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THE ANALYSIS OF FAILURE OF DRIVING REDUCER FOR BUCKET WHEEL EXCAVATOR DIGGING SUBSYSTEM

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Abstract: *Bucket wheel excavators for continuous exploitation belong to the modern, complex and expensive production systems, manufactured in small series or individually for certain operating environment. During exploitation of bucket wheel excavators, as an effect of variable amplitude loading induced by working conditions and their own low-frequency oscillations, unpredictable failures (damages and fractures) of main parts and assemblies may occur. In this paper, the methodological approach to the analysis of failure of the digging subsystem has been presented with particular attention turned to the driving reducer for bucket wheel. The possibility of application of experimental methods in an analysis of condition of the main parts and assemblies in exploitation and failure analysis has been presented, together with the possibility of application of the methods in failure analysis from the point of view of evaluation of the system reliability (FTA method – Fault-Tree Analysis, FMEA method – Failure Mode and Effects Analysis). The measures for prevention of damages and fractures of the main parts and assemblies of the driving reducer have also been presented.*

Keywords: *bucket wheel excavator, experimental analysis of failure, FTA method, FMECA method, prevention of failure*

1. INTRODUCTION

The size, design and structure of the bucket wheel excavators mainly depend on required capacity, mode of material loading and specific conditions of an excavation site (worksite stability, strength of stone mass, allowable loading of the ground). Having in mind that nowadays there is a series of different types of bucket wheel excavators differing in bucket-wheel diameter, number and shape of showel on working wheel and length of working boom.

The loading of the main parts and structural components of the bucket wheel excavators cannot be expressed in a form of a simple mathematical function, i.e. it cannot be completely represented by a model in which the variables and parameters are uniformly varied under working conditions, as such a model should predict a series of approximations caused by real conditions of manufacture and exploitation.

Based on the above mentioned, it becomes obvious why new trends in research of integrity and reliability of continuous production systems such as the belt conveyor - based on the failure analysis, are aimed at making the field of research narrower – from level of a system to level of a subsystem (for details see [1].). The researches relate to the study of parametric reliability, i.e. establishment of dynamic loading, wearing, aging and as a consequence destruction.

2. METHODOLOGICAL APPROACH TO THE ANALYSIS OF DAMAGE AND FRACTURE

Premature fracture or damage of the parts and structural components is caused by simultaneous effects of a large number of technological, metallurgical, structural an exploitation factors.

Some important information on improvement of the main parts and components of supporting structures, improvement of properties of the existing materials and technologies for their treatment and development of new materials are obtained from the analysis of damages and fractures of the parts and components of supporting structures, see [2-4]. The analyses of damages and fractures provide the possibility of development of new technical solutions and methods of testing already in the prototype phase. The analysis flowchart is shown in Fig. 1.

The data on loading, properties of a base metal and its welded joints, technology of manufacture, technical and physical properties of reported fractures and predicted preventive issues related to damages and destruction are entered into a database, see [4].

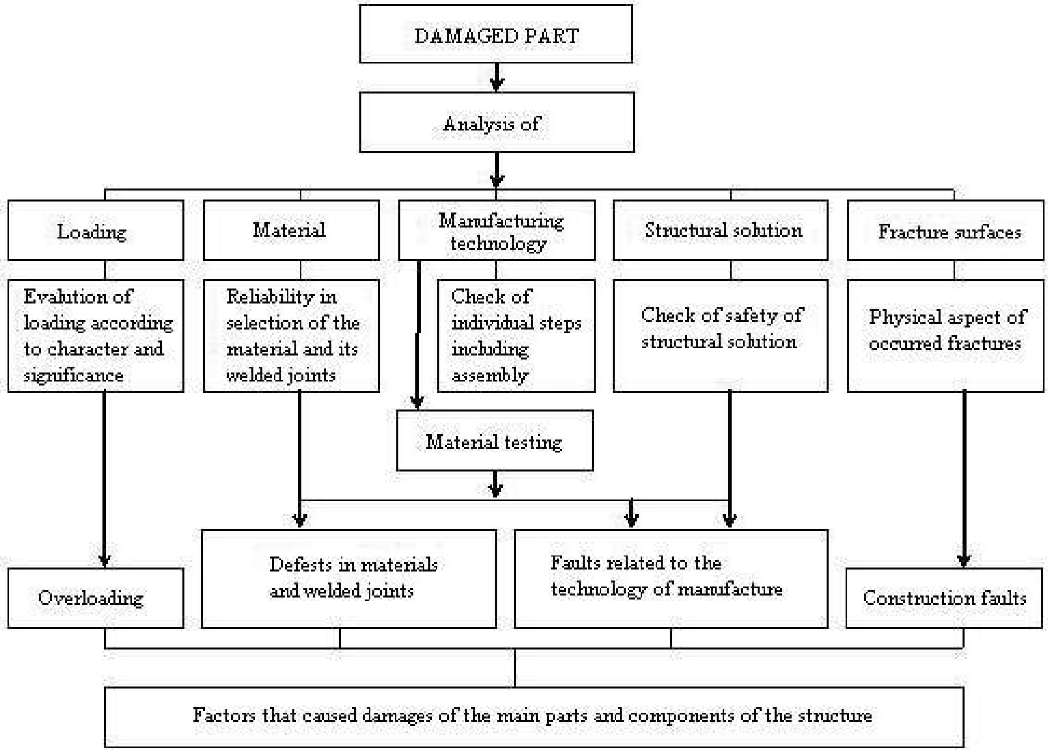

Figure 1. The flowchart of analysis of damages and fractures of the main parts and assemblies

3. THE ANALYSIS OF THE DIGGING SUBSYSTEM AND DRIVING REDUCER IN EXPLOITATION

Having in mind that the process of digging is a complex process influenced by various cutting parameters and relation digging – working environment, it is obvious that the digging subsystem represents one of the most important and most responsible subsystems of a bucket wheel excavators. The digging subsystem consists of a bucket wheel with showels, electromotor, coupler, gears and driving shaft.

Through the analysis of condition of the driving reducer in real conditions of exploitation of the bucket wheel excavators the following can be determined: thermic state of the bearings, flow of oil for lubrication of the bearings, state of gears (visual control), noise generating within the gearing, loading of the gears by measurement of power ensured by electromotor for its operation (the method of watt-meter output), oscillatory behaviour of systems of gears by monitoring of acceleration or by applying vibration method, and stress state of stationary housing of the reducer and rotary driving shaft by tensimetric measurement of strains converted into stresses.

Among the above-specified parameters for the analysis of state of the driving reducers in real conditions of exploitation of a excavator, the most complex procedure is determination of a range of operating stresses on driving shaft under conditions of non-stationary regime of loading of the bucket wheel excavator.

For realization of experimental tests of stress state, a system of measuring devices covering characteristic properties of stress-strain distribution with time is necessary. The role of the system of measuring devices is, in fact, signal processing. A structure of a disassembled measuring system is shown in Fig. 2 and details can be found in [2].

The measurements are conducted using strain gages of XY-120-HBM type that are suitable for measurement of the strains induced by the torque on the shaft. For transmission of an electric signal from rotary shaft to equipment for signal registration and processing, it is necessary to prepare suitable sliding Cu-rings to be placed on the shaft, and contact graphite brushes to be placed on stationary supporters, Fig. 2b.

Determination of corresponding stress range based on tensimetric measurement of established relations stress-time for the sake of quantitative evaluation of behaviour of the components of a digging subsystem in the region of fatigue strength of a material is realized through discreteness of the parameters of an random process and their statistic processing. The most reliable procedure to obtain discrete parameters of random processes is the "rain-flow" procedure, while the graphical methods of the probability theory and mathematical statistics have shown that two-parameter Weibull's distribution is most suitable for presentation of the amplitude distribution and operating stresses.

The results of measurement, expressed in a form of nominal strain ε, can be converted into shear stress through the modulus of elasticity E and Poisson' coefficient ν that with polar moment of resistance of cross-section W_p determines torque T on the driving shaft which can be used for assessment of life of a transmission mechanism:

$$\tau = \varepsilon \cdot E/(1+\nu)\ ;\ \ T = W_p \cdot \tau \qquad (1)$$

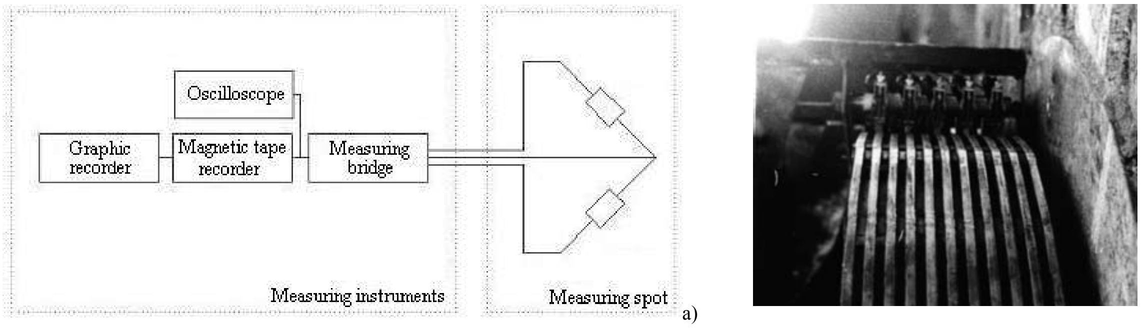

Figure 2. Layout of measuring equipment (a) and view of placement of the rings and brushes (b)

By using the method of comparison of loading and carrying capacity through maximization of the ratio of their indicator, the driving factor K_A at the gear with largest number of rotations is determined. Factor K_A allows for the effect of variation of external loading on operating life of transmission mechanism, with certain approximations of the loading regimes in different stages of exploitation. It is determined for the for the norm numbers that are defined in terms of root of the tooth, as the theoretical analysis conducted according to /6/ have shown that the safety of the tooth root is lower than the safety of its sides.

4. THE ANALYSIS OF FAILURE OF THE DRIVING REDUCER

As the reliability, as an essential property of functional safety and usable quality, is present in all phases of life cycle of a production system, the theory of reliability has found a wide application in many fields of research and development. One of the fields of research is the failure analysis, too.

The most frequent methods of the failure analysis aimed at establishment of the phase of life time of a production system during which a fault was made in design, production or exploitation phase are as follows:

- FTA (Fault Tree Analysis);
- FMEA (Failure Mode and Effects Analysis) and extended methods that includes failure criticality
- FMECA (Failure Mode, Effects and Criticality Analysis).

4.1 The Analysis Conducted by Applying the Method of Fault Tree

The fault tree is a graphic presentation of a series of causes, events and effects leading to failure of a function under consideration in terms of which the system reliability is evaluated. The base issue is that one should identify the events that directly disturb the function under consideration, as well as the logical interdependence of these events. Quantitative dependence continues as long as in this deductive process the level of fundamental events independent from other events has been achieved. Fundamental events represent the failures of the system components.

Based on the above discussion following the principle of cause and effect for possible damages and failures of the interior components of the driving gearing, it is possible to form a fault tree that includes graphically presented analysis of the possibility of occurrence of failure in the shafts, pairs of coupled gears, bearings and components for connection (e.g. wedges). The tree shows in detail the effect of external loading on each of the system components, the effect of structural material, heat treatment and the method of lubrication. The details of the specified analysis are given in [1].

To conduct the quantitative analysis of certain causes and the processes of the gearing damage, it is necessary to form an algorithm for solving the fault tree. The algorithm should enable evaluation of all possible tree-defined causes of failure. An example of the algorithm for quantitative evaluation of the phenomenon of failure of internal components of the driving reducer is given in [1].

4.2 The Analysis of Failure Mode, Effect and Criticality

Through the analysis of mode and effects of failure using the FMEA method, the causes of failure of critical components and assemblies as well as the consequences of their failure on safety of whole system are established.

In quantitative analysis, it is also necessary to conduct an analysis of failure criticality (CA), i.e. "severity" of the effects caused by certain failure. Combined FMEA and CA methods in literature are known as FMECA (Failure Mode, Effects and Criticality Analysis).

The FMECA analysis is methodologically conducted in several steps, see Fig. 3.

On principle, as far as production systems are concerned, the FMECA analysis is suitable for qualitative and quantitative analysis of the systems design, its development and construction and in an analysis of reliability, suitability for maintenance and exploitation of the system.

According to the flowchart presented (Fig. 3), when qualitative and quantitative analysis of the failure mode, effects and criticality have been completed, the acceptability of the data obtained is evaluated. If the assessment of criticality of some components is unfavourable, certain precautions for improvement or reducing the state of criticality are taken. That is the most important advantage of the method.

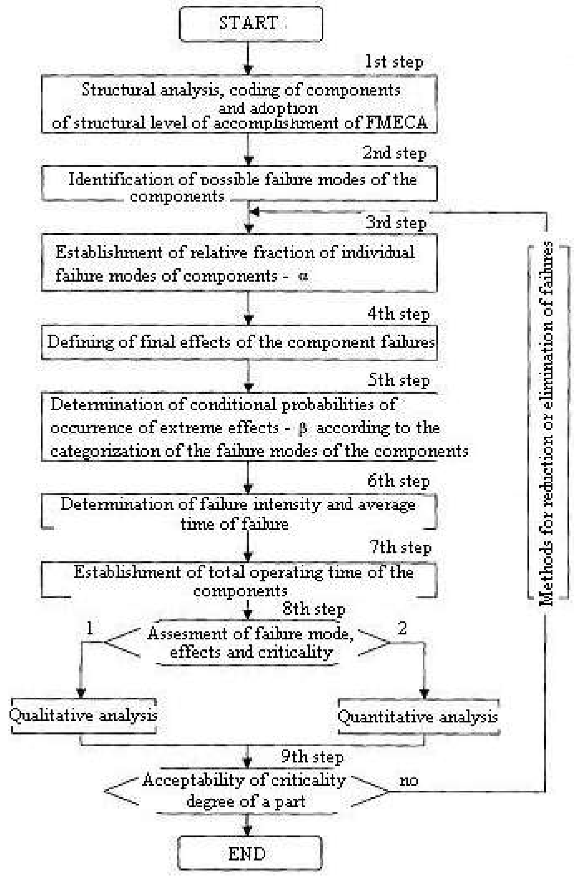

Figure 3 Algorithm of FMECA procedure of failure analysis

The results of application of the FMECA method in an analysis of failure mode, effects and criticality analysis of a driving gearing are given in Table 1. More details can be found in [7].

Quantitative calculation according to the classified evaluations is conducted through relation for failure criticality:

$$CR = \alpha \cdot \beta \cdot \lambda \qquad (2)$$

where: α - relative fraction of individual types of failure,
β - probability of occurrence of extreme effects
λ - probability of occurrence of failure.

Table 1: Presentation of the failure analysis of a gearing using the FMECA method

FMEA: Electric power comp. of Serbia	System: bucket wheel excavator	□ FMEA of structures	code s/d:
	Digging subsystem - driving reducer s/d:	□ FMEA of process	
		Designed by:	Page:
		Date:	from:

Item No	name s/d code	Failure mode and causes	Failure final effects	Category of the failure severity	β	α	λ	CR	CR_{DR}
1	REDUCER	Lack of lubricant	E1	I	10	8	9	720	564
		Mechanical damage	E2	I	8	2		144	
		Impact overloading	E1	I	10	8		720	
		Exhausted s/d	E3	II	7	9		567	
		Inadequate mounting	E3	II	7	8		504	
		Worn out s/d	E3	II	8	9		648	
		Inadequate maintenance	E1	I	9	8		648	

Note:
The effects of failure are as follows:
a) catastrophic (category I) - instantaneous termination of system operation (E1) and serious safety risks (E2),
b) critical (category II) - termination of the system operation after a certain period of time (E3) and
c) non-complicating (category III) - loss of the possibility of control of the system operation (E7) and floor-control (E9) *
* due to complexity of failure analysis, only categories I and II are included in Table 1

Relative fraction of failure criticality in terms of average value of failure possibility is expressed by:

$$CR_{DR} = \frac{1}{i} \cdot \sum CR \quad (3)$$

where: i – number of failure modes and effects of assembly/part.

Evaluation of the probability of failure effects and possibility of failure detection have been obtained by an expert assessment, while the values for the probability of failure occurrence are numerical values obtained based on statistical data processing for failures of the digging subsystems of a specific bucket wheel excavators.

According to the described procedure of the analysis of failure mode and effects conducted on the gearing, the data were obtained that are necessary for identification of the elements and failure modes which are most significant for further analysis in terms of system maintenance.

5. ACTIVITIES FOR PREVENTION OF DAMAGES AND FRACTURES

The data bases of conducted investigations of considered structures offer the large possibilities for detailed analysis of behaviour of the main parts and components of supporting structures, aimed at establishment of changes in mechanical properties of the materials, parts and welded joints on the structures by varying a large number of influential factors with minimization of undesirable effects, i.e. for realization of a safe design solution on the whole system.

Besides, the degradation of the material properties and/or deformation of the components may become more rapid because of the faults in exploitation and repair, and that is why periodical diagnostic measurements are obligatory. The aim is to create a reliable system for continious control of occurrence of damages.

Conducting of technical diagnostics should be based on three fundamental principles:

a. The scope of testing and measurement must be based on the history of exploitation of considered bucket wheel excavator, together with expert knowledge on its construction and operating conditions;
b. Testing and measurement must be conducted according to appropriate procedure, using adequate equipment and by skilled personnel;
c. The results of examination must be presented so that the conclusions should include exploitation of considered system, availability of testing personnel and a team of experts with adequate experience and knowledge in the field of design, manufacture, assembly, exploitation, maintenance, reliability, fracture mechanisms.

Based on conducted examination of failure and causes of malfunction of the digging drive and gearing using the fault-tree method, through analysis of failure mode, effects and criticality according to the FMECA method and the indicators of reliability obtained based on the analysis of collected data for real conditions of exploitation, it is possible to establish with sufficient accuracy optimum system for continuous diagnostics of a gearing for drive transmission at digging. By applying the PLC-PC combination, it is possible to make direct connection between an operating interface and manual programming device. The device for manual programming has a numerical keyboard with light-emitting indicators showing the status and operator's terminal where, if these are updated models, it is possible to define up to 200 numerical and alpha-numerical messages. Operator's interface has an alpha-numerical display with a functional keyboard and is intended for presenting the values of processing variables, status, alarms and messages, daily reports of the faults – both of the system and those defined by the user programme, with the time when they appear and default parameters according to the nickname or address, for details see [8].

Through the analysis of damages and fractures of the main parts and components of supporting structures the causes leading to destruction are established, with the possibility to make decision on elimination of unsafe technical solution or preventive measures, see Fig. 4.

The decision on elimination of misapropriate technical solution means development of new, optimum design solution by varying loading, operating regimes, dimensions of the parts and components of supporting structures, shape of welded joints, type of materials, processes and quality of their manufacture.

Change of the loading character according to the conditions of exploitation consists of experimental establishment of operating loading of the main parts and components of supporting structures and modification of the design solution, or determination of operating conditions and loading regime for reliable operation of certain technical solution.

Modification of a technological process of manufacture consists of search for various shapes and dimensions of the parts and components of supporting structures, welding processes, base metal and heat treatment process.

Modification of quality control of manufacture includes prediction of more severe requirements related to control and testing before the beginning of manufacture, during manufacture and after assembling.

As the above specified activities for prevention of damages and fractures present a complex and expensive solution for increase of reliability of the main parts and components of supporting structures, for past few years many eminent world institutes have conducted thorough experimental investigations to develop techniques and methods for more simple and less expensive improvement of static and fatigue properties of the parts and structural components.

The techniques for improvement that have been developed are not equally successful in different construction solutions, as their effect depend on the loading type and regime, material properties and structure of welded components, so that the recommendation for application of individual methods depend on the possibility of manufacture and exploitation of considered structure and experience of a designer in the first place.

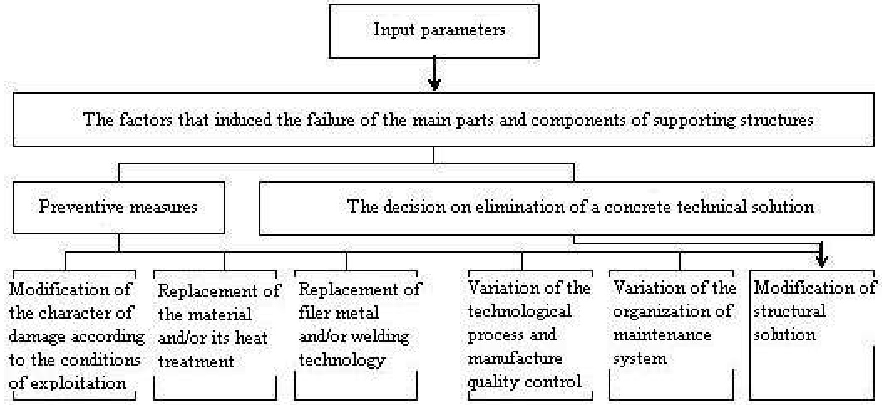

Figure 4. Activities for prevention of damages and fractures

6. CONCLUSION

The results shown in present paper and conducted investigations [1-5, 7, 8] provide good possibilities for detailed analysis of behaviour of the main parts and components of bucket wheel excavators, aimed at establishment of variations in mechanical properties of the materials, parts and welded joints of the structures by varying a large number of influential factors in order to manufacture a safer structure or to reduce some undesirable effects to an acceptable level. On driving reducer assembly the method of fault tree and FMECA method are presented.

Brief summary of used methods leads to the following conclusions:

- in addition to quantitative demonstration of possible causes, consequences, final effects and failure-severity category, the analysis using the quantitative system of evaluation provides the level of the possibility of failure occurrence, possible effects and the possibility of failure detection;
- the influence of failure is described by presenting the values for each mode and effect of failure of the constituent parts of digging assemblies;
- the method enables, after scheduled and concretized activities of precautions, what should be achieved with these measures at the most critical assemblies, in order to diminish criticality, severity and effects of failure.

Fast and reliable solution of the problems in main parts and components of driving reducer could be realized only by creation of appropriate database. Adequate software environment should enable more efficient utilization of the databases, the analysis of some influential factors and techniques of construction improvement. The aim of that system is to prevent failure due to searching and suggesting alternative solutions in all stages of design, manufacture and exploitation of the bucket wheel excavators.

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