INFLUENCE OF POWER TRANSMITTER DYNAMIC LOAD ON PHYSICAL AND CHEMICAL PROPERTIES OF USED LUBRICANT

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ABSTRACT

The tribological conditions within gear power transmitters as a real tribomechanical system are quite complex and are conditioned to a large extent by the characteristics of used lubricant. Complexities of the conditions are determined by temperature of the elements in contact, current properties of the used lubricant, external load in reference to specific pressures in contact zone, dynamic nature of contact creating, transfer of power and movement. The aim of this paper is to establish the influence of power transmitters dynamic load on its lubricant degradation. Also, the basic elements of analytical approach to lubricant film behaviour under the dynamic loaded conditions are given in this paper. Variations in exploitative conditions lead to variations in load of elements in contact and provoked variation of friction coefficient, so as temperature and pressure decrease. By means of all listed, those variations lead to changes of lubricant characteristic and its degradation. Besides all, stability of lubricant physical and chemical properties during working life is a key element of power transmitters safety and reliability. Experimentally obtained results point out the necessity of considering the lubricant present properties as timely depended constructive element. Paper conclusions bring the proposals for reduction of the undesirable consequences of lubricant degradation.

Keywords: dynamic load, power transmitter, lubrication, pressure, temperature.

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AIMS AND BACKGROUND

Basic task of the gears sets is to transmit rotation and torque using the so-called form connection which in this case is represented by the teeth in contact. Gear power transmitter can be used in a wide diapason of speeds and loads, thus ensuring high kinematic accuracy, working continuance, and reliability needed for different exploitative conditions. The development of transmission is characterised by continuously increasing levels of torque and power, lightweight design, increasing life-cycle, improved efficiency and low noise requirements[1–3]. These demands, together with tribological aspects, make selection of the gear materials a complex element of the gear design. In order for gears to achieve their intended performance, life-cycle and reliability, the selection of a suitable gear material is very important. The final selection should be based on an understanding of material properties and application requirements. If you are looking for a high performance gear with reliable operation, the selection of suitable material is very important. Based on applications, gears for high load capacity require a tough and robust material like carbon steel, whereas high precision gears require materials having lower strength and hardness rating. To reduce wearing and damaging of transmission elements they have to be lubricated. Dissipative processes, which occurred, are identified as undesirable effects expressed in loss of material, energy, moving, functionality and reliability, reduce of exploitation life and increase of maintenance coasts[4–6]. The lubricant may be considered as constructive element and thus it is very important to know the composition of lubricants, their characteristics, properties and effects. Moreover, a complex unit which consists of material, lubricant and application must be analysed with comprehension.

THEORETICAL APROACH – HYDRODYNAMIC THEORY OF LUBRICATION

The usual considerations of some real problems refer to the approach that uses the approximate differential equations of viscous liquids flow that are obtained from the full differential equations by neglecting non-linear inertial members while retaining the members who are conditioned by viscosity. Further improvement of development of the approximate solving methods is based on differential equations that are obtained from the Navier–Stokes equations when some members which are conditioned by viscosity except the nonlinear inertial members are ignored. A very important technical problem of lubrication gave the impulse for the development of approximate method based on these differential equations[7].

The founder of the hydrodynamic theory of lubrication is the Russian scientist Petrov who considered the possibility of direct application of the Newton hypothesis of stress and displayed the solution in case of shaft and bearing surfaces being coaxially cylindrical. In order to confirm the theoretical conclusions, Petrov has performed a large number of experiments which did not only confirm the basic assumptions of his theory but also contributed to explanation of the problems related to the mineral oil use.

Petrov has observed circular flow of parts of viscous fluid between 2 cylinders that rotate around axes which correspond, under conditions of partial fluid sliding along the walls, unlike the approach that includes complete liquid sticking to the walls. On the basis of experiments and further development of theories that deal with these problems, it was found that the basic links that Petrov obtained correspond to borderline case of shaft rotation with a large number of revolutions, whereby the shaft carries a relatively small load. For this borderline case the shaft axis creates only a small deviation from the bearing axis, so that this deviation without loss of generality can be neglected. Under normal conditions of exploitation, however, the bearing axis does not correspond with the shaft axis. This kind of eccentric shaft position in the bearing leads to forces that balance the shaft load. Lubrication theory for the eccentric shaft position was developed by Zhukovsky and Chaplygin[7].

By comparison of the Reynolds differential equations for the lubricant film with the Navier–Stokes equations it is shown that for their production there is a need to disregard not only all the non-linear inertial members but also the members who are conditioned by viscosity. With the assumption of differential equations solutions in the form of rows and by comparison of the members with the same degrees, the row of differential equations systems is obtained, with the first system of this row being the Reynolds equation, while the other system contains the Laybenson equations for the lubricating film[7].

PROPERTIES OF LUBRICANT USED

Viscosity is one of the most important properties of lubricants from the tribological aspect and it represents a measure of internal friction. Viscosity occurs as a result of action of the intermolecular forces in the lubricant and as forces grow stronger the viscosity grows higher. Viscosity shows its greatest impact during total lubrication, because film thickness, temperature increase and losses due to friction depend on it. Lubricants behave as the Newtonian or non-Newtonian fluids, depending on whether the link between shear stress and velocity gradient is linear or not. Viscosity can be viewed through the dynamic and kinematic viscosity. Dynamic viscosity is obtained by applying the Newton law that connects the shear stress in the fluid and velocity gradient. Kinematic viscosity is the ratio of dynamic viscosity and fluid density. With lubricants that behave as the Newtonian fluids, viscosity is a function of temperature and pressure. Oil viscosity decreases with temperature increase by a certain regularity that increases with temperature drop. During the exploitation viscosity change tends to be as small as possible. Change of viscosity with temperature change is expressed through the dimensionless number – viscosity index. With the non-Newtonian fluids, viscosity is not constant at the given temperature and pressure, but depends on the change of shear velocity. Emulsions, suspensions and multigrade oils are among the non-Newtonian fluids. Apparent viscosity is the measurement of viscosity at the specific shear gradient, while the structural viscosity represents the viscosity drop due to increase of shear velocity. Apparent viscosity describes the behaviour of oil at low temperatures. At the beginning of growth of shear velocity, multigrade oils retain their Newtonian character. The non-Newtonian area, which then follows, features a dramatic drop of viscosity. By continuing growth of shear velocity, oil re-enters the Newtonian area, which differs from the previous one. In this area, the present polymer molecules are no longer deformed. The relative viscosity drop increases with temperature lowering and pressure growth at amounts to 10–70%. Typical example of a complex tribomechanical system with gear power transmitter operating in very changeable conditions of exploitation is the vehicle gearbox transmission. Transmission of the vehicle consists of elements of power transmission and motion (gears and grooved shafts), elements of information transfer (leverage), elements of conduct (guides) and seals (gaskets). Each of these elements of the transmission can be analysed as a set of special tribomechanical systems, such as gear pairs, bearings, etc. Also, each gear pair can be further analysed as a single element which makes the contact. And finally each gear tooth flank or ball of roller bearing can be seen as a basic unit of tribomechanical system. This analysis suggests the fact that the tribological characteristics of a complex tribomechanical system can not be seen in a simple matter and that it is not possible to establish reliable methods and determine the diagnostic parameters for assessing the state of an observed system. Direct participation of lubricant in the contact processes of gear transmitter as tribomechanical system, with the main task to prevent the direct contact of surface elements, provides the lubricant with a special role from the aspect of testing. The lubricant is the carrier of information about the state of gear transmitter as a whole, with attention specially paid to the processes that affect the functionality and reliability. The importance of this information is expressed in monitoring and system diagnosis, because lubricant analysis can point to signs of potential problems that lead to failure, as well as to provide consideration of lubricant influence on the system operation[4–6].

EXPERIMENTAL TESTING OF OIL PROPERTIES AND THEIR CHANGES DURING THE EXPLOITATION

The subject of testing in this paper is the experimental determination of property changes of gear oil during operation depending on the dynamic proper-

Table 1. Values of basic physicochemical properties of the new oil SAE 80W-90

Properties	Value
Appearance	clear
Colour	ASTM 5.0
Density	0.902
Viscosity at 40°C (mm^2/s)	212.5
Viscosity at 100°C (mm^2/s)	18.27
Viscosity index (%)	97
Level of combustion (°C)	216
Level of solidification (°C)	–18
Foaming (sequence I, II and III)	0/0
Corosity to Cu (100°C/3)	1[a]
TAN (mgKOH/g)	0.9
Humidity (%)	0

ties of loads. The oil SAE 80W-90 of API GL-5 quality was tested which was used in gear group of working machines whose main properties are shown in Table 1.

During the testing, the oil that belonged to the gear group of working machines used in real conditions of exploitation[6] was tested. Allowed quantities of certain elements in used gear oil and allowed values of deviations in physicochemical properties of new and used oil are given in Table 2. Experimental testing included determining colour, density, viscosity at 40 and 100°C, determining viscosity index, fire point and compressibility, TAN, foaming control, humidity content control, control of the insoluble residue in toluene and content control of wear products. The oil of 3 gearboxes after various intervals of exploitation was tested to examine the influence of power transmitter load[6].

Table 2. Allowed values of deviations in physicochemical properties of oil

Physicochemical properties of oil and wearing products	Maximum deviation allowed
Viscosity at 40° C (mm^2/s)	15%
Viscosity at 100°C (mm^2/s)	15%
Viscosity index (%)	±5%
Total acid number, TAN (mgKOH/g)	3 mgKOH/g
Insoluble residue in toluene (%)	0.50%
Wear products – Fe content (ppm)	500 ppm

The results of experimental testing are presented in Table 3. Experimental testing was carried out in accordance with manufacturer specifications and proper standards by using the necessary testing equipment. Besides determining the impact of dynamic load characteristics on changes in the physical and chemical properties of oil, the goal of experimental testing was also checking of the oil replacement intervals, checking the choice of the lubricant and monitoring the oil quality during exploitation.

Density change has a trend of slight growth expressed during whole period of exploitation (Fig. 1) (Ref. 6). Figure 2 presents diagram of the change of fire temperature of the tested oil. The growth of fire point indicates the oxidation (ageing) of oil or evaporation of easily volatile components. Fire point of oil, on which

Table 3. Values of the tested physical and chemical properties of used gear oil SAE 80W-90, API classification GL – 5 during exploitation

Properties	Values of the tested physical and chemical properties												
	sample	gearbox 1				gearbox 2				gearbox 3			
		exploitation time (h)				exploitation time (h)				exploitation time (h)			
		42	111	217	349	42	111	217	349	42	111	217	349
Colour	ASTM 5.0	black	black	black	black	black	black	black	black	black	black	black	black
Density	0.902	0.903	0.907	0.909	0.913	0.905	0.908	0.91	0.915	0.906	0.911	0.916	0.919
Fire point (°C)	216	218	221	225	227	220	224	229	230	222	226	230	231
Level of solidification (°C)	-18												
Humidity (%)	0	0	0	0	0	0	0	0	0	0	0	0	0
Foaming	0/0												
Viscosity at 40°C (mm^2/s)	212.5	215.2	223.8	226.1	229.6	216.3	224.7	226.6	230.3	223.6	224.9	227.2	231.1
Viscosity at 100°C (mm^2/s)	18.27	18.53	18.96	19.16	20.15	18.76	19.12	19.56	20.34	19.05	19.63	20.04	20.71
Viscosity index (%)	97	97	96	96	96	98	95	96	96	98	97	96	96
TAN (mgKOH/g)	0.9	1	1.25	2	2.6	1.1	1.7	2.4	2.7	1.2	1.9	2.5	2.75
Insoluble residue in toluene (%)	0	0.03	0.06	0.08	0.15	0.05	0.07	0.1	0.17	0.09	0.13	0.19	0.25
Fe content (ppm)	0	25	41	270	349	76	260	375	670.5	112	335	536.5	873.4

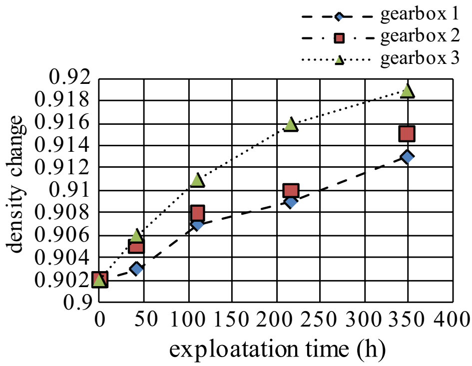

Fig. 1. Density change of sampled gear oils

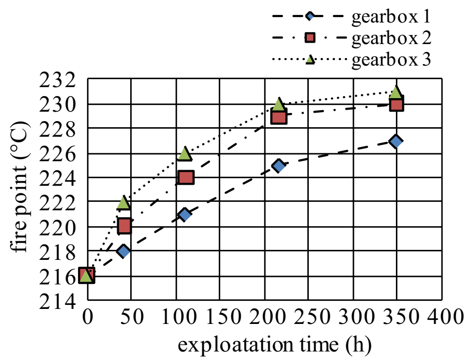

Fig. 2. Change of fire point of sampled oil

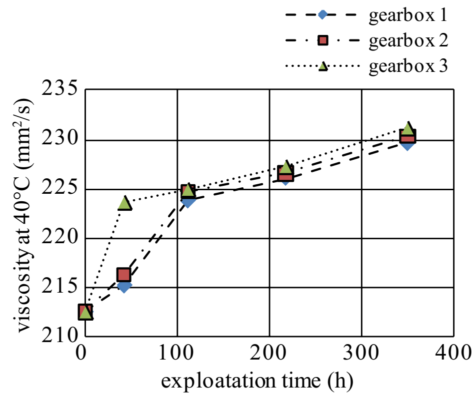

Fig. 3. Viscosity change of tested oils at 40°C

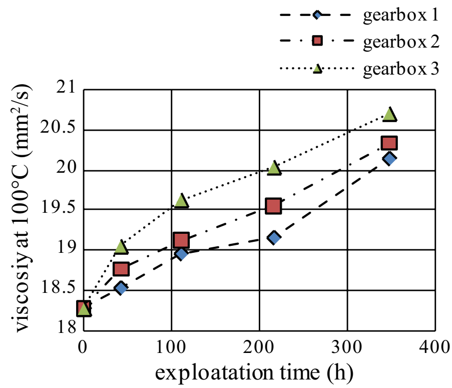

Fig. 4. Viscosity change of oils at 100°C

sampling was conducted, has a trend of continuous growth (Fig. 2), which is another inevitable indicator of oil oxidation due to dynamic load characteristics. Figure 3 shows viscosity change of the tested oil at 40°C, while Fig. 4 – viscosity change at 100°C.

In Figs 3 and 4 there is an evident trend of constant viscosity growth during exploitation. This increase in viscosity is a consequence of properties change of tested oils due to dynamic loads during exploitation. The increase in viscosity indicates a process of oil oxidation as well or oil contamination with water and dirt, as well as wear products. In the analysed oil there was no oil contamination with water, because during the analysis of the tested samples indications of water presence are missing. This conclusion is suggested by the fact that in the examined samples there was no foaming, given that one of the reasons for foaming is the presence of water. It is concluded that one of the main reasons for the increase of viscosity is oil oxidation and contamination of oil by wear products. Water is an undesirable contaminant in the oil, and it is the most present liquid contaminant in lubricating oil originating from the environment or it is a result of condensation. Water was not the cause of oil degradation in terms of oxidation, the destruction of the oil film, causing corrosion, deposit formation and hydrolysis of certain additives. Particles that got into the oil caused an increase in the intensity of oxidation processes in which process acidic compounds and insoluble products are formed that are internal contaminants. Also, these products neutralise the additive polar molecules in the oil, particularly antiwear and EP additives, corrosion inhibitors and dispersants. Furthermore, very fine solid particles in stable oil suspension cause an increase in oil viscosity. In regard to the fact that allowed deviations of viscosity at 40 and 100°C amount to a maximum of 15% to initial values it can be concluded that tested oils meet this criterion. Viscosity drop may be due to mixing with the oil of lower viscosity or due to lower concentration of viscosity improver. Causes of this process can also be high temperature, load, long exploitation interval, insufficient quantity of oil, inefficient cooling, etc.

As shown in Fig. 5, TAN values have a trend of increase which indicates oil degradation. During the exploitation testing of the change in TAN were reached values which were within the permissible range of values according to an appropriate standard and specifications of manufacturers. With mineral oils with fewer additives TAN grows rapidly, while with oils that has high additive content, in the initial period of exploitation it decreases, and then receives a growing character. By degradation of oil during exploitation, certain types of polymeric insoluble residues are formed. The content change of these insoluble residues during exploitation is shown in Fig. 6 (Ref. 6).

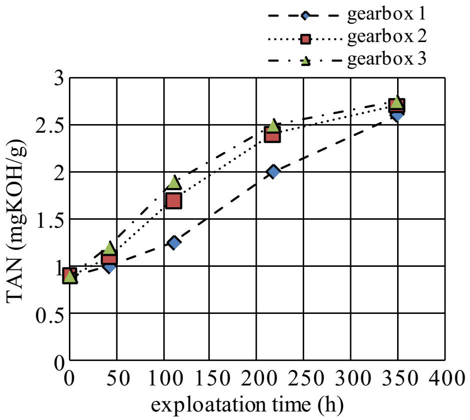

Fig. 5. Change of TAN for sampled gear oils

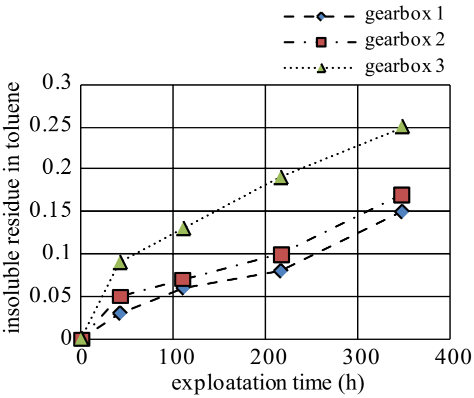

Fig. 6. Insoluble residues in toluene of the sampled oils

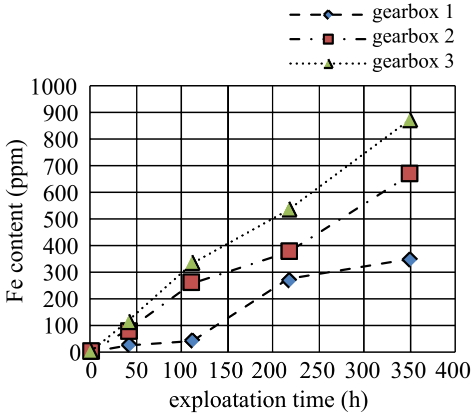

Fig. 7. Content changes of wear products of sampled oils

During the testing, observed oils are considered to meet the criterion change of the insoluble residue amount in toluene. The content change of wear products of sampled oils during exploitation is shown in Fig. 7 (Ref. 6). Wear products caused the contamination of oil well above the permissible limit and now an intensive degradation of oil starts that will be more intense due to their catalytic action. Also, it can be concluded that the strong growth of iron concentration, as wear products, leads to failure of gearbox elements which are mutually located in relative motion.

RESULTS AND DISCUSSION

During exploitation, the analysed oil has achieved its primary function and meets the intended replacement interval, which was determined by analysis of characteristic physicochemical properties and concentration of wear products during exploitation. The increase in viscosity occurred during the examination period of exploitation. Maximum viscosity growth during oil exploitation is less than 15% of the allowed value. Degradation of oil during testing was analysed by an increase in TAN and the increase of insoluble residues (in toluene). Both features showed changes that are within the maximum permitted levels. Oil fire point has a trend of constant growth pointing to the process of oil oxidation (ageing). The content of wear products in oil came out of the limits of maximum value allowed, indicating the need of check of the functional characteristics and oil change interval. In the tested samples of oil there has been no occurrence of water or foaming. The conducted experimental analysis of the changes of oil properties during exploitation, reveals the great influence of dynamic load characteristics[4–6].

Testing of physical and chemical properties of oil in the function of determining the state of gearbox group as a complex tribomechanical system aims to identify mechanisms of change in the system elements. By appropriate sampling and testing during exploitation, based on the model presented it is possible to identify the state of system elements and predict its future behaviour in exploitation[7]. The conditions in which the gearbox group elements are found as real tribomechanical system are complex and are determined to a large extent by oil properties. The complexity of the conditions is determined by temperature of elements in contact oil, temperature and properties, external load, that is the specific pressure in the contact zone, the dynamic character of contact and transfer of power and movement, etc. During exploitation the gearbox group is exposed to time variable, dynamic and unsteady loads that represent the function of a range of factors. Dynamic loads conditioned complex physicochemical processes that cause changes in oil. The amplitude as well as frequency of load primarily affect the change in pressure and temperature in the contact zone and thus cause a change in oil physicochemical structure. Processes created this way are manifested through unwanted effects that can be identified through the loss of material, energy, movement, functionality and reliability, reduced life cycle and increase in maintenance costs. Gearbox group is a set of very complex tribomechanical systems composed of series of subsystems that are also complex tribomechanical systems. Requirements regarding the oil properties, the type of use and their replacement interval are becoming stricter because designers of gearbox groups continually put before oil manufacturers new and more difficult conditions in terms of improving performance and efficiency[8–10]. This inevitably leads to reformulating existing and creating new kinds of oils that are different in chemical composition, exploitation properties and viscosity grading.

CONCLUSIONS

Direct participation of oil in the contact processes in tribomechanical systems with the main task to prevent direct contact of surfaces of elements gives it a special role in terms of maintenance. This role becomes more important since the oil is a carrier of information about the state of the whole system in which process the particular attention is paid to the processes that affect the functionality, reliability and durability. The importance of this information comes into play in monitoring and system diagnosis because oil analysis can point out to signs of potential problems that lead to failure, as well as to provide an insight into the influence of oil on the functioning of the gearbox group. The current state of the gearbox group system can be analysed by examining oil without disrupting exploitation. Also, the conditions of exploitation, especially the dynamic characteristics of the load gearbox groups can be analysed[11–13]. Full understanding of the theoretical basis of the dynamics of oil and lubricants as a viscous incompressible fluid with the experimental testing of properties allows an adequate evaluation and application of results obtained by modern software packages such as Ansys, Fluent, FlowTech, PowerFlow, Flovent, etc., that use this kind of numerical algorithms for solving the adequate system of equations. Usage of these software packages for computational fluid dynamics provides relevant information about the oil behaviour that can be used in the design, improvement and optimisation of complex tribological systems within the gearbox group[14,15]. Numerical approach to oil dynamics includes consideration of the global geometry of elements, establishment of finite elements and establishment of shapes and sizes of oil particles and their conditions, as well as global boundary conditions so that the results obtained by analysis of numerical models created in this way, verified experimentally, are the important parameter that must be taken into consideration for solving the problems of lubrication of modern gearbox group.

ACKNOWLEDGEMENT

Financial support for the work described in this paper was provided by Serbian Ministry of Education and Science, project (TR35033).

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Received 31 May 2011
Revised 18 July 2011