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SELECTED PROBLEMS OF DIAGNOSING TOOTHED GEARS IN THE ASPECT OF DEVELOPING HUMS SYSTEM

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Abstract

A diagnostic FDM-A method, based on the measurement of modulation of constituent frequency of direct current (DC) generator pulsation as well as FAM-C method, established on the measurement of frequency modulation of alternating current (AC) generator, were developed in the Air Force Institute of Technology [3, 9-10]. The essence of their accuracy lies in "natural" synchronizing of sampling with angular speed of the observed kinematic pair – if the dynamic processes of the observed object accelerate, the sampling becomes faster too [9-10]. At the same time, around the "synchronization points", due to the clearance in the power transmission there is a certain natural oscillation between the observed kinematic pair and *generator's rotor − vibrations are created. These vibrations are called jitter [9, 23] and they constitute an additional supplement to this method, because they provide more information on resolution and accuracy. Moreover, the abovementioned method enables to define the level of subassembly abrasive wear and its location in the time of normal operation of the powerplant [9-10]. This method allows also detecting resonances of elements on the basis of observation of shape and relative position of characteristic sets, which i.e. enable to calculate the mechanical quality factor of kinematic pair − it is possible to establish the operation time of kinematic pair until entering the resonance degradation. Other numerous parameters associated with the assembly of power unit rotor were also outlined: rotor skew angle, level of frictional wear of bearing cage − lack of contact of bearing components, bearing assembly ovalisation.*

Keywords: *aviation, alternator, frequency modulation, helicopter gearbox, bearing wear, gear wear, Health and Usage Monitoring System (HUMS), power transmission, characteristic pattern*

1. Introduction

Toothed gears were commonly applied already in the ancient Greece and were utilized, as nowadays, to change the angular speed. In modern gears their loading has increased several time, what puts them at risk of intensive wear. Owing to this fact, it is essential to possess systems of their monitoring and diagnosing. This need is entirely relevant in the case of multi-purpose helicopters, where reduction of mass causes the decrease of wear resistance and in case of powerplants of vessels operating far beyond the overhaul back-up facilities. The necessity to install semi-automatic diagnosing systems is extremely urgent as regards multi-purpose helicopters. It should be borne in mind that as on vessels and aircrafts the steering is separated from powerplant, in helicopters these two components are correlated with each other, or even integrated. Therefore, e.g. the excessive clearance between teeth might, in certain conditions, causes instability of revolutions of tail rotor, what is reflected in the difficulty of maintaining the direction of the flight. During rescue operation in difficult weather conditions on the sea, it might result in the instability of the centre of suspension and pose a threat to both rescued persons and rescuers. In extreme cases it can also lead to the stoppage of tail rotor – in such a case the pilot is no longer able to control the direction of the flight and according to Newton's Third Law, the helicopter fuselage starts to rotate in the opposite direction to the direction of revolutions, what ends in its break or airplane crash.

In the Air Force Institute of Technology (AFIT), works are being conducted on the monitoring of transmission system of multi-purpose helicopter with non-destructive methods: vibroacoustic and FAM-C method. By the implementation of one of the aforementioned methods (vibroacoustic method), it is observed that there are operational vibrations of main gearbox of the helicopter at issue. This method is applied to determine the curve of gearbox wear and establish the trend of changes of vibrations speed characterizing the spectrum of vibrations of multi-purpose helicopter on certain operating ranges.

On the basis of vibration measurements, by calculating the speed V, it is possible to estimate the time of a potential breakdown. By performing the analysis and spectral distribution of vibrations, in comparison to rotational frequency f_0 and the knowledge on gearbox kinematics, it is viable to define the component (assembly) which should be subject to repair, exchange, or as it is in the case of operational aviation, stop the operation of a given helicopter in time, in order to avoid the plane crash. For instance, spectrum components of frequencies mentioned below are the symptoms of f_0 – unbalance, $2f_0$ – clearances, $2f_0$-$3f_0$ – misalignment, $n{\cdot}f_0$ – tooth frequency of the wheels with the number of teeth n and revolutions f_0. By studying the trend of changes of the given amplitudes of spectral components, which are vibrating symptoms of elements, their operational condition might be assessed. During the evaluation of the structural health of the main gearbox of multi-purpose helicopter, it should be taken into account that it is a complex object, which is affected by various kinds of input functions. Due to this fact, an attempt of modelling and dynamic describing of this gearbox is a difficult process, because it is a very nonlinear object and it depends on many variables [2, 20-23, 25]. Gearbox producer defines certain technical conditions (TC) for the given performance parameters. Dynamic state of transmission (Fig. 1) is described by dependencies between the type of input function, dynamic properties of mechanical system and amplitude of vibrations, generally a response of the system to the input function.

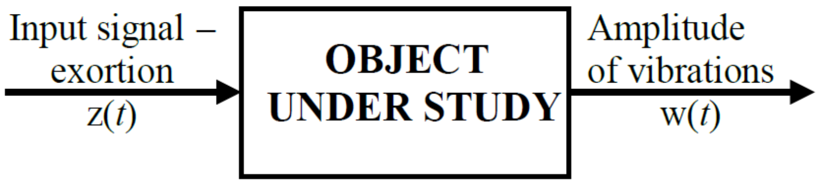

Fig. 1. The block diagram of a machine

Another non-destructive method, applied to carry out the studies of the main gearbox, is an author's FAM-C method [2-3, 8, 10], based on the measurement of frequency modulation of voltage of alternating current (AC) generator, developed in the Air Force Institute of Technology. This method effectively monitors the wear and damage of subassemblies, which is difficult to access for vibroacoustic sensors. FAM-C method, owing to the application of the on-board generator as a transducer, is identified by a "natural" sampling synchronization with the angular speed of the monitored powerplant [8-10, 23]. FAM-C diagnostic method might also provide data on structural health of many relevant mechanical pairs. It derives information from generator, which gets a wide spectrum of vibrations of rotational speed with the powerplant being mechanically coupled with it. Every kinematic pair of this assembly has its own chrominance frequency, which enables its quick identification like rated frequencies of particular instruments in the orchestra [9, 19]. All features of FAM-C method lead to the conclusion that this method might aim to complement the currently applied HUMS systems, which are presently based on "traditional" vibroacoustic sensors installed in selected subassemblies of the powerplant [4, 11-13].

Both powerplants of aircrafts and helicopters require a comprehensive monitoring system and effective diagnostic methods. In aircraft's powerplants the speed of the main shaft changes substantially (more than twice) depending on the cruising speed [9, 21]. A complex metrology aspect is determining the structural health of bearing supports and geometry of compressor shaft relative to turbine shaft. However, a crucial problem of helicopters consists in strong dynamic interactions of rotating rotor blades and other elements (free vibrations of airframe elements, the influence of aerodynamic forces as a result of the superposition of forward speed onto the speed in rotational motion of main rotor blade) on power transmission system. It should be also mentioned that as compared with the airplane, in which the phenomenon of generating the aerodynamic lift and changing the aerodynamic lift values (at least by small change of altitude) barely affects the powerplant, in helicopter, both these issues are strictly connected with each other [2, 9]. Therefore, when a helicopter starts to e.g. ascend or change the direction of the flight, the dynamics of influence on various kinematic pairs of the powerplant (on transmission shafts' assembly, on numerous subassemblies of powerplant gearboxes and on the swashplate bearing). The dependence in the opposite direction is also discovered − if mechanical elements of the powerplant would be excessively employed, it might lead to atypical airframe vibrations of high amplitude above the standard level disturbing aerodynamics of flight, or it might also induce the worsening of steering accuracy.

Thus, when it comes to the wear of the transmission elements transferring power to tail rotor, it is always associated with certain difficulties associated with maintaining the direction of the flight [1-2, 9, 26]. So far, for diagnostic measurements of aviation powerplants, including helicopter gearboxes, the following measurements were applied [9]:

a) vibroacoustic measurements [13, 21];
b) tribology measurements in a lubricating oil;
c) measurements of thermal fields;
d) measurements of rotational speed and displacements of rotating parts (e.g. compressor blades) by means of electromagnetic sensors [4-5, 21].

Based on these measurements, Air Force of the Armed Forces of the Republic of Poland develops various structural health monitoring systems of aircraft gearboxes.

2. General information on HUMS type monitoring systems

HUMS (Health and Usage Monitoring Systems) collect significant diagnostic information, which are used for maintenance works conducted by the crew during the flight. First practical applications since 1991 targeted mainly at increasing the dependability of transmission powerplant. Currently, airplanes and helicopters are provided with different HUMS systems, with higher or smaller range of observed parameters [11-12, 24]. In general, one notes a tendency of increasing the number of sensors, what leads to the more versatile spectrum of dangers occurring on board of the aircraft, but at the same time, the peril of the crash of the monitoring system is also growing. Owing to this fact, the authors of this elaboration suggested to get rid of some of sensors, thanks to the implementation of FAM-C method, which enables to trace lot (frequently geometrically remote) subassemblies on the basis of signals from on-board generator. By applying a variable phase configuration of FAM-C electronic measurement system, it is possible to monitor almost all rotating parts in the powerplant. The only condition is to mechanically couple the generator-transducer with the subassembly at issue – if this condition cannot be met, then traditional methods (e.g. a vibroacoustic method) remain. Versatility and observation accuracy of FAM-C method increases with the simultaneous use of signals from a few generators, by its different phase configuration – it is then feasible to observe the motion dynamics of rolling bearings and even monitoring of changes of the size of clearances between certain teeth.

3. General description of the powerplant of the multi-purpose helicopter

A multi-purpose helicopter is one of the most efficient weapons to destroy tanks and other on-ground targets, but it is also used as a means of transport.

A powerplant of the multi-purpose helicopter under consideration consists of (Fig. 2) certain subassemblies:

propulsion engines (detail 1),
main gearbox (detail 3),
power transmission shafts assembly (detail 4, 5, 7) transferring the part of power from main gearbox onto the tail rotor,
generator power gearbox (detail 6) attached in series between transmission shafts.

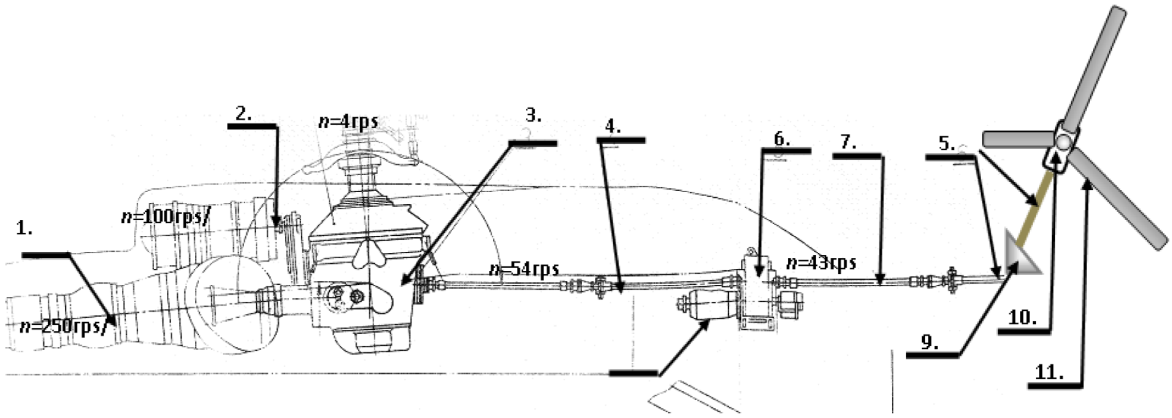

Fig. 2. The location of transmission elements between engine and generator on the multi-purpose helicopter: 1 – powerplant, 2 – mechanical fan, 3 – main gearbox, 4, 5, 7 – power transmission shaft, 6 – generator power gearbox, 8 – left generator (behind it, to the same power and accessory gearbox a right generator is mounted), 9 – intermediate tail rotor gearbox, 10 – tail rotor gearbox, 11 – tail rotor

Some of the helicopters operated in Poland are characterized by a generator power gearbox being mounted outside the transmission shaft – in the middle of main gearbox and tail rotor – Fig. 2. The defect of toothed wheels in the generator power gearbox is tantamount to the interruption of power in tail rotor. Such an interruption of power implies an immediate rotation of the fuselage in the opposite direction to the direction of rotation of the main rotor. This is also connected with the loss of aerodynamic lift and manoeuvrability. Not to mention the fact that it might cause a plane crash.

4. Dynamics of wearing transmission elements of multi-purpose helicopter

Every helicopter should be distinguished by the ability to conduct dynamic geometry changes of the flight path [2, 9]. It induces a substantial loading of powerplant and transmission system, i.e. upper bearing (maintaining main rotor drive shaft) of the main gearbox. Monitoring structural health of this bearing is a vital matter for safety of flights. As particularly dangerous one should always consider the long-term operation of this rolling bearing in resonance state, due to the fact that its destruction proceeds then very quickly. On the display of FAM-C one observes a disintegration of set typical for this bearing on the few (2-3) subassemblies [1, 9] – Fig. 3.

A quality value of these sets is also increasing; usually during this process, the rotation speed of bearing cage is also rising, thus enhancing its carrier frequency from the level f_P of 20-22 [Hz] to the value f_p of 50÷52 [Hz]. At the same time, from time to time in the powerplant (mounted in the middle of a transmission shaft − detail 6 on Fig. 2) there is also wear of bearing supports shaft of Z30 toothed wheel, ensuring the transfer of mechanical power onto the tail rotor. At times, the skew of the toothed wheel Z30 occurs. In that event, the free-running frequency of this shaft increases from f_P equalling 100÷102 [Hz] to f_P amounting to 50÷52 [Hz]. Occasionally, a spatial resonance between the main bearing and Z30 toothed wheel [9] might take place − synchronized modulations of angular motion of Z30 toothed wheel are generated and detected with FAM-C method in the form of FM modulations of instantaneous frequency in the time function − Fig. 4.

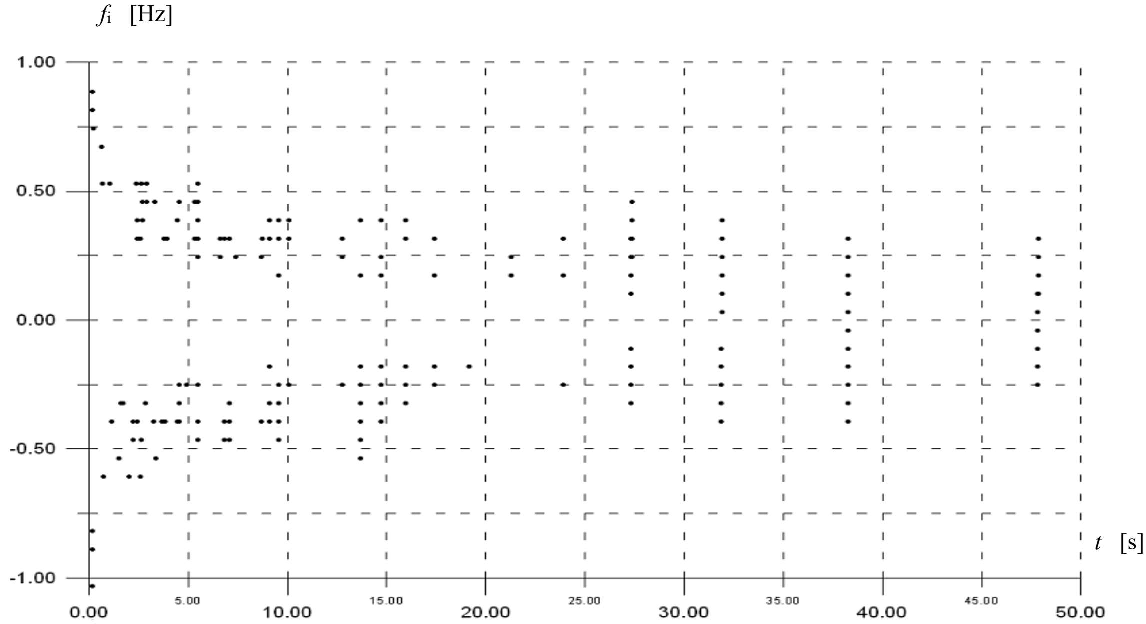

Fig. 3. Characteristic sets acquired for the powerplant of "negative standard" of the multi-purpose helicopter with damaged upper bearing of the main gearbox

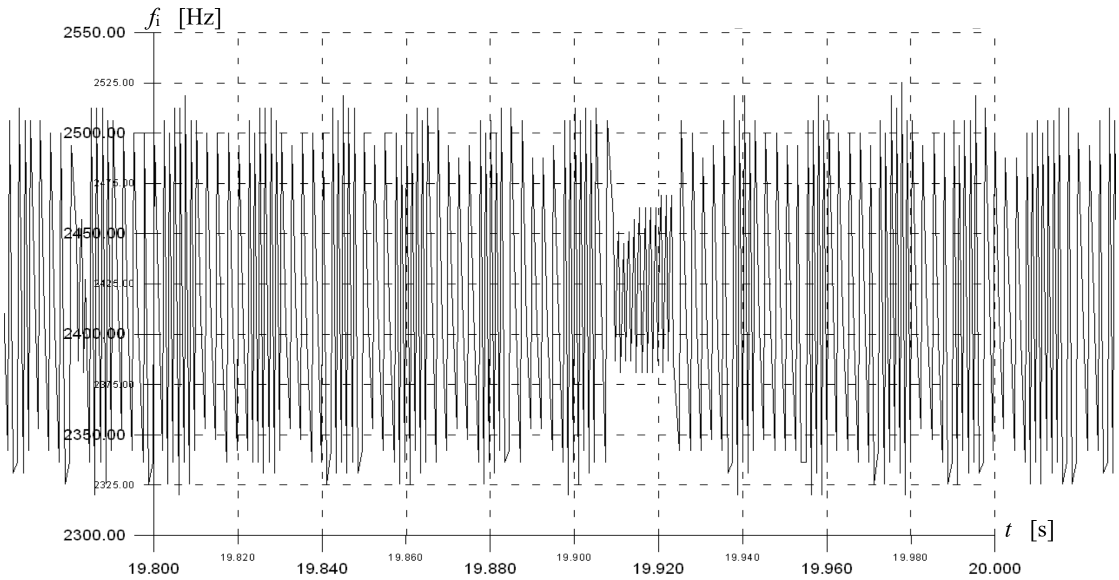

Fig. 4. Modulations of instantaneous frequency in time function during spatial resonance between the worn upper bearing of the main gearbox and worn bearing supports of Z30 toothed wheel in generator power gearbox

They reflect the variability of forces influencing the Z30 toothed wheel. Long-term occurrence of this state has an impact on the increased wear of the same 2÷3 teeth. It might end in their being so considerably undercut that it will lead to their rupture − Fig. 5. Moreover, the rupture of even one tooth usually generates so substantial impact forces that the neighbouring teeth also start to break. Besides, it might result in the loss of continuity of transferring the mechanical power onto the tail rotor. In this case, maintaining the direction of the flight becomes more difficult or even impossible − helicopter fuselage starts to rotate increasingly faster in the opposite direction to the direction of rotation of the main shaft.

Fig. 5. Z30 toothed wheel with broken teeth

A modern multi-purpose helicopter permitted for flights over water areas (a necessary condition in case of orders for the Naval Forces of the Republic of Poland) has to have two powerplants connected with the main gearbox with the aid of one-way clutches – Fig. 6 – ensuring the unidirectional transfer of power from engines to the main gearbox.

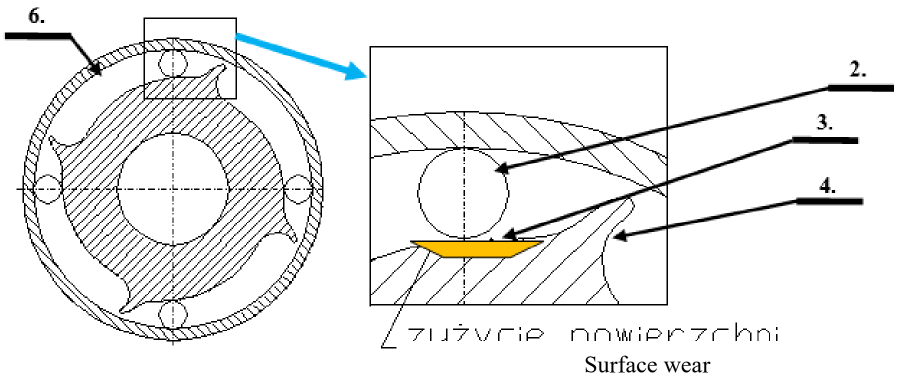

Fig. 6. One-way clutch − pictorial diagram:
1 − external ring (with internal raceway), 2 − rolling element, 3 − exfoliation of internal raceway, 4 − cage – separator

Sometimes, as a result of exfoliation of clutch internal raceway (detail 3) the interruption in providing mechanical power to the engine might follow. In FAM-C method, these interruptions are illustrated on the waveform of instantaneous frequency in the time function as the so-called fadeout impulses – Fig. 7 i.e. a substantial reduction of frequency level to the level below 0,707 of rated frequency – Fig. 7. Using the FAM-C method, it is possible to precisely determine the time and intensity of the duration of such interruptions in order to approve the clutch to overhaul.

5. Summary

This article portrayed the possibility to monitor three subassemblies of power transmission system of multi-purpose helicopter:

- main rotor drive shaft;
- upper bearing of the main gearbox;
- power generator gearbox.

These subassemblies are relevant for the safety of flights. The authors depict the chances to monitor dangerous wearing phenomena taking place in these subassemblies. Currently, in the Air Force Institute of Technology intensive works are being conducted on the intensification of wear levels of other kinematic pairs of multi-purpose helicopter, operated in the Armed Forces of the Republic of Poland. According to the authors, transferring experience gathered in the course of tests onto the helicopter fuselages in the form of modified HUMS systems, after the completion of these works, will be just a formality. Both suggested methods mutually do not interfere in the structure of the airframe and do not require a modification neither the user, nor by the producer. Not to mention the fact that these methods enable to take measurements and conduct analysis during normal operation of the helicopter.

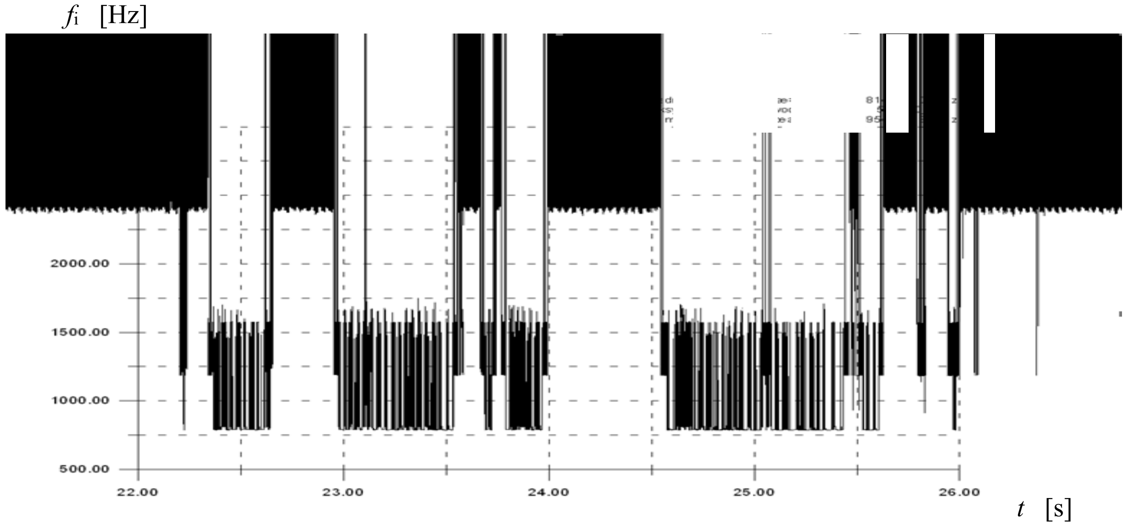

Fig. 7. The rupture of one-way clutch of the helicopter − the imaging obtained by the application of FAM-C method

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