gear flank failure, elementary reliability ( $R$ ) is a complex load probability ( $p_i$ ) (caused by operating stress  $\sigma_{Hi}$ ) and failure probability for occurred stress ( $P_{Fi}$ ). The opposite of reliability is unreliability ( $F_p$ ). Equations for the representation of reliability are as follows, /8/:

$$R = 1 - F_p; \quad F_p = \sum_{i=1}^n p_i P_{Fi}; \quad p_i = \frac{n_{\Sigma i}}{n_{\Sigma}}; \quad P_{Fi} = 1 - e^{-\left(\frac{\sigma_{Hi}}{\eta_i}\right)^{\beta_i}} \quad (1)$$

Weibull's function integrates the stress level and the number of cycles for that stress level in order to get the failure probability for certain combinations of the stress-cycle number (Fig. 1).

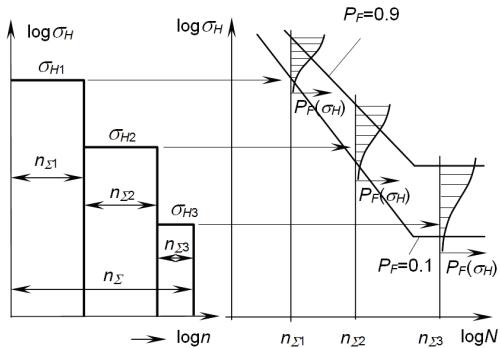


Figure 1. The relation between the operating stress spectrum and the probability of gear teeth failure, /8/.

Slika 1. Odnos spektra radnog napona i verovatnoće razaranja zubaca zupčanika, /8/

A part of "Design for X" /9/ models in technical system design methodologies is "Design for Reliability". Technical system monitoring during exploitation will collect important information for future "Design for Reliability" applications. Even if gear units are not a subject of particular investigation, it is possible to consider them in a broader approach through broader technical system monitoring. Many researches are oriented to gear, bearings, gear unit and other failures in gear transmission units, /10-23/. A lot of research papers treat reliability only in the sense of maintenance instead of improving the future design of it. In order to avoid misunderstandings caused by the above mentioned type of approaches it is essential to establish a new specific approach "Reliability for Design".

#### ELEMENTARY RELIABILITY FOR THE DESIGN OF THE PLANETARY GEAR SET

Possibilities of failure in gear units are various and can include failures of all components: gears, bearings, shafts, gaskets and other connections. Failures can be divided into two groups: accidental failures and failures as a result of a permanent process in the course of exploitation such as fatigue and wear. The subject of this discussion is the second group, especially failures caused by wear processes.

Gear flank wear is the consequence of contact either by rolling or sliding the surfaces, or in most cases the combination of these two. Any of these types of surface contacts

cause wear of the surface. Possible wearing off of the gear flank are micropitting, pitting, spalling and scuffing, /24/. They often appear in combination and the process of wear is random. Depending on many characteristics such as the type of material, surface hardness and roughness, lubrication, loads, mesh frequency, depends on the type of the wearing-off process. The type of gear connections and gear unit (transmission) concept has also a significant effect on the failure process. For further analysis we have chosen the planetary gear unit for rotor traction of the bucket wheel excavator – BWE. In Fig. 2 we present the 3D model of the last stage of this unit and a 2D model of the planetary gear mesh.

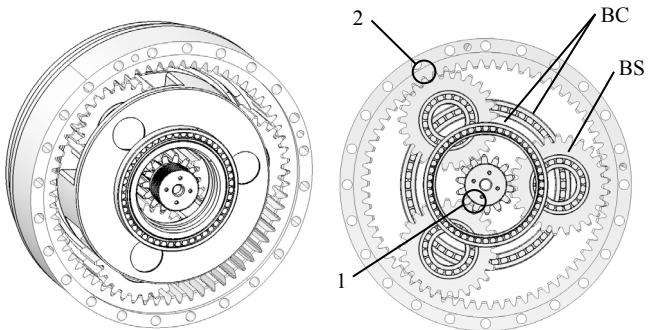


Figure 2. Scheme of the last planetary gear set.  
Slika 2. Shema poslednjeg planetarnog seta

The planetary concept of gear mesh contains two types of teeth connections: pinion – the satellite connection – 1 and other ring – the satellite gear – 2. Comparing these two contacts, contact 1 is exposed to higher Hertzian stress and in the course of the time it has more changes of stress i.e. the stress cycle number.

The calculation of elementary reliability for the design of gear teeth contact 1 (Fig. 2) according to the model presented by Eq.(1) and in Fig. 1 for the BWE is as follows. In Figure 3 we present the Load spectrum, determined by measurement and by assessment, and the combination of operating conditions. Load spectrum is formed for output shaft torque  $T$  and for the block of  $10^6$  shaft revolutions. In the case of BWE heavy regime a high participation of high loads dominates. In Fig. 3 we present the middle regime with less participation of high loads as well.

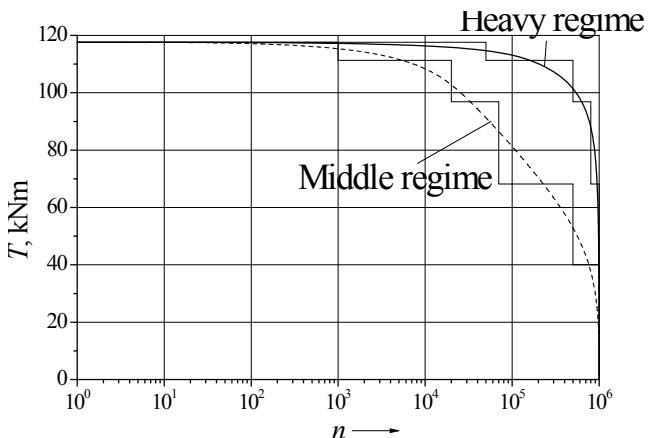


Figure 3. Load spectrum range of bucket wheels.  
Slika 3. Opseg spektra opterećenja rotora sa vrednicama

Failure probability distribution is the result of tests for certain gear material and the hardening method. In Fig. 4 we present the range of failure probability for the central pinion in Fig. 2. The range is bounded by lines for failure probability  $P_F = 0.1$  and for  $P_F = 0.9$ . Figure 4. presents every stress level and stress cycle number of the central pinion teeth, from the presented spectrum, along 10 years of exploitation. Using stresses (endurances) from this diagram, for  $P_F = 0.1$  and  $P_F = 0.9$ , parameters  $\eta$  and  $\beta$  of Weibull's distribution function are calculated and presented in Table 1.

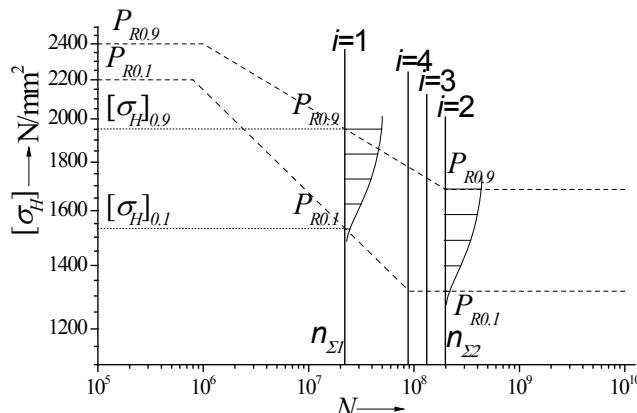


Figure 4. Wear probability distribution of carbonized tooth flanks for the number of stress cycles during 10 years service life.

Slika 4. Raspodela verovatnoće razaranja cementiranih bokova zubaca za broj ciklusa tokom 10 godina rada

In Table 1 we present the results of elementary reliability for central pinion of last planetary set of the BWE traction unit, calculated according to Eq.(1).  $P_{Fi}$  represents the elementary reliability for certain stress level and its number of cycles to failure. Participation of certain stress in the load spectrum is included by factor  $p_i$ . The sum of all products of  $P_{Fi}$  and  $p_i$  is the elementary unreliability  $F_p = 0.206$ , and the reliability is  $R = 0.794$ .

Table 1. Wear unreliability calculation of central planetary pinion (heavy service regime in duration of 10 years).

Tabela 1. Proračun verovatnoće razaranja centralnog zupčanika (težak radni režim tokom 10 godina)

$i$	1	2	3	4
$T$ (kNm)	117.6	111.3	96.9	68.2
$\sigma_{Hi}$	1511.2	1470.1	1371.9	1150.9
$n_{\Sigma i}$	$2.2 \cdot 10^7$	$1.98 \cdot 10^8$	$1.32 \cdot 10^8$	$8.8 \cdot 10^7$
$[\sigma_H]_{0.1}$	1532	1315	1315	1318
$[\sigma_H]_{0.9}$	1952	1687	1733	1779
$\beta(\sigma_{Hi})$	12.73	12.38	11.17	10.28
$\eta(\sigma_{Hi})$	1828.2	1577.1	1608.4	1640.4
$P_{Fi}(\sigma_{Hi})$	0.08473	0.34229	0.15561	0.02580
$p_i = n_{\Sigma i} / n_{\Sigma}$	0.05	0.45	0.3	0.2
$p_i \cdot P_{Fi}(\sigma_i)$	0.0042365	0.1540305	0.046683	0.00516

The second most important components in planetary gear sets are bearings. Two groups of bearings are dominant in planetary gear sets: bearings for satellite gears (BS, Fig. 2) and bearings for satellite gear carriers (BC, Fig. 2). A large number of bearings are used in planetary gear sets. Various effects can cause failure of bearings. In the case of

BS-bearings, reduced design space causes the increase of the bearing load and the reduction of bearing service life. Additional effects can be the metal particles from the damage of bearings and other components, assembly mistakes, problems with lubrication and cooling, etc. Bearings for the satellite gear carrier are not highly loaded because forces in planetary sets are balanced.

Gaskets at input and output shafts are components that periodically have to be replaced. Damage of gaskets can cause penetration of impurity in housing. These impurities will cause damage to gears and bearings. Failure probability and elementary reliability of gaskets is also defined by Weibull's distribution with parameters connected to the shaft revolution in the course of service life.

#### GEAR UNIT INTEGRITY INDICATED BY RELIABILITY FOR DESIGN

The term *gear unit integrity* presents the ability of every unit component to carry out the corresponding function with acceptable level of failure. When the level of failure becomes a non-acceptable level, such as the stricken wear process or component fracture, the structure will fail. Since these processes are stochastic in terms of operating conditions and failure processes, as well as in the terms of the complexity of structures (large number of parts), reliability is imposed as a convenient indicator of the integrity. For this purpose it is necessary to define the term of component failure (disintegration) and probability level which indicates the disintegration.

Every design structure including gear transmission structure consists of components which have to be completely replaced when the system is disintegrated. These components can be at the level of machine parts or at the level of more and less complex assembly. Many and various failures are possible in all of them. Elementary reliabilities in relation with these failures have various levels and various trends of a decreasing service life. The minimal elementary reliability related to a certain failure at the end of service life is an indicator of this component integrity.

In the case of the planetary gear set (Fig. 2) the elementary reliability in contact 1, especially of the central pinion is less than in contact 2, i.e. satellite gears and toothed ring. When one gear in the gear set has a failure in function, the whole set of gears needs to be replaced. This is the reason that the elementary reliability of the central pinion indicates durability and integrity of gear for the complete planetary set.

Another important component for planetary gear unit integrity analysis are the bearings of satellite gears. It is necessary to underline two important facts in relation to these bearings. The first is that the space for these bearings is not sufficient and service life has to be shorter compared to the service life of gears, i.e. central pinion. In Fig. 5 we present the relations between the decrease in elementary reliability of the central pinion and satellite bearing. These bearings need to be replaced when the resource of the elementary reliability (integrity) expires. The second fact is that these resources do not expire at the same time. In order to avoid exploitation downtime, it is necessary to replace all of these bearings when the first fails.

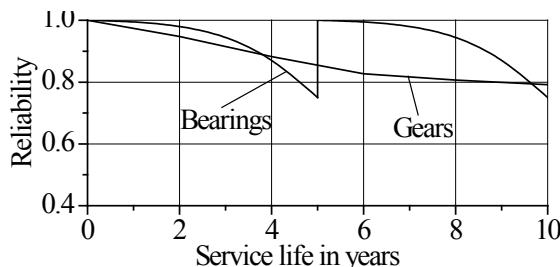


Figure 5. The decreasing trend of reliability during the service life for various components.

Slika 5. Trend smanjenja pouzdanosti tokom radnog veka za različite komponente

Overall system reliability determined by equalized elementary reliabilities of the decomposed system, is the indicator of system integrity. Main design constraints are: the desired overall reliability of the gear unit, and the equal or similar resources of elementary reliabilities (integrities) of components. When these resources are not equal at the end of the service life, some of the components are not completely used.

## CONCLUSION

The reliability of technical systems is a well-known term and subject. This article introduces a new aspect of the reliability definition and application. The new term is *Reliability for Design* and it is related to the probability of certain failure in the course of exploitation, i.e. operating conditions. This is a very important constraint in selecting design parameters in order to fulfil the desired reliability. This is also the basis for integrity indication of complex systems such as gear transmission units. In this study in a form of a case study, one stage of the planetary gear unit for the BWE traction is presented.

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