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Computer Diagnostics of Helicopter Kinematic System from the Perspective of Hums System

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ABSTRACT

In the kinematic system of airplanes and helicopters there are critical elements of structures on which accelerated symptoms of fatigue use are observed, e.g. in the form of: damage (peeling) of the raceway of the rolling bearing, fatigue undercuts of the gears. The article presents a method for diagnosing a kinematic system based on an on-board generator (state observer). At the beginning, some of the research problems occurring in helicopters, based on their own research data, were approximated. Particular attention was paid to the phenomenon of resonance of rolling bearings and resonance excitation of a pair of gear wheels under its influence. The effectiveness of detection of such resonance phenomena by means of the proposed diagnostic method was presented. The conclusion summarizes the conclusions that the method provides a reliable diagnosis and would be a valuable complement of previously used HUMS. The directions of further research on the development of the diagnostic method were also indicated.

KEYWORDS: computer diagnostics, diagnostic method, HUMS system

1. Introduction

Drive units of modern aircrafts and helicopters require good monitoring system and effective diagnostic methods. In helicopters, the crucial problem is the strong, dynamic impact of blades (natural vibrations, aerodynamic forces' impact due to overlapping of forward velocity on the rotational velocity) on the power transmission system. It should be added that while in the aircraft, the phenomenon of formation of lift and changes in the value of this force (at least in a small change in altitude) almost does not affect the drive unit, in the helicopter this impact is large. During climb or change of the direction of the helicopter's flight, the dynamics of impact on multiple nodes of the drive unit increases. The dependence of the opposite perspective is also observed – if the mechanical elements of the drive undergo wear beyond norms, abnormal vibrations of an airframe, disturbing aerodynamics of flight or the deterioration of control precision may occur [1].

So far, in diagnostic measurements of aircraft drive units, including the transmissions of helicopters, the following measurements were used [2-6]: vibro-acoustic, inclusions in lubricating oil, temperature fields, rotating velocity and displacement of rotating parts (e.g. compressor blades) using electromagnetic sensors. All these methods require mounting of additional sensors. The proposed FAM-C (the diagnostic method based on the application of an AC generator, where FM – frequency modulation symbol (Frequency Modulation), A – alternating current symbol (AC – Alternating Current), C – method progression degree) [4, 5] diagnostic method uses a permanent on board power generator as instantaneous angular velocity (IAS) transmitter. The IAS signal depends on the operating range and AM/FM/PM modulation parameters generated by dynamic processes in the engine, control units, kinematic system and power receivers. The IAS and the instantaneous voltage of on-board generator are carriers of diagnostic information. It is possible to obtain a voltage signal of a direct current (DC) or alternating current (AC) on-board generator for the comprehensive evaluation of many elements of a power train. The use of FAM-C method, which does not require interfering in the structure of the power train, would make the HUMS (health and usage system) [7] system cheaper and more reliable.

2. General description of the FAM-C method

The FAM-C method was developed at Air Force Institute of Technology (by A. Gębura) in the 90 s of the twentieth century. The FAM-C method has been initially used (1990) only in LUZES (Ground Power Unit – constructed by Air Force Institute of Technology for Polish Air Force) airfield electrical power supply units with turbo-shaft engine GTD-350 [4], in which several diagnostic systems were installed. In this application, the FAM-C method was used for monitor the axial and radial run-out of the transmission shaft, as well to assess the rotational dynamics leading to rupture of tachometer shafts. High sensitivity of production and assembly errors detection (e.g., tooth gap between gear stages, shaft alignment) and reliable diagnosis made the FAM-C method applied to diagnose fatigue problems of the hydro-electrical GP 21 (Fig. 1.b, element 16) block installed on the gearbox KSA-2 (Fig. 1.a, element 15) on MiG29 aircraft. In this block there was the problem of screwing the drive shaft – (Fig. 1.b, element 17). Also in this application, the high efficiency of the method was confirmed, which was the basis for the development of the tester DIA-KSA-CM – (Fig. 1.a) and the implementation of the FAM C method for the diagnosis of the kinematic system of RD-33 engines and MiG29 aircraft transmissions (1993) [4]. The FAM-C method, based on the TTM idea, using on-board power generators as diagnostic transmitters, is a cheap, comprehensive, easy to automate, diagnostic method of monitoring the drive system of the helicopter. The power generator transmits diagnostic signals into bandwidth of the relatively high frequencies, and these signals obtain significant resistance to any kinds of interferences. Thanks to the development of the method of control over the bandwidth of the observability of mechanical processes ("a visibility window") of the power generator [8], we can observe almost all of the kinematic bonds of the drive system of a given helicopter. With this method, the technical condition of the main bearing and the gears of the gearbox of Mi24 helicopters was observed. While observing vibrations of the upper bearing of the main transmission of the Mi24 helicopter, it was stated that when a characteristic set of the bearing breaks into two subsets (Fig. 3), and the value of the Q factor increases to the level of Q = 4, this bearing must be decommissioned immediately.

In subsequent years, the FAM-C method has been used to diagnose the Mi24 helicopter kinematic system (main gearbox, generators' gearbox, transmission). The idea of the FAM-C method is presented in Fig. 2

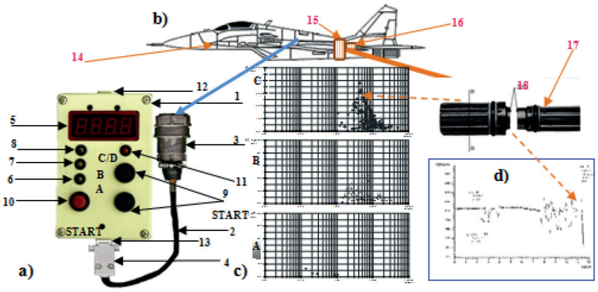

Fig. 1. DIA-KSA-CM diagnostic tester to a MiG29 aircraft: a) tester: 1. - housing, 2. - Kab-DIA-KSA-CM cable (intended for connection with the airplane), 3. - 2RMD33KPN32G5W1 connector, 4. - CANON DB9 connector, 5. - display, 6. - diode LED (yellow) indicating the zone of partial wear, 8. - LED (red) signaling the danger zone or failure zone, 9. - balloon ("+" and "-" for the test, 10. - button for running the test, b) 11. - LED (orange) indicating the duration of the test, 12. - connector for connection with the computer, 13. - tester connector, d) MiG-29 aircraft: 14. - fuselage, 15. - KSA-2 case chest, 16. - GP-21 generator (115V, 400 Hz), 17. - hydraulic and current stabilizer) - broken shaft connecting GP-21 with KSA-2, 18. – place of breaking, c) FAM-C imaging in the form of characteristic pattern ΔF = f (fp): A. - low level of wear KSA-2, B. - average level of wear KSA-2, C. - high level of wear KSA-2, d) = f (t) at night breakage of the aggregate shaft GP-21 [own study]

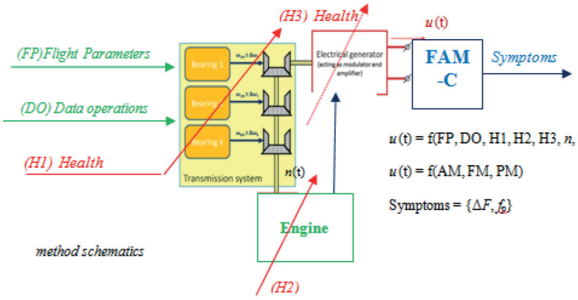

Fig. 2. FAM-C method schematics [own study]

The FAM-C method prefers steady-state of engine operation when power layer angle PLA = const and the derivative of engine IASe is small in relation to the transient states.

Under these operating conditions, the IASg signal of AC and DC generators reveals modulation components generated by:

- the fuel controller of engine (IASFC),
- kinematic system (ΔIASKS)
- external disturbances (Δ IASED),

which describes the mathematical formula (1)

$$IASg = f(ig \cdot IASe, \Delta IASFC, \Delta\ IASKS, \Delta\ IASED) \qquad \textbf{(1)}$$

where: ig is a kinematic transmission between the generator shaft and the motor shaft.

The generator voltage signal u(t) additionally contains information on: design features (DF) of the generator (number of poles, type - Alternating Current (AC) or Direct-current) [4, 9]; the modulation applied by: the voltage regulator VR(t), the inductance of the generator winding Lcoil and electric capacity of the generator winding and cables C.

$$u(t) = f\left(DF, IAS_g(t), VR(t), L_{coil} \cdot \frac{di(t)}{dt}, \int \frac{i(t)}{C} dt \right) \quad (2)$$

The reactance (inductance and capacity) components of u(t) can be omitted when the generator is not loaded with receivers (after disconnecting from the on-board electric network, i(t) ≈ 0). The influence of the voltage regulator VR(t) can be omitted for the quasi-constant engine IAS and i(t) ≈ 0. With such assumptions of measurement and (1) there is a relationship (3).

$$u(t) \approx f(DF, ig \cdot IASe, \Delta\ IASFC, \Delta\ IASKS, \Delta IASED) \quad (3)$$

The spectrum of the modulating components IASg maps the modal properties of the fuel system, kinematic system and external disturbances. A change in the technical condition of the test object, e.g. play in meshing of gears, misalignment results in a change in the spectrum u(t). The generator voltage u(t) in addition to the carrier frequency contains numerous characteristic frequency bands, which are the status observers of individual elements of the monitored object. This observation is the foundation of the FAM-C method.

For observation of the instantaneous spectrum u(t), the time of arriving u(t) by the reference level (zero for AC generator) is recorded and numerical analyzed. Measurement of the arrival time TOA(k) = f(u(t)) is carried out using the frequency method, with time resolution 0,5 µs (fclock = 2 MHz). Before the measurement, the signal u(t) is clipping (in the amplitude) and amplified G times in an analog-front-end (AFE), which describes the mathematical formula (4). The output signal from AFE is optically isolated.

$$u_{AFE}(t) = \begin{cases} u_{max} & if\ G \cdot u(t) > u_{max} \\ G \cdot u(t) & if\ \left[G \cdot u(t) \right] \epsilon u_{min}; u_{max} \\ u_{min} & if\ G \cdot u(t) < u_{min} \end{cases} \quad (4)$$

The analog signal u1N(t) is not spectrally limited before TOA measurement, as a result the discrete time TOA(k) maps the spectrum u(t) along with the alliances. FAM-C methods is in essence a Tip-Timing Method (TTM) [ ], which used for non-contact monitoring of vibrations and health of rotating blades: fan, compressor and turbine as well as complex diagnostics of jet engine [4]. In the TTM method, measurements are made in steady and transient states of the engine (set speed, acceleration, deceleration, start-up and run-out).

The measured TOA time describes the relationship

$$TOA(k) = \frac{1+\zeta_g(k)}{1+\zeta_\omega(k)} TOA_{carrier}(k) + noise(k) \quad (5)$$

where: ζg is a jitter of encoder phase markers (AC or DC generator), ζω is a jitterer generated by changes in the IASg; $TOA_{carrier}$ is the average arrival time of the encoder phase marker for a given range of engine operation; noise is a colorful noise of the measuring path and electromagnetic interference, *k* is a discrete time.

The noise level is minimized in AFE (in the analog part of the measurement path) after completion of laboratory tests and recognition of the spectrum of diagnostic symptoms. The AC or DC generator has rigid phase markers, arranged circumferentially with a constant error Δθi for the individual marker. Therefore, the FAM-C method is based on the calculated parameter - the instantaneous frequency IF(k) of the u(t) determined between each phase marker (two-sided comparisons of signal transitions through the reference level).

$$IF(k) \approx \left(1+\zeta_\omega(k)\right) \frac{1}{TOA_{carrier}(k)} = \left(1+\zeta_\omega(k)\right) f_{avg} \quad (6)$$

where: f_{avg} is the average carrier frequency u(t).

IF(k) decomposition on the carrier and modulating components is implemented in the PRAZEK software [4]. Quantitative and qualitative analysis of jitter *ζg* is carried out on the plane (Δ*F*, *fp*).

2.1 Results

Selected possibilities of the FAM-C method are illustrated in the examples of dynamics of the helicopter Mi24's transmission parts wear and tear. The helicopter's propulsion system (Fig. 3) consist of turbine engine, mechanical fan, the WR-24 main gearbox (with main shaft, upper bearing – Fig. 3, element 3a) helicopter propeller, power transmission shaft, generator's gearbox, tail rotors. On the destructive wear and tear of the gearbox if the Mi24 helicopter as a result of the impact of upper bearing (Fig. 3, element 3a) of the WR-24 main gearbox (Fig. 3, element 3) and the possibility of early recognition of this phenomenon, the authors already writes in. With the increase of the level of this bearing tribological wear and tear, the frequency of modulating's of the main shaft's angular velocity emitted in the direction of the tail rotor, and, therefore, the gearbox increases. At a certain level of tribological wear and tear of the upper rolling bearing (Fig. 3, element 3a), such frequency reaches a level equal to the rotational velocity of the generator's gearbox. Then, it is possible to synchronously induce the modulating's of these input rotational velocities, and, hence, the formation of a single, well-defined angular position of the dynamic surpluses and associated additional stresses on gearings. The gearbox itself is a generator of mechanical, self-excited vibrations of positive feedback. Synchronous excitation of the input rotational velocity and the said dynamic surpluses may cause undercutting of a gear pair in a well-defined angular position [4]. To prove this hypothesis, subsequent pieces of a puzzle, starting from the worn upper bearing of the WR-24 (Fig. 3, element 3a) and ending on the broken off gear-tooth of the generators gearbox (Fig. 3, element 6), should be traced. The main shaft is subject to an unbalanced torque due to the imbalance of the helicopter main propeller in its upper part, and, at the bottom, there is no significant moment of inertia. Therefore, all dynamic impacts of imbalance of the main propeller as well as a shield and a control head is transferred by the upper bearing.

Its damage may cause incalculable consequences, including the disaster. Therefore, the need of its monitoring is obvious. Traditional methods, for example, vibroacoustic ones, seem to be little effective due to: a) considerable thickness of the WR-24 main gearbox and damping of material structure (a cast made of a so-called electron); therefore intensively dampen acoustic vibrations and signals from the depths of the upper bearing, b) neighbourhood of mechanical nodes of exceptionally high levels of vibration and sound intensity in WR-24. In relation to these relationships, the FAM-C method seems to be the only alternative monitoring method.

2.2 Detection of the damaged upper main shaft bearing and other WR-24 main transmission component with the FAM-C method

After analysis of the parameters of the characteristic sets, it can be concluded that, between the main shaft bearing and the gearbox, mechanical resonance occurred [4, 5]. This resonance manifested itself with the decrease in the amount of the characteristic set of the upper bearing and separation into two subsets: A21 and A22 (Figs. 4 and 5).

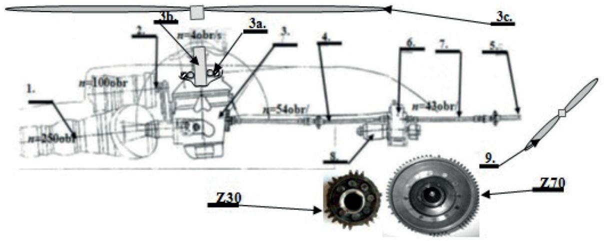

Fig. 3. Distribution of transmission elements between the engine and the power generator on the Mi24 helicopter: 1 – the turbine engine, 2 – a mechanical fan, 3 – the WR-24 main gearbox, 3a. – upper rolling bearing, 3b. – main shaft, 3c. – main propeller, 4, 5, 7 – power transmission shaft, 6 – generators' gearbox, 8 – the left GT 40PCz6 power generator (behind it, the right GT-40PCz6 power generator it attached to the same genera-tors' gearbox), Z30, Z70. – wheels of generators' gearbox [own study]

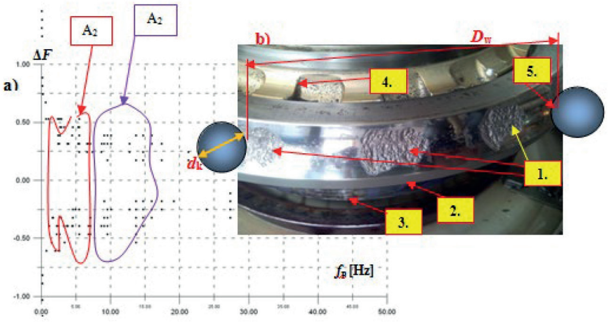

Fig. 4. Upper rolling bearing of the WR-24 main gearbox in resonance: a) Characteristic sets acquired for powerplant of "negative pattern" of a Mi24 helicopter – characteristic sets of upper (main) bearing A2 divided into two subsets: A21 and A22, b) upper rolling bearing with false brinelings of the WR-24 main gearbox: 1. – false brinell prints, 2. – inner treadmill of a roller coaster, 3. – main shaft, 4. – locking nut, Dw – inner race diameter, dk – rolling element diameter [own study]

The verification conducted then proved the existence of a long mechanical resonance, manifesting as the so-called false brinellings (Fig. 4.a, detail 1) [4]. Such brinellings are the clear evidence of radial, internal resonance of the roller bearing. At the same time, for such bearings, the author was observing (during operation of the turbine engine) the increasing relative amount of sets obtained with FDM-A method (relative amount of the characteristic set – the quotient of the amount of the characteristic set $A=|\{\Delta Fi\}max|+|\{\Delta Fi\}min|$ to its width, i.e. the width of the frequency band occupied by this characteristic set (subset):

$$\Delta fpj = fpmaxj - fpminj \qquad \mathbf{(7)}$$

The amount of the also increased the value of the Q factor of the characteristic sets

$$Q = foj / \Delta fpoj \qquad \mathbf{(8)}$$

where: foj – "carrier" frequency of the characteristic set ($fo \approx psN \cdot fN$) of bearing no. j, Δfpoj – width of the bandwidth of the characteristic set of a given bearing no. j.

Where: psN – nominal bearing rolling coefficient (concept I created – in mathematical terms, this coefficient is a complement to unit of the slip coefficient encountered in the literature) as a significant parametric supplementation of the rolling bearing efficiency evaluation, including the development of formulas for a reference bearing, is exposed by a formula [4]:

$$p_{sN} = \frac{D_w}{2*\left(D_w + 2*d_k\right)} \qquad \mathbf{(9)}$$

where: D_w – inner race diameter, d_k – rolling element diameter (Fig. 4.b, detail 1).

The carrier frequency fo (in the theory of teletransmission and telemetry, often called a lift frequency) of FAM-C and FDM-A characteristic sets – calculating the current value of the rolling coefficient4 for a rolling bearing (operating within a monitored power train) from the formula [4]:

$$p_{so} = \frac{f_o}{n*N} \qquad \mathbf{(10)}$$

where: n – rotational speed of a bearing mounted shaft (bearing journal), N – number of rolling elements of a given rolling bearing.

3. Conclusion

The diagnostic method FAM-C allows detailed monitoring of multiple mechanic nodes at the same time, and change of the measurement configuration from single-phase to the triple-phase one allows the movement of the observability bandwidth of mechanical processes towards higher frequencies fp. The FAM-C does not require any sensors – their role is played by the on-board power generator. It is possible to detect failures and damages quickly. Bad technical condition of the WR-24 main transmission, and, in particular, its upper bearing affects the wear rate of the gearbox. Replacement of the main bearing in the WR-24 transmission should be associated with replacement of the gearbox co-operating with it.

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