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ANALYSIS
OF PUMPING UNIT REDUCERS DIAGNOSTIC ALGORITHMS
BY FORMALIZED METHODS

1. INTRODUCTION

In domestic and foreign petroleum the oil production by pumping units is the most widespread method and plays a leading role in comparison with other methods of petroleum production through the simplicity of its design and simplicity in operation. Ukraine and Poland operate a significant number of oil wells equipped by pumping units, with an increase in the number of failures and emergency states, due primarily to a long term of operation (more than 30 years).

Reliability – ability to perform specified functions of the object, preserving the value of its performance indicators in the set limits that meet the specified regimes and conditions of use, maintenance, repair, storage and transportation. Reducer of pumping unit (Fig. 1) is the least reliable of ground equipment [1–4].

An important feature of pumping units reducers is reliability, which is measured by indexes such as infallibility, durability, maintainability, conservation.

One of the main reasons for slow performance of pumping units’ reducers is a significant deterioration of working surfaces of the teeth, so we need to analyze factors that influence the wear of tooth surfaces and choose the working methods and technical means to monitor their condition. An effective method of predicting and preventing of wear is the use of diagnostic algorithms by formalized methods.

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Diagnostic model is designed for the construction and analysis of algorithms by diagnosing formalized methods. The using of the diagnostic model allows us to ease and formalize decisions on the diagnostic problem.

In [5, 6] are described the most common forms of diagnostic models:

- Analytical form of diagnostic models, which are the result of the analytical description of processes of passing signals, or systems of equations that solve the parameters of the object;
- The graph model to represent a description of the object under investigation based on set theory and graph theory as a way of visual representation of objects;
- Functional and logical models that are built on the basis of logical analysis of the functional diagram of the object of research.

The presence of a large number of links between structural assemblies of pumping unit’s reducers complicates the detection of certain analytical patterns in the transfer and change of diagnostic signs [7, 8, 9]. Pumping units reducer can be attributed to a complex oscillatory system with distributed parameters, so accurate analytical modeling of processes in the same vibration reducers is a complex task. The problem of modeling is complicated by the presence of linear and nonlinear relationships between assemblies of reducer, a significant inertia of the facility and many other factors. In order to find ways [10] to reduce the
intensity of vibration of reduction gear drive we considered its simplified linear analytical model and the possibility of system simplifying or splitting it into parts.

Therefore, for the synthesis of algorithm for diagnosing the functional-logical model has been selected, which allows to consider the links between individual elements and nodes of the object by simple means and consider the impact of these items on measuring diagnostic features.

For a more detailed study of processes occurring in the gearbox of pumping unit, and facilitate the development of its diagnostic model, we build a functional diagram of reducing gear given in Figure 2. Analyzing the structure of the gear, we will select its three major functional parts: driving motor, v-belt transmission and gearbox. Through the
constructive complexity and considerable operating charging the reducer is more vibroactive part of the drive compared to the driving motor. All major components and parts are linked between them by following types of interconnections: rigid connection, dry and semidry friction, electromagnetic forces, hydrodynamic friction. Rigid connections do not play a significant role and, if we do not take into account that over time the quality of such connections get worse (such as backlash in V-belt pulley and transmission gears relatively to shafts due to jam of spline and spline grooves), the influence of this type of connection can be neglected.

The transfer of momentum from the electric motor to the gearbox via v-belt transmission makes relatively little impact in the process of drive performance. Very important types of relationships are dry, semidry and hydrodynamic friction and to overcome them in the process of work the much of the energy is spent, which consequently is transformed into noise and vibration or into heat. Since the torque and hence loading, which is perceived by toothed gear shafts are different, respectively, and will be different for them the work performed by friction. It is very important in constructing a model of pumping unit gear.

Since the consideration of all listed in Figure 2 the relationships are too complex scientific problems, so the construction of the diagnostic model should ask some simplification and limitation. To build a diagnostic model of reducer we take for background information to the simplified scheme (Fig. 3), taking into account all the basic relationships of its parts and assemblies.

The main structural units are grouped in the gear drive blocks and marked $P_2 \ldots P_n$. The input of block $P_i$, which are external inputs, have been indicated by $X_1 \ldots X_m$, input of block $P_i$, which are the outputs of other blocks – $Y_{i,1} \ldots Y_{i,n}$, and outputs of block $P_i$ – $Z_{i,1} \ldots Z_{i,n}$, where $i = (1, n)$. Each block has a number of inputs (outputs), equal to the number of its input (output) parameters. The simplified block diagram is presented in Figure 3.

The structure of the pumping unit reducer includes such working parts as motor (shaft $P_1$, stator winding (stator) $P_6$, cage rotor $P_7$, the first bearing $P_8$, the second bearing $P_9$, motor pulley $P_2$), V-belts $P_3$ and reducer gear (gear pulley $P_4$, driving shaft $P_5$, the first bearing of drive shaft $P_{16}$, the second bearing of drive shaft $P_{17}$, the bearing housings of drive shaft $P_{22}$, and $P_{23}$, intermediate shaft $P_{10}$, the first bearing of intermediate shaft $P_{18}$, the second bearing of intermediate shaft $P_{19}$, intermediate shaft bearing housings $P_{24}$, and $P_{25}$, gear wheels of intermediate shaft $P_{12}$ and $P_{13}$, output shaft $P_{11}$, the first bearing of output shaft $P_{20}$, the second bearing of output shaft $P_{21}$, bearing housings of output shaft $P_{26}$, and $P_{27}$, gears wheels of output shaft $P_{14}$ and $P_{15}$).

Next forces act on the elements:
- $X_1$ – force of reaction of bearings;
- $X_2$ – friction force of lubricant;
- $X_3$ – strength of electromagnetic interactions;
- $X_4$ – force of torque.

Gear drive blocks are combined together by following links:
- output $Z_{7,6}$ and input $Y_{6,7}$ strength of electromagnetic interactions of electric motor stator-rotor;
output $Z_{6,1}$ and input $Y_{1,6}$ tension forces on the rotor shaft of the electric motor;
output $Z_{1,2}$ and input $Y_{2,1}$ force of tension of pulley on the shaft of the electric motor;
output $Z_{2,3}$ and input $Y_{3,2}$ power torque of motor shaft;
output $Z_{4,3}$ and input $Y_{3,4}$ complex forces of reaction (friction, force torque, hydrodynamic effects);
output $Z_{5,4}$ and input $Y_{4,5}$ tension pulley force on drive shaft;
output $Z_{12,10}$ and $Z_{13,10}$ and input $Y_{10,12}$, $Y_{10,13}$ forces of tension of gears on the intermediate shaft;
output $Z_{12,5}$ and $Z_{13,5}$ and input $Y_{5,12}$, and $Y_{5,13}$ frictional forces between the surfaces of teeth, hydrodynamic effects, force torque of drive shaft and intermediate shaft gears;
output $Z_{14,11}$ and $Z_{15,11}$ and input $Y_{11,14}$ and $Y_{11,15}$ forces of tension of gears on the output shaft;
output $Z_{14,10}$ and $Z_{15,10}$ and input $Y_{10,14}$ and $Y_{10,15}$ frictional forces between the surfaces of teeth, hydrodynamic effects, force torque of intermediate shaft and output shaft gears.

Fig. 3. Simplified block diagram of the pumping unit reducer
After analyzing a simplified block diagram of gear reducer diagnostic logic model has been built (Fig. 4). As the drive of gear reducer is designed to perform a work function algorithm, in the implementation of which all the elements are involved, and all links of the functional diagram, for the entire diagnostic workflow is built only one functional circuit. For the logical model each block is changed by simplified block diagram of the unit with the
appropriate links. In this case the functional block diagram corresponds to a subset of the logical model of the set of $Q_1 \ldots Q_n$, where $n = \Sigma n_i = 23$.

Denote the blocks of logic model as: $Q_1$ – electromagnetic motor defects; $Q_2$ – increasing of gap in the motor bearings, $Q_3$ – curvature of the shaft of the electric motor, $Q_4$ – wear of V-belts, $Q_5$ – wear of drive shaft, $Q_6$ – increasing of gap in the shaft bearings of drive shaft, $Q_7$ – wear of housing of bearing of drive shaft, $Q_8$ – wear the intermediate shaft, $Q_9$ – wear of gears of intermediate shaft, $Q_{10}$ – increasing of gap in the intermediate shaft bearings, $Q_{11}$ – wear of the intermediate shaft bearing housings, $Q_{12}$ – wear of the output shaft, $Q_{13}$ – wear of gears of output shaft, $Q_{14}$ – increasing of gap in the output shaft bearings, $Q_{15}$ – wear of the output shaft bearing housings, $Q_{16}$ – weakening of the foundation fastenings, $Q_{17}$ – wear of pulleys, $Q_{18}$ – violation of the parallel axis of gear shafts, $Q_{19}$ – imbalance, $Q_{20}$ – mechanical losses, $Q_{21}$ – change between axis distance, $Q_{22}$ – inappropriate tension of v-belts transmission, $Q_{23}$ – buckling of pulley.

Electromagnetic motor defects $Q_1$ causing excessive load on the rotor and it leads to increased clearance in the bearings of the electric motor $Q_2$ (communications output $Z_{1,2}$ – input $Y_{2,1}$) and distortion of the electric motor shaft $Q_3$ (communications output $Z_{1,3}$ – input $Y_{3,1}$). $Q_3$ results the effects of pulley wear and of v-belt transmission $Q_{17}$ (communication output $Z_{17,3}$ – input $Y_{3,17}$) and clearance in the bearings of the electric motor $Q_2$ (communications output $Z_{2,3}$ – input $Y_{3,2}$).

Quite common defect in $Q_4$ – wear V-belts – can be caused by a number of reasons: due to distortion of the motor shaft $Q_3$ (communications output $Z_{3,4}$ – input $Y_{4,3}$), wear of pulley $Q_{17}$ (communication output $Z_{17,4}$ – input $Y_{4,17}$), weakening of the foundation attachment $Q_{16}$ (communication output $Z_{16,4}$ – input $Y_{4,16}$), and through the inappropriate tension of belts $Q_{22}$ (communication output $Z_{22,4}$ – input $Y_{4,22}$).

Main reasons that cause the failure of reducers are gear drive shaft wear $Q_5$ due to bearings wear of drive shaft $Q_6$ (communications output $Z_{6,5}$ – input $Y_{5,6}$), wear of gear of intermediate shaft $Q_9$ (communications output $Z_{9,5}$ – input $Y_{5,9}$) and buckling of pulley $Q_{23}$ (communications output $Z_{23,5}$ – input $Y_{5,23}$). In turn, drive shaft bearings $Q_8$ are worn through the wear drive shaft $Q_5$ (communications output $Z_{5,6}$ – input $Y_{6,5}$). The housing of drive shaft bearing $Q_7$ wears due to damage of the bearing of drive shaft $Q_6$ (communications output $Z_{6,7}$ – input $Y_{7,6}$).

Equally very important is the failure of the intermediate shaft $Q_8$ due to wear of gear of output shaft $Q_{13}$ (communication output $Z_{13,8}$ – input $Y_{8,13}$) and wear of bearings directly of intermediate shaft $Q_{10}$ (communication output $Z_{8,10}$ – entrance $Y_{10,8}$). Defects of the intermediate shaft gears $Q_9$ arise through the wear of drive shaft $Q_5$ (link output $Z_{9,5}$ – input $Y_{5,9}$). Intermediate shaft bearings $Q_{10}$ wear through injuries and defects of teeth of intermediate shaft $Q_8$ (communication output $Z_{10,8}$ – entrance $Y_{8,10}$). The housing of bearing of the intermediate shaft $Q_{11}$ goes down due to the influence $Q_{10}$ – bearing wear (contact output $Z_{10,11}$ – input $Y_{11,10}$).

Main reasons that cause the failure of output shaft $Q_{12}$ is wear directly of gearbox bearing of output shaft $Q_{14}$ (communication output $Z_{14,12}$ – input $Y_{12,14}$) and from the wear of bearings $Q_{14}$ the output shaft wear $Q_{12}$ depends (links output $Z_{12,14}$ – input $Y_{14,12}$).
Damage of gear of output shaft \( Q_{13} \) depends in turn on the failure of the intermediate shaft \( Q_8 \) (communication output \( Z_{8, 13} \) – input \( Y_{13, 8} \)). Wear of the housing of bearing of output shaft \( Q_{15} \) depends on the wear of bearings \( Q_{14} \) (communication output \( Z_{14, 15} \) – input \( Y_{15, 14} \)). Defects of pulley \( Q_{17} \) can cause the weakening of the mounting base \( Q_{16} \) (communication output \( Z_{16, 17} \) – input \( Y_{17, 16} \)).

There are several reasons that affect the parallel of shafts in gearbox \( Q_{18} \): wear of drive shaft bearing \( Q_6 \) (communications output \( Z_{6, 18} \) – input \( Y_{18, 6} \)), intermediate shaft bearings wear \( Q_{10} \) (communication output \( Z_{10, 18} \) – input \( Y_{18, 10} \)), wear of bearing of output shaft \( Q_{14} \) (communication output \( Z_{14, 18} \) – input \( Y_{18, 14} \)). Wear of gear of intermediate shaft \( Q_9 \) causes common defect – an imbalance \( Q_{19} \) (communications output \( Z_{9, 19} \) – entrance \( Y_{19, 9} \)), gears of output shaft \( Q_{13} \) (communication output \( Z_{13, 19} \) – input \( Y_{19, 13} \)), pulley \( Q_{17} \) (communication output \( Z_{17, 19} \) – entrance \( Y_{19, 17} \)). Significantly affect the mechanical losses \( Q_{20} \) the tension of belts \( Q_{22} \) (communication output \( Z_{22, 20} \) – input \( Y_{20, 22} \)).

The problem of keeping a distance between axis \( Q_{21} \) depends on the wear of bearings of drive shaft \( Q_6 \) (communications output \( Z_{6, 21} \) – entrance \( Y_{21, 6} \)), intermediate shaft bearings \( Q_{10} \) (communication output \( Z_{10, 21} \) – input \( Y_{21, 10} \)), bearings of output shaft \( Q_{14} \) (links output \( Z_{14, 21} \) – input \( Y_{21, 14} \)), parallel shaft \( Q_{18} \) (communication output \( Z_{18, 21} \) – input \( Y_{21, 18} \)).

The problem of tension of belts \( Q_{22} \) is caused by two reasons: the weakening of the mounting base \( Q_{16} \) (communication output \( Z_{16, 22} \) – entrance \( Y_{22, 16} \)) and buckling of pulley \( Q_{23} \) (communication output \( Z_{23, 22} \) – entrance \( Y_{22, 23} \)). Pulley buckling \( Q_{23} \) occurs for two reasons: distortion of the electric motor shaft \( Q_3 \) (communications output \( Z_{3, 23} \) – input \( Y_{23, 3} \)) and weakening of the foundation fastenings \( Q_{16} \) (communication output \( Z_{16, 23} \) – input \( Y_{23, 16} \)).

3. CONCLUSION

Thus, the diagnostic logic model provides a visual representation of the most prone to initiation of defects of elements and assemblies in the reducing gear, and also the links of structural and diagnostic parameters that ultimately will choose the diagnostic signs and give the possibility to put them on the basis of methods of control of pumping unit reducing gear, that may be developed. Diagnostic logic model will help to establish and classify defects in development, to determine the direction of their development and cause-effect relationship with other defects.

REFERENCES
