e-ISSN 2719-3306 Mining Machines, 2021, Vol. 39 Issue 1, pp. 36-45

DOI: 10.32056/KOMAG2021.1.4

Predictive maintenance techniques for wear reducing and elimination of equipment failures in hydrostatic drive systems

Published online: 30-04-2021

Alexandru Daniel MARINESCU [1a], Teodor Costinel POPESCU [1], Krzysztof NIEŚPIAŁOWSKI [2], Ana-Maria Carla POPESCU [1]

[1] Hydraulics and Pneumatics Research Institute INOE 2000 – IHP, 14 Cutitul de Argint Street, Bucharest, Romania

[2] KOMAG Institute of Mining Technology, Pszczyńska 37, 44-100 Gliwice, Poland

[a] e-mail: marinescu.ihp@fluidas.ro

Keywords: predictive maintenance, hydraulic drive systems, infrared thermography, vibration analysis, oil analysis, wear reducing

Słowa kluczowe: konserwacja predykcyjna, hydrauliczne układy napędowe, termografia w podczerwieni, analiza drgań, analiza oleju, zmniejszenie zużycia

Abstract:

Maintenance is a very important activity, which is necessary for the good operation of any technical system, even for the hydraulic drive systems. The predictive maintenance evaluates the state of technical performances of a system, by identifying the wear and thus avoiding the failures of the equipment. Using three methods of the predictive maintenance, namely infrared thermography, vibration analysis and oil analysis, the authors present their results of an experimental research on hydraulic pumps. The authors obtained thermograms, vibration spectra and diagrams of the oil contaminants which helped them indicate the proper or the malfunction of the studied pumps. Although they were only made on pumps, their investigations highlight the need of widely implementation of these modern and efficient methods in the industrial activities for the quick monitoring of the hydraulic machinery and equipment wear, before their failure occurs. Obviously, the goal is to have strong maintenance instruments in hydraulic drive systems diagnosis.

Streszczenie:

Konserwacja to bardzo ważna czynność, niezbędna do prawidłowego działania każdego systemu technicznego, nawet hydraulicznych układów napędowych. Konserwacja predykcyjna ocenia stan wydajności technicznej systemu poprzez identyfikację zużycia i unikanie w ten sposób awarii urządzeń. Wykorzystując trzy nowoczesne metody konserwacji predykcyjnej, tj. termografię w podczerwieni, analizę drgań i analizę oleju, autorzy przedstawiają wyniki badań eksperymentalnych hydraulicznych pomp. Autorzy uzyskali termogramy, widma drgań i diagramy zanieczyszczeń olejowych, które pomogły wskazać prawidłową lub nieprawidłową pracę badanych pomp. Chociaż zostały wykonane tylko na pompach, ich badania podkreślają potrzebę szerokiego wdrażania tych nowoczesnych i efektywnych metod w działalności przemysłowej do szybkiego monitorowania zużycia maszyn i urządzeń hydraulicznych, zanim dojdzie do ich awarii. Oczywiście celem jest posiadanie mocnych narzędzi konserwacyjnych w diagnostyce hydraulicznych układów napędowych.

1. Introduction

When we talk about the quality of products and services, it is mandatory to refer to maintenance, seen as an integrated model input-output system, which is characterized by planning, organizing, monitoring and checking operations [1]. The input process output model (IPO model) of the maintenance process is shown in Fig. 1. Regarding the maintenance and its management, in the technical literature the following notions are made known:

– corrective (or breakdown) maintenance;
– time-based (or use-based) preventive maintenance;
– condition -based preventive maintenance.

Other maintenance strategies are:

- opportunity maintenance;
- fault finding;
- design modification;
- overhaul;
- replacement;
- reliability-centred maintenance;
- total productive maintenance (TPM), in Japan, mainly.

Choosing a specific strategy or policy depends on the links between the maintenance system and the objectives of the organization [1].

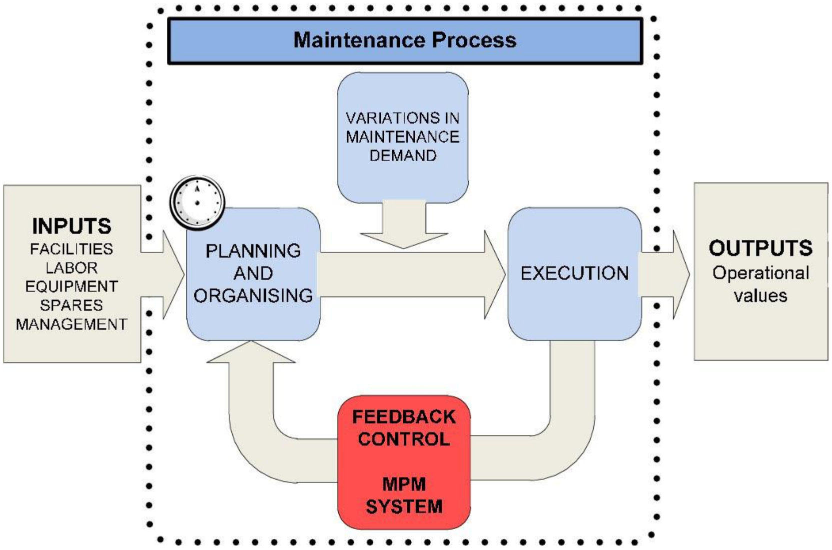

Fig. 1. Input process output model (IPO model) of the maintenance process [2]

- ✓ Corrective maintenance (**CM**) has its main purpose the performance of repairs immediately after the failure of the component or system.
- ✓ Time-based preventive maintenance (or simply, preventive maintenance, **PM**) is a planned maintenance made to prevent and fix problems before defect occurs.
- ✓ Condition-based preventive maintenance (**CBM**) is based on monitoring and gathering of information regarding the condition of the equipment aiming to prevent unexpected defects and to indicate optimal maintenance plans. [3] Condition-based maintenance is a form of predictive maintenance strategy and is more than a simple preventive maintenance (**PM**); in this case the reliability indicators of the system are improved and the maintenance costs are low. In **CBM** the time between two pauses is shorter than in **PM**. Condition-based maintenance is applied to a machine system, and also to a sub-assembly, or a component. In time, all data obtained from the monitoring parameters, according to the predictive maintenance program (**CBM**) are studied and compared with the existing data. The periodicity of the future maintenance program and its optimization is possible by statistical analysis.

In hydraulic drive systems, the most common predictive maintenance methods (Fig. 2) are the follows:

- Vibration analysis;
- Oil analysis;
- Infrared thermography;
- Ultrasound control.

For monitoring the parameters of a hydraulic system and its components, the specialists recommend mainly the first three methods [3].

Fig. 2. The most common predictive maintenance methods [4]

2. Vibration analysis

Vibration remains among the first status indicators of a machine. Vibration allows any problems to be identified before other symptoms occur, including overheating, possible noise, power consumption, and lubricant impurities. [5].

Hydraulic pumps vibration analysis

Internationally, there are notable concerns regarding the monitoring of vibrations in hydraulic pumps and especially where they work in high-risk working environments, such as mining facilities. Thus, in Indonesia, the Underground Mining Education and Training Unit (ETUUM) which has hydraulic groups used to support the mine galleries has conducted researches on the vibration behavior of a hydraulic pump, a basic component in their operation. Hydraulic groups are hydraulic units used to help installing of supports in underground mines [6, 7]. The installation of underground mining supports that require a hydraulic unit means the installation of active supports, such as the hydraulic support and the ceiling support, operated by means of a fluid under pressure. This pressure is obtained by means of a piston pump driven by an electric motor (Fig. 3) [6].

Fig. 3. Hydraulic piston pump and electric motor[6]

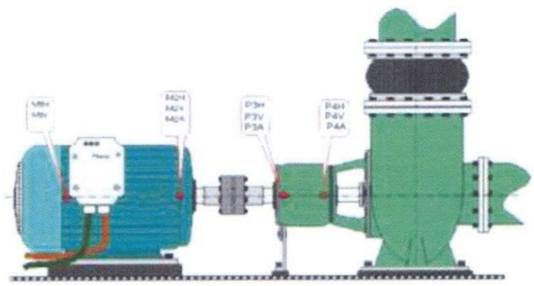

Fig. 4. Measurement points vibration data [6]

Vibrations occur when the capacity, rotation, cavitation, imperfection of the pump drive system lead to instability [8]. Vibration analysis can be used not only to measure the vibration phenomenon caused by mechanical forces, but also for electrical or hydraulic phenomena [9]. With the advancement of technology and predictive maintenance management of mechanical equipment, it is necessary to test mechanical vibrations as an indicator of attention [10]. Knowing the general state of the feasibility of machines requires the analysis of the vibration spectrum [11].

Vibration monitoring was done at various points on the pump and motor. The measuring points on the motor and pump (horizontal and vertical) for the vibration data are represented in Fig. 4. The Indonesian research estabilshed the general state of feasibility of the analyzed hydraulic group based on the analysis of vibration spectra from the pump and motor, using the ISO 10816-3 vibration standard.

Vibration analysis of five hydraulic pumps in a pumping station

In the Hydraulics Laboratory of the Hydraulics and Pneumatics Research Institute INOE 2000-IHP Bucharest, several experiments at the pumping station of the testing stand for hydrostatic equipment have been conducted in order to evaluate its operation, through research method based on vibration analysis. Following the tests, vibration diagrams were obtained for a number of five pumps of different types. The pumping station of the testing stand is equipped with a tank of 800 l capacity, for H46 mineral oil (Fig. 5). The hydraulic oil in the tank is moved to the stand by 5 pumps (Fig. 6-10 and Table 1).

Fig. 5. Pumping station

Fig. 6. Pump P1

Fig. 7. Pump P2

Fig. 8. Pump P3

Fig. 9. Pump P4

Fig. 10. Pump P5

Table 1. Technical characteristics of the pumps

P1	hydraulic vane pump, very compact model, fixed displacement, with catalog code PVV4-1X/122RA15UMC, Manufacturer: Rexroth/ Spain
P2	hydraulic simple vane pump, fixed displacement, with catalog code PVV2-1X/060PA150MB, Manufacturer:Rexroth/ Spain
P3	hydraulic bent axis axial piston pump, variable displacement, model D-89275, type A7VO55EP/63R-NZB01, Manufacturer:Rexroth/Germany
P4	hydraulic bent axis axial piston pump, variable displacement, model D-89275, type A7VO55EP/63R-NZB01, Manufacturer: Rexroth/Germany
P5	hydraulic external gear pump, model 7930, catalog code 510425009, Manufacturer: Rexroth/Germany

In order to perform the tests, an accelerometer – model SN 126981 (Piezotronics PCB - USA) was attached to the pump bodies. The accelerometer was connected to the data acquisition board via a signal conditioner, model 480 B10 (Piezotronics PCB - USA) to an analog input of the board. The signal conditioner was powered by a 24 V DC voltage.

The signal from the analog input was scaled in the LabView application to be displayed as acceleration value, according to the accelerometer measurement range, i.e. the 5 V signal will be displayed on the diagram as 50 g (g = 9.81 m/s^2). The test for each pump was performed by attaching the accelerometer with a magnetic support on the discharge line in the pump. Each pump was started and the vibration level (acceleration) was recorded in two operating modes (idle and load). The working pressure used during the tests was 130 bar. For example, the vibration diagrams thus obtained for the pumps P1 and P2 are presented below (see Fig. 11-14).

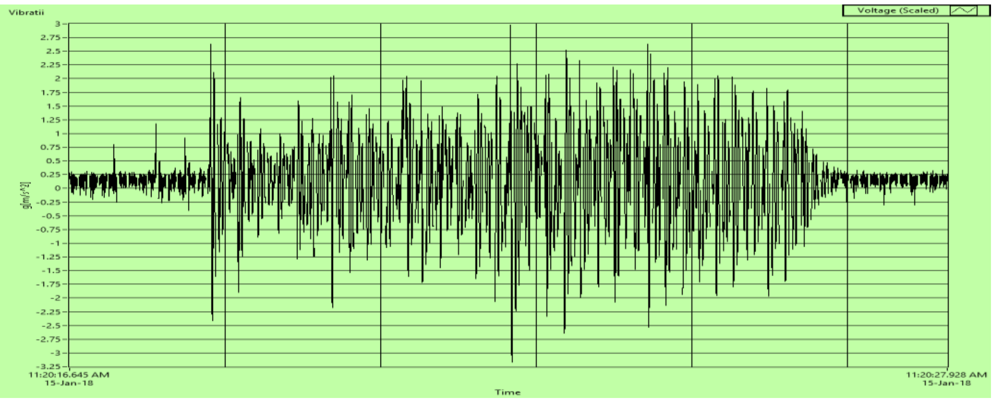

Fig. 11. P1 (idle working) vibration diagram

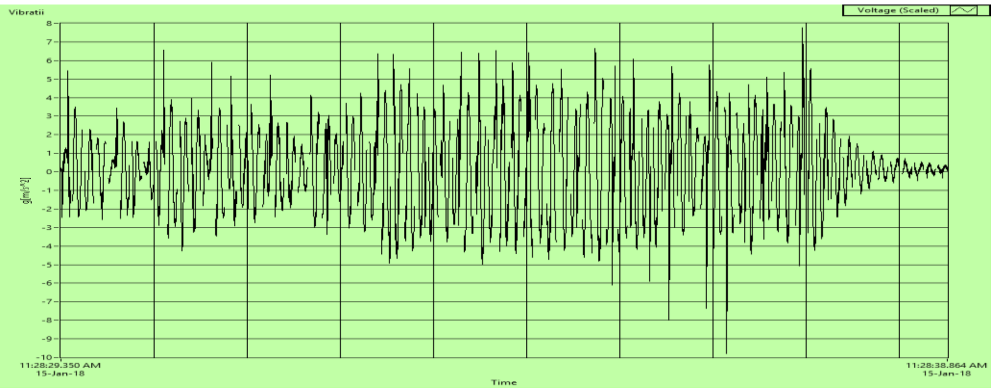

Fig. 12. P1 (load working) vibration diagram

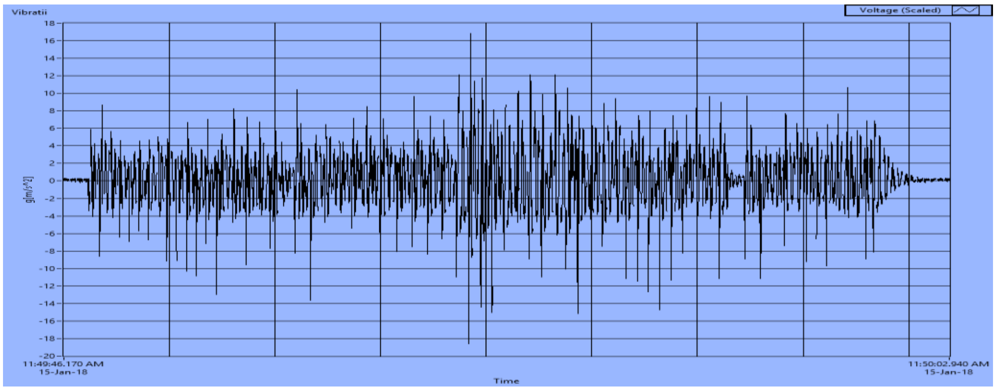

Fig. 13. P2 (idle working) vibration diagram [12]

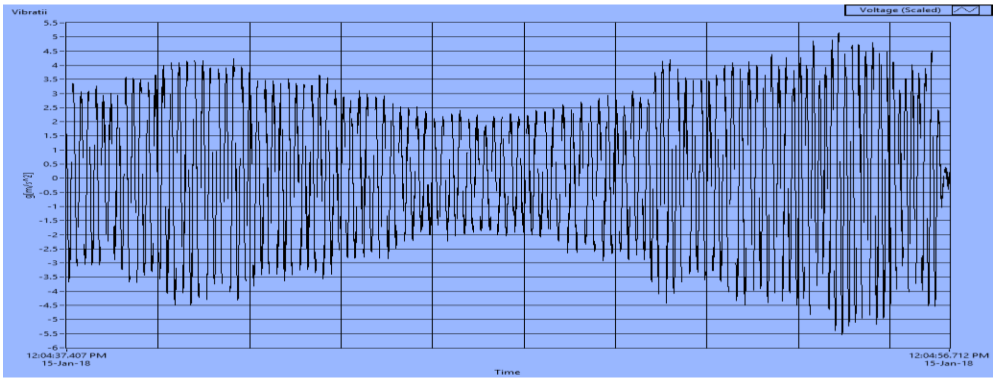

Fig. 14. P2 (load working) vibration diagram [12]

Publisher: KOMAG Institute of Mining Technology, Poland

Comparing the two sets of resulting diagrams, it can be seen that the amplitude of the vibrations of the pump **P1**, load working, is greater than the amplitude of vibrations corresponding to the idle pump mode, while the amplitude of the vibrations of the load working pump **P2**, is smaller. than the amplitude of the vibrations corresponding to the idle pump mode. If we consider these vibration diagrams as a reference, for the load working or idle working behaviour of the pumps, at a pressure P = 130 bar, then all the vibration diagrams resulting from the load or idle operation at the same pressure , will be able to be compared with them, in order to be able to draw some relevant conclusions regarding the state of wear / functionality of the analyzed hydraulic equipment. Obviously, this reason is also valid for the other three component pumps of the pumping block: **P3, P4, P5**.

Further in-depth research was carried out separately, on an experimental stand (Fig. 26) in which the behaviour of a hydraulic gear pump, identical to the **P5** pump, subjected to the cavitation phenomenon, was studied. Specifically, the pump cavity was induced by mounting an adjustable throttle on the suction line. At a working pressure in the system Pm = 100 bar, corresponding to a depression Pv = -0.20 bar, from the analysis of the obtained vibration spectra, it was possible to demonstrate the direct connection between the defect appeared in the pump as a result of the cavitation phenomenon and the measured vibration frequency. on the pump body using three accelerometers, Bruel & Kjaer brand, type 4507 B (Denmark)

The processing of the accelerometers signals was done using a data acquisition plate National Instruments brand, type NI 9233 (USA) connected to a laptop.

The obtained results analysis

We can see on the overlays spectra that in the high frequencies range (9000-16000) Hz, the levels of the accelerations is bigger at big cavitations (-0.7 bar; -0.6 bar) and lower at small values of pressure (-0.2 bar and -0.5 bar).

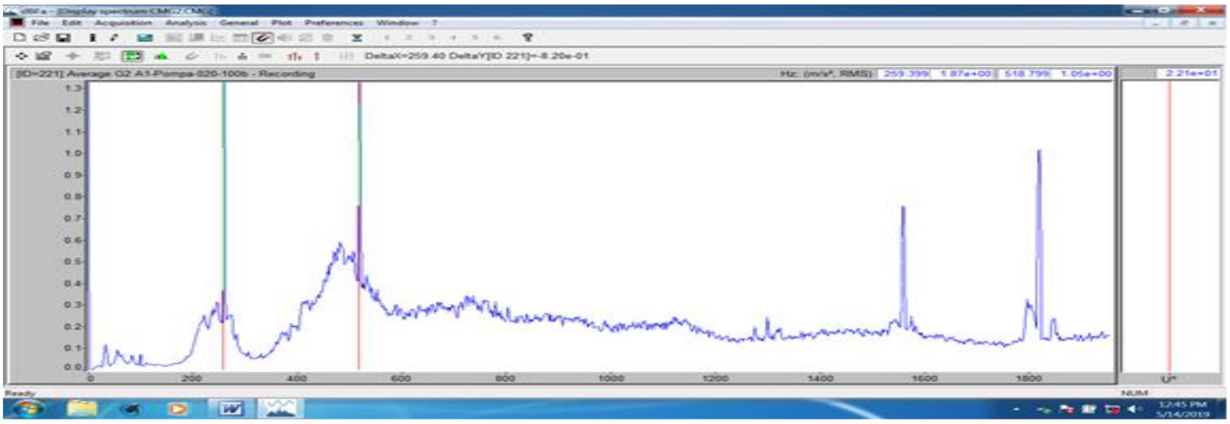

Fig. 15. Spectrum analysis for Pv= -0.20 bar; Pm = 100 bar [13]

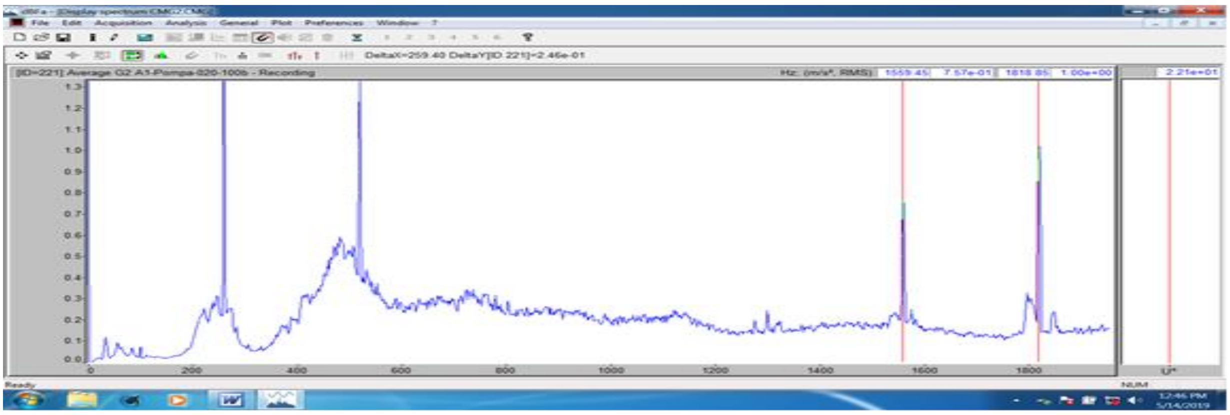

Fig. 16. Spectrum analysis for Pv= -0.20 bar ; Pm = 100 bar [13]

- At the Fig. 15 spectrum, we see it appears a frequency of about 259.4 Hz, with a harmonic of 518.8 Hz [13].
- At the Fig. 16 spectrum, we see this frequency then it's repeating with superior harmonics 1559 Hz (6x 258.4 Hz), then 1818 Hz, etc., that indicate a pump defect [13].

3. Oil analysis of three hydraulic gear pumps

Solid particles, soot, heat, air, glycol, fuel detergents and process fluids are all contaminants that are frequently found in hydraulics oils [14]. Generally, a particle counter is probably the most versatile tool for implementing the concept of proactive maintenance[14]. However, remarkable results can be obtained in this direction with the help of oil analyzers.

At INOE 2000 –IHP, the first attempts to use the oil analysis method started from the mid-2019 by predicting the behavior of three hydraulic gear pumps (HGP1, HGP2, HGP3), mounted on three stands prepared for testing specific endurance to a partner company. The experiments traced the evolution over time of the number of particles of oil contaminants, appeared as a result of the running-in of the pumps, having diameters d > (4 µm; 6 µm; 14 µm; 21 µm; 38 µm; 70µm), and its particular contributions to the wear of the pumps. The authors highlight the important role that monitoring of the clarity level of hydraulic oil has. If big levels of impurities particles are noticed in the working fluid, the malfunction can be removed in short time, avoiding damages to the pumps and reducing the costs of repairing them. In order to conduct the experiments, the oil samples taken from the partner company, were carefully monitored at INOE 2000-IHP Bucharest, using a laser analyzer within the Fluid Mechanics Laboratory.

The Laser CM 20 portable laser analyzer (Fig. 17) used for experiments is a product of Parker company (USA) that incorporates the most modern technology in the field for the analysis of solid particle contamination. The appliance is particularly complex and reliable and is designed to be easy to handle [15]. The average time to perform a test is about 2 minutes. In addition to the analyzer printer that is mounted in its body, the appliance consists of a keyboard with a display to show the obtained data (Fig. 18) and a sampling module (Fig. 19) equipped with two oil containers that can work separately, except for a pressure tap. 100 ml of hydraulic oil samples from the monitored endurance stands were placed in the container on the left side of the appliance. At the beginning of any analysis, the Flush command must be activated so that the oil sample is filtered and cleaned of impurities [15]. The amount of oil that has been processed in this way is then transferred to the container in the right of the appliance. Immediately after the operation of calibrating the analyzer printer, the Print command was given, which allowed the printing of a receipt indicating the number of solid particles of corresponding impurities in the ascending order of their diameters > 4 µm,> 6 µm,> 14 µm, > 21 µm,> 38 µm > 70 µm. Examples are shown in Fig. 20-22, for the last oil sample analysis of the pumps HGP1, HGP 2, and HGP3.

Fig. 17. Laser CM Analyzer Parker

Fig. 18. Keyboard analyzer

Fig. 19. Sampling module

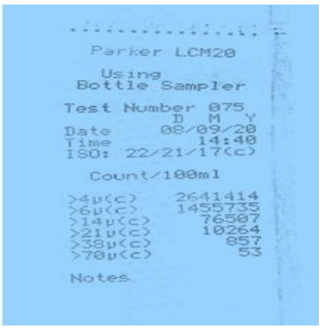

Fig. 20. HPG1 receipt

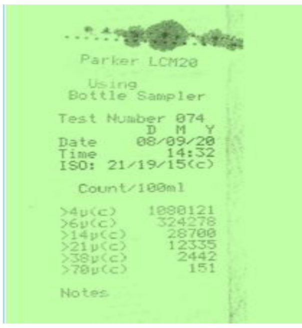

Fig. 21. HPG2 receipt

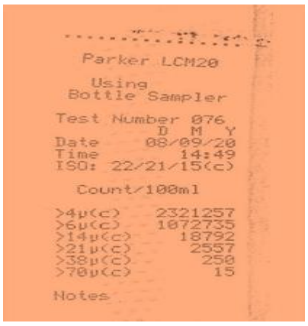

Fig. 22. HPG3 receipt

Immediately after the end of the endurance cycles of the 3 pumps, the trend diagrams of the contaminant particles with diameters d> (4 µm, 6 µm, 14 µm, 21 µm, 38 µm, 70 µm) will be drawn up and the contribution of each of these classes of impurity sizes to the wear of the related pumps will be determined precisely.

4. Infrared thermographic analysis method applied to hydraulic gear pumps

The infrared thermography method comes in support of the "20-20-20" program, which requires a 20% reduction in greenhouse gas emissions (CO2 equivalent) compared to 1990, and also reducing the final energy consumption by 20% compared to 2005, by increasing energy efficiency and increasing the share of renewable sources in the total energy mix to at least 20% by 2020 [16]. Predictive maintenance by infrared thermography is a method that meets the current requirements of reducing the CO_2 footprint and protecting the environment; it is non-polluting and has low energy consumption. The predictive maintenance is a maintenance method in which measurements and signal processing methods are able to accurately diagnose the equipment behavior during operation mode [17]. Vibration analysis and thermography are predictive maintenance techniques that can be used to monitor of an engineering system [18].

In the field of hydraulic drive systems, infrared thermography has been used at INOE 2000-IHP Bucharest since September 2016 and the first thermographic analyzes on hydraulic equipment were conducted.

The experimental research aims to demonstrate the possibility of using infrared thermography to evaluate the state of wear and functionality of hydrostatic pumps used in hydraulic drives. The measurements and analyzes carried out by the authors of this paper on hydraulic gear pumps have led to the conclusion that their abnormal operating conditions, resulting either from increased wear or from the appearance of cavitation or any other defects which result in an increase in their temperature, can be detected in short time by measuring the temperature with infrared thermal imaging cameras. This allows remedial action to be taken before the pumps are completely destroyed. It can be concluded that the use of infrared thermal imaging cameras can be the basic tool for elaboration / developing methods or methodologies for preventive and predictive maintenance on the behavior of hydrostatic pumps, in order to assess their state of wear and functionality. Using infrared cameras, more information is obtained then infrared thermometers. Infrared cameras can give a structural deficiencies image and temperatures on any point of the structure's surface; infrared thermometers measure only the temperature from a distance. Each method is a non contact method to measure the temperature [19, 20, 21]. Fig. 23-24 show two FLIR models of infrared thermal imaging cameras used by the authors of the paper in their work. In order to achieve the research objective, at INOE 2000-IHP Bucharest, a test stand was designed and developed, to demonstrate the usefulness and efficiency of using the infrared thermography method in the behavioral prediction of hydrostatic drive systems (Fig. 25). The stand is used to test hydraulic gear pumps, currently used in hydraulic drive systems. The tests consists in the simulation of the different working regimes, and the operation at different pressure levels, as well in the gradual modification of the suction conditions of the pump, after a suitable procedure. With the help of thermograms one can find out if the pumps work correctly or have defects. For example, Fig. 26 and Fig. 27 show two obtained thermograms for the same pump, but in different state of working: normal and abnormal, respectively. The difference between the two pumps is given by the normal temperature (39.9°C) and the very high and abnormal temperature (89.7°C) measured by the FLIR thermographic camera on the pump housing, which indicates the malfunction of the pump, because the temperature in its normal operating mode, as specified in the manufacturer's data sheet, must not exceed 70°C.

Fig. 23. FLIR camera

Fig. 24. Pocket model FLIR camera

Fig. 25. Testing stand for gear pumps

Fig. 26. Proper working pump

Fig. 27. Defective working pump

5. Summary

The paper aims to present part of the research carried out by the specialists at INOE 2000 – IHP in the field of the predictive maintenance activities. Although, so far, the work has focused only on the analysis of several pumps, further in-depth research on other types of hydrostatic equipment will be conducted, such as research on directional valves, or rotary and linear hydraulic actuators. With regard to the three non-invasive methods presented, the following clarifications are required:

- The vibration analysis applied to to the 5 component pumps of the pumping station allowed to draw some vibration diagrams that will serve as a comparative model for other such diagrams that will have to be periodically raised by the personnel involved in the predictive maintenance activities. With these results thus obtained a database can be built which can provide important information about the state of wear or functionality of the pumps.
- The oil analysis applied to the monitoring of the 3 hydraulic gear pumps will allow a complete image of their state of wear/functionality, immediately after the end of the endurance cycles to which they have been subjected by the manufacturer. The authors intend to present in a future paper the complet results of their researches carried out in this direction.
- The method of thermographic analysis applied to hydraulic gear pumps allows one to obtain reference (standard) thermograms corresponding to the normal operating regimes of the analyzed pumps. A database may also be set up in conjunction with thermograms indicating the malfunction of the same types of pumps, operating under the same pressure and temperature conditions, which can provide important information about the state of wear/functionality of the pumps.
- Practically, in many important industrial fields, such as military, aeronautical, metallurgical, power or mining, hydrostatic equipment is widely used, on the proper functioning of which complex machines, systems and equipment depend.
- For this reason, the authors consider that this article will capture the interest of those specialists who carry out maintenance activities in these basic sectors and will make a good contribution to the development of the field through the information provided.

References

[1] Duffuaa S.O., Raoul A.: Planning and control of maintenance systems. Modelling and analysis. 2nd Edition, Springer 2015.

[2] https://www.semanticscholar.org/paper/Maintenance-performance-metrics-a-state-of-the-art-Kumar Galar/65d35c09f9ccd068dafae30bc222b2c5fab9a3e1/figure/8 [accessed: 15.10.2020].

[3] Mobley R.K.: Maintenance Engineering Handbook. 7th Edition. McGraw-Hill. Section 7. Instruments and Reliability Tools 2008.

Publisher: KOMAG Institute of Mining Technology, Poland

[4] NTT Inc. - What's The Impact of Predictive Maintenance Programs? https://www.nttinc.com/blog/whats-the-impact-of-predictive-maintenance [accessed: 15.10.2020].

[5] Bernet J.: Vantaggi relativi all'analisi delle vibrazioni, Fluke Nota applicativa http://www.farnell.com/datasheets/1600460.pdf [accessed: 15.10.2020].

[6] Hajianto M.R., Yulianto A.: Vibration analysis for monitoring the condition of hydraulic powerpack for underground mining supporting simulation at education and training unit of underground mining (ETUUM). American Journal of Engineering (AJER) 2017. 6(5), pp. 123-129, e-ISSN:2320-0487 p-ISSN:2320.

[7] Prasojo H. A.: Hydraulik Powerpak, (BDTBT). Sawahlunto, 2014.

[8] Sihombing S.: Kalibrasi Mesin Pompa Sentrifugal Single Stage terhadap Respon Getaran Untuk Daerah Axial dan Vertikal. VISI 2009, 17 (2), pp.108-131.

[9] Bakhri S.: Investigasi Pemantuan Kondisi Vibrasi Untuk Keselamatan Operasi Pompa Pendingin PWR. Sigma Epsilon 2013. 17(3), pp. 88-101.

[10] Kelly S.G.: Fundamentals of Mechanical Vibration. Second Edition. Mc Graw Hill 2000.

[11] Harjono R. N., Sukmadi T., Karnoto: Permanfaatan Spektrum Vibrasi Untuk Mnegindkasikan Kerusakan Motor Induksi di PLTU Indramayu 3x 330 MW. Transient 2013. 2(3), pp. 408-414.

[12] Marinescu A.D., Safta C.A., Popescu T.C., Cristescu C.: Maintenance of hydraulic drive systems via vibroacoustic diagnosis. 18th Multidisciplinary Conference "Professor Dorin Pavel – founder of Romanian Hydropower"- Cluj Napoca, 2018, June 1-2. Revista "ŞTIINȚĂ ȘI INGINERIE" ("SCIENCE AND ENGINEERING" Magazine) 2018. 34, pp. 247-256, ISSN 2067-7138 https://stiintasiinginerie.ro/34-29-mentenanta-sistemelor-de-actionare-hidraulica-prin-diagnoza-vibroacustica [accessed: 17.10.2020].

[13] Marinescu A. D., Orășanu N., Safta C. A., Cristescu C.: Vibroacoustic predictive investigations on normal or defective operation of hydrostatic pumps. In Proceedings of the 25th International Conference on Hydraulics and Pneumatics – Hervex 2019, November 13-15, Băile Govora, România. pp. 169-176 http://www.fluidas.ro/hervex/proceedings2019/pp.169-176.pdf

[14] Mačužić I., Jeremić B.: Proactive approach to oil maintenance strategy. Tribology in industry 2004. 26 (1&2). pp. 27-31http://www.tribology.rs/journals/2004/1-2/5.pdf

[15] https://manualzz.com/doc/6598462/laser-cm20__park%20Erhfde [accessed: 17.10.2020].

[16] http://arpee.org.ro/strategia-europa-2020-programul-20-20-20/ [accessed: 18.10.2020].

[17] Dhillon B.S.: Engineering Maintenance. A Modern Approach. CRC Press 2002, pp. 13-15.

[18] Mobley R. K. (ed.): Maintenance Engineering Handbook. 7th Edition. Section 7. Instruments and Reliability Tools (by Mobley R. Keith), pp. 7.105-125. McGraw-Hill 2008.

[19] Childs P. R N.: Practical Temperature Measurement. Butterworth Heinemann 2001, pp. 238-287.

[20] Mihai Al.: Termografia în infraroşu. Fundamente. Ed. Tehnică, Bucureşti 2005.

[21] Marinescu A. D., Cristescu C., Popescu T. C., Safta C. A.: Assessing the opportunity to use the infrared thermography method for predictive maintenance of Hydrostatic Pumps. In: Proceedings of the 8th International Conference for Energy and Environment (CIEM), University Politehnica of Bucharest, October (19-20), 2017, #127, in Section Hydro Power Engineering, pp. 270-274; DOI:10.1109/CIEM.2017.8120790

Publisher: KOMAG Institute of Mining Technology, Poland