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MONITORING THE HELICOPTER TRANSMISSION USING THE FAM-C DIAGNOSTIC METHOD

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Abstract

Dynamics of the helicopter rotor (blade vibrations, ground resonance, influence of forward speed etc.) plays a significant role in wear of transmission and engine systems. Particularly severe wear of these elements can be expected on military helicopters operating in battlefield conditions, where exceedances of dynamic flight parameters and harsh maneuvers occur more frequently. The "FAM-C" diagnostic method, developed by the Air Force Institute of Technology in Poland, has been used for assessing and monitoring a fatigue wear. Particularly, this method may be applied to monitor defects of power plant and helicopter transmission system, where other "classical" methods are less efficient due to the very complex variable system as for the direction and frequency, system of forces generating vibrations in kinematic pairs situated close to each other. Due to this reasons certain vibroacoustic and thermal effects develop around these pairs and they interfere with each other. In a helicopter, a power plant, including a power transmission system is also a carrying assembly. It forced designers to construct a power plant with increased number of joints and bearing supports. This article depicts possibilities of FAM-C method regarding wear of the main bearing of helicopter rotor, wear of surface of teeth contact, clearances between axles of gear wheels in gear and the evaluation of circumferential clearances on splined connections. In the FAM-C method, signal from the AC generator used in routine operation of the helicopter is processed. Signal analysis enables simultaneous monitoring of several engine and transmission elements at the same time. It doesn't require any separate sensors – one permanent electric generator or tachometer generator is – by the appropriate way of picking up and converting the output voltage signal – a source of the whole gamut of diagnostic information.

Keywords: helicopter gearbox, frequency analysis, blade tip timing, bearing wear, gear wear, system HUMS (health and usage system), alternator, frequency modulation, power transmission, characteristic pattern

MONITOROWANIE TRANSMISJI ŚMIGŁOWCÓW Z ZASTOSOWANIEM METODY FAM-C

Dynamika wirnika śmigłowca (drgania łopat, rezonans przyziemny, wpływ prędkości postępowej itp.) odgrywają istotną rolę w zużywaniu systemu transmisji i zespołu napędowego. Szczególnie szybkie zużycie tych elementów należy oczekiwać śmigłowcach wojskowych w warunkach bojowych, w których to często występują przekroczenia parametrów dynamiki lotu. Metoda FAM-C opracowana w Instytucie Technicznym Wojsk Lotniczych w Polsce została użyta do oceny i monitorowania tego zużycia. W szczególności metoda ta może być używana do monitorowania uszkodzeń zespołu napędowego i transmisji śmigłowca, gdzie inne „klasyczne" metody są mniej skuteczne z uwag na bardzo skomplikowany układ zmiennych co do kierunku amplitudy i częstotliwości układ sił wywołujący wibracje w blisko siebie położonych parach kinematycznych. Z tego powodu tworzą się wokół tych par kinematycznych efekty wibroakustyczne i termiczne , które się wzajemnie zakłócają. W śmigłowcu zespół napędowy w tym zespół transmisji mocy jest jednocześnie zespołem nośnym. Wymusiło to na konstruktorach konstruowanie układu napędowego ze znacznie większa liczbą przegubów i podpór łożyskowych. W tym artykule przedstawiono możliwości metody FAM-C dotyczącej zużycia głównego łożyska wirnika nośnego, zużycia płaszczyzny styku zębów, luzów pomiędzy osiami kół zębatych w przekładni oraz oceny luzów obwodowych na połączeniach wielowypustowych. W metodzie FAM-C przetwarzany jest sygnał z generatora prądu przemiennego w czasie normalnej eksploatacji śmigłowca. Analiza tego sygnału umożliwia jednoczesne monitorowanie wielu elementów silnika i przekładni jednocześnie.

Słowa kluczowe: przekładnia śmigłowca, analiza częstotliwościowa, metoda wirującego obserwatora, zużycie łożyska tocznego, zużycie przekładni, system HUMS, prądnica prądu przemiennego, modulacja częstotliwości, transmisja mocy, zbiór charakterystyczny

1. INTRODUCTION

Maintaining helicopter flight safety is connected with many stability and control issues comparing to the case of fixed-wing aircrafts. These issues are caused by the complex dynamics of variable pitch control of helicopter blades [13, 21], especially since high stability and maneuverability is necessary for typical helicopter missions. The interference between aerodynamics of the fuselage and the main rotor is also an important factor of helicopter dynamics. Dynamics of the rotor blades (mechanical vibrations, ground resonance) amplified by the effects of fuselage aerodynamics, influences the airflow around the rotor blade profile, which in turn has an impact on the dynamics of the helicopter as a whole. This feedback loop is a factor that accelerates the mechanical wear of helicopter's transmission and related systems (engine + transmission shafts + rotors + control systems). Conversely, any deterioration of mechanical parameters of transmission elements directly affects the airframe dynamics, due to the fact that there might arise some problems with control systems and vibration of rotor systems. [5, 9]. Particularly intensive wear of the helicopter components is encountered in military operation scenarios when flight dynamics parameters are more severe and acceleration amplitudes are much greater than in peacetime missions [4, 10, 13].

Currently, since many years there is a tendency to move away from operation pursuant to flying time expressed in hours and calendar operation period, due to the fact that it occurred repeatedly that generators with a very good technical condition were subject to repair and maintenance works and such mandatory works worsened their technical condition. What is more, between maintenance works determined in this system, it frequently resulted in a failure, which complicated the process of planning flights and performing tasks. Owing to this, from some time in aviation the extensive works associated with modelling damage scenarios [12, 16, 19-20, 22] and monitoring the current technical condition of aircraft subassemblies, in particular its power unit, is applied. According to the authors, FAM-C method fits well into the aircraft operational scenario pursuant to technical condition.

The FAM-C diagnostic method [3, 9, 11], devised at the Air Force Institute of Technology and patented in Poland is a tool suitable for assessing a helicopter component wear. In particular, this method might be applied to diagnose wear of helicopter power plant elements, such as rotor bearing, gear tooth contact surface, control bearings, evaluate circumferential clearance of swashplate linkages and circumferential clearances on splined connections. For these elements, "classical" methods are less efficient due to the very complex system of forces and mutual interference of vibroacoustic and thermal effects.

In FAM-C, signal is converted from on-board alternating-current generator during the normal helicopter operation. Analysing this signal enables to monitor many engine and gear elements at the same time – for comparison "classical" vibroacoustic and thermal methods, as well as the current TTM [5, 7, 15, 17] methods require to install a separate sensor in case of every kinematic pair. FAM-C doesn't demand any separate sensors for this purpose - one permanent electric generator or tachometer generator might – by the appropriate way of picking up and converting the output voltage signal – be a source of the whole gamut of diagnostic information. Therefore, one generator is a state observer of technical condition of many elements of power plant at the same time. Due to this fact the authors often use a working name "generator-converter". Furthermore, picking up the signal might occur from any location of electrical network, because frequency modulation of on-board power voltage (in contrast to amplitude modulation, which is damped), is equal in all points of electrical network of the aircraft. Thus, it makes it possible to establish a measurement system in safe places and connecting a FAM-C measurement apparatus is feasible even during the operation of a power plant. One described some examples of diagnostic symptoms of wear of helicopter subassemblies, which were observed by applying the FAM-C method and then verified by mechanical measurements during dismantling these subassemblies.

2. GENERAL DESCRIPTION OF THE FAM-C METHOD

The FAM-C method (developed in AFIT) has been initially (1990) applied to diagnose the dynamics of LUZES airfield electrical power supply units, which were equipped with several diagnostic systems. The LUZES unit used the FAM-C to monitor the axial and radial run-out of transmission shaft, as well as to assess the rotational dynamics leading to the rupture of tacho-generator shafts. Subsequently, the method was applied to monitor aircraft gearbox systems (helicopter main gearbox, accessory gearbox), as well as to diagnose the wear of unidirectional clutch elements of MiG-29 fighter aircraft (1993) [10-11].

The present research of AFIT is focused on monitoring the propulsion and transmission systems of military helicopters. This method, according to the authors, is still in a prototype stage, because it was tested only on a narrow subset of aircrafts and helicopters (20÷30 units for every type of aircraft) of polish Armed Forces and so far it didn't gain many followers in other countries. It is due to the modest financial means on conducting research on this method and lack of effective communication regarding its highly beneficial, or even breakthrough characteristics, in comparison to other previously applied diagnostic methods, for plants producing power units or aircrafts in highly developed countries. It is however proved difficult to understand the principle of this method consisting in dual conversion of frequency modulation.

FAM-C is in essence a Tip-Timing Method (TTM). Classical TTMs are based on indirect measurement of angular speed and displacement of rotating elements (e.g. turbine blades) with the use of specially designed electromagnetic, optical, microwave or capacitive sensors. The idea of this method was developed and implemented by Campbell in [4] the form of analogue cracking of deflection of steam turbine blades in thermal power station. It was performed by the application of strain gauges and analogue technique. After that, it was developed to be used in other objects and finally it evolved to the digital technique, which was more appropriate for this purpose due to the abrupt signal change. At the same time the idea of using strain gauges was abandoned (due to the complex commutation system of strain gauge from turbine blade to measurement site) in favour of motion sensors mounted on turbine casing. Reluctance, capacitive and optical sensors were applied. Emitted signals of voltage impulses, from specially designed sensor, activated electronic triggers, which started time-meters. Time increments between consecutive impulses were collected in a buffer and then analysed. In this way deflection dynamics of turbine blades was observed [4, 5, 7, 15, 17-18].

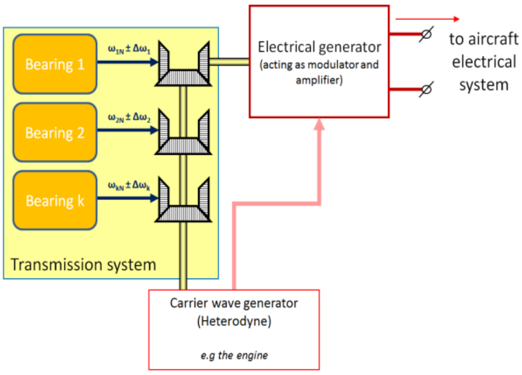

Fig. 1. FAM-C method schematics

FAM-C is in essence a Tip-Timing Method (TTM). TTMs are based on indirect measurement of angular velocity and displacement of rotating elements (e.g. turbine blades) with the use of electromagnetic, optical, microwave or capacitive sensors. The FAM-C method uses the Time of Arrival (TOA). In contrast to the classic tip timing, the FAM-C doesn't require installation of any additional sensors as it uses the regular, on-board alternating current electric generator (see a diagram on figure 1) [10-11]. Each generator pole serves as a reluctance sensor which observes the rotation of generator's rotor grooves. Hence generator poles are equally distributed on the circumference and their number is different from the number of rotor grooves, the negative impact of measurement aliasing is mitigated – Fig. 2. Also, since the cross-section area of the generator rotor teeth and stator poles is greater than those of turbine blades or gear teeth used as modulators in the classic TTM, the saturation of the metallic elements is less likely.

The generator teeth are made of soft magnetic materials distinguished by high magnetic permeability and high saturation intensity level in relation to working point with high intensity level – in practice, the generator manifests a linear magnetization character – a working point is much lower than magnetic saturation level [11].

In addition, the generator introduces a little phase measurement error because of the significant rigidity of generator rotor elements (which serve as a modulator of the diagnostic device) – i.e. the precision of generator rotor teeth spacing is very high, especially in comparison to tolerances used for spacing of engine compressor blades. The spacing between teeth remains stable during the measurement process, while it changes in the case of compressor rotor blades. The cores of generator's magnetic circuits are composed of plate packets, which gives significant resistance to eddy currents.

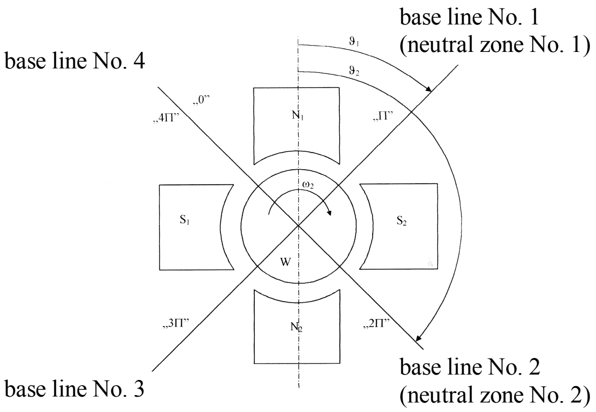

Fig. 2. Alternating current machine with two pole pairs. N1, N2, S1, S2 – magnetic poles of generator's stator; Base line (No. 1, 2, 3, 4) – neutral zone of generator stator's magnetic field; ϑ1 – angle between symmetry axis of generator's cross-section and base line No. 1

An indirect method by a measurement of time increment (slot) between succeeding zero crossing voltage ($e(t) = 0$) is used for measuring frequency. The inverse of double slots is the frequency. Considering that sinusoidal voltage $e(t) \to 0$ attains the greatest gradient [11], it was concluded that alternator's output voltage is least misshapen of these points. Time increases between succeeding level $e(t) = 0$ crossing, which is evaluated by counting succeeding pulse packets of time base with frequency f_z (frequency of first counter cards f_z=1.6 MHz and measuring errors $\Delta t_z = 0.625$ μs). Maximum absolute error of time increase Δt_z can be expressed by the formula:

$$\Delta t_z < 1/f_z \tag{1}$$

maximum relative error:

$$\Delta t_z \leq 2f_n/f_z \tag{2}$$

where f_N - face value[1]

The measurement of output voltage frequency during diagnostic observation can be shown on surface (f, Δt) (Fig. 3, b). The point pattern (conglomeration) can be observed $\{fi(t)\}$, i =1, 2, 3, …, n (where n – number of alternator's voltage half-periods during the measurement).

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[1] generator's frequency dependent on power transmission.

In diagnostic practice, these patterns have been perceived as “time frequency changes”[12].

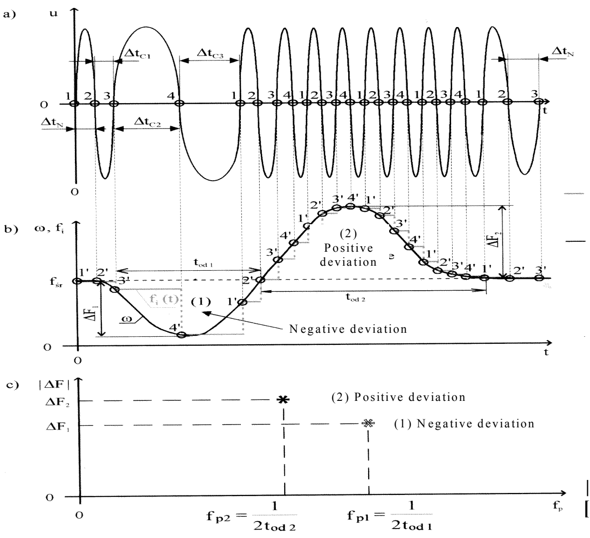

Fig. 3. – Characteristic points on surface (f_p, ΔF)

a) changes of output voltage;
b) changes of generator’s angular speed and frequency;
c) frequency changes on surface (f_p, ΔF).

Frequency changes at time $\{f_i(t)\}$ have provided diagnostic information but required a review of “long frequency changes” as well as recording of maximum frequencies and modulation periods. Deviation from average frequency $f_{\acute{s}r}$:

$$f_{\acute{s}r} = \frac{1}{n}\sum_{i=1}^{n}\frac{1}{2\Delta t_{odi}} \tag{3}$$

Fast Fourier transformation (FFT) used for these waves provided the authors only with information about modulation effect, but “lost” random modulation enabled to collect fundamental diagnostic information. Authors have decided to present it in an completely different manner . It has been resolved to measure? succeeding time of deviation from reference frequency $f_{\acute{s}r}$. Succeeding time increases Δt_{od1}, Δt_{od2},.., Δt_{odk} were obtained. Simultaneously corresponded them? frequency deviations from reference frequency ΔF: ΔF_1,… , ΔF_k were measured. Point patterns were obtained on rectangular co-ordinates surface (f_p, ΔF) (Fig. 3, c) where:

$$f_{pk} = 1/(2\Delta t_{odk}) \tag{4}$$

These points create concentrations [8] that authors named "characteristic patterns" [9-11]. It was experimentally established that every such pattern characterises itself with different faults of drive’s kinematics couples.

Systematic inspections ensured to establish a strict relationship between the duration of frequency deviation’s t_{od} and the corresponding drive’s characteristic set (patterns) (Fig. 4).

It is quite an original way to analyse measurement signal, which is modulated by the frequency. In FAM-C method, it is easy to convert digital data of frequency deviation by performing a harmonic distribution. These harmonics resemble striae acquired from Fourier or Wigner distribution [2, 14, 11]. The advantage of conducting analysis with the FAM-C method is a possibility to detect even some individual snips of a given frequency spectrum of defected subassembly from generator-observer output voltage signal. Thus, the FAM-C method is perfectly suitable for runs with a relatively short exposure and long periods of diagnostic symptom fading. Furthermore, this method does not require to apply complicated digital filtering or signal multiplication, what is often indispensable in other methods.

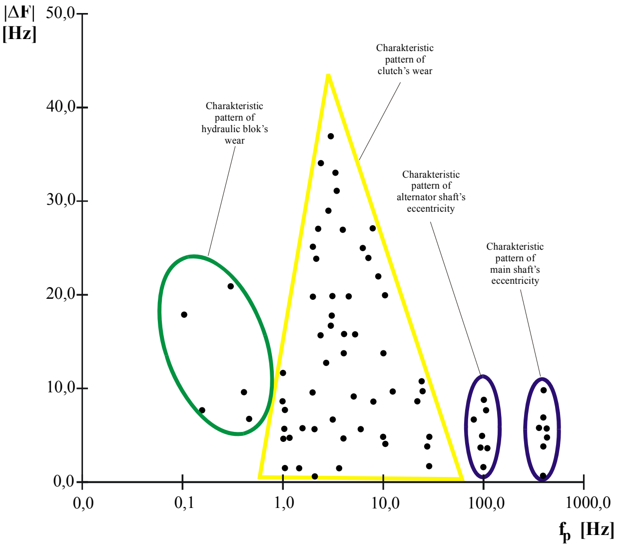

Fig. 4. Characteristic points patterns for selected defects of gear box kinematics pairs

3. DAMAGE OF HELICOPTER MAIN GEARBOX BEARING INNER RACE

The FAM-C method was used by the authors for the diagnostics of Mi-24 helicopter transmissions. The method is able to distinguish several rotating component wear modes, including bearing elements. Research of diagnostic wear symptoms for the main gearbox upper bearing of a Mi-24 helicopter is presented in this section. In FAM-C rotational speed deviations are recorded and analyzed. Rotational speed signal (frequency) for an undamaged bearing element is shown in figure 5, whereas rotational speed signal for a damaged bearing can be seen on figure 6. These signals were recorded during inspections of WR-24 main gearboxes on two Mi-24 helicopters [9-11]. The inspected bearing contained 16 rolling elements. On the undamaged bearing plot, 13 frequency oscillations can be seen for each 4 rotor revolutions. Based on this, the rolling coefficient [11] p_s

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[2] in spite of these idea is used? for line (not for discrete) function according to theory [5,6].

(a measure of retainer rotation relative to the bearing races, equation 1) is calculated as 0.203.

$$p_s = \frac{n_{osc}}{N} \tag{5}$$

where n_{osc} – number of oscillations per revolution, N – number of rolling bearing elements

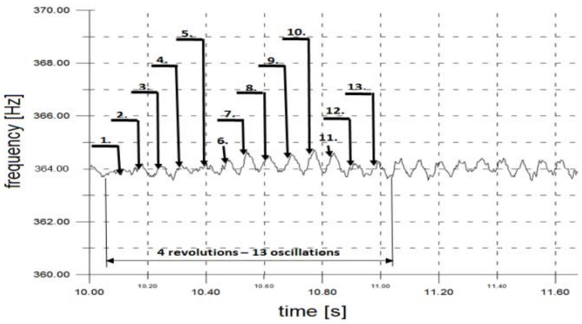

Fig. 5. Frequency deviation, undamaged bearing

On the basis of geometrical data of a bearing it is possible to calculate a rated value of an "ideal" rolling coefficient from the following equation:

$$p_{sN} = \frac{D_w}{2 \cdot (D_w + 2 \cdot d_k)} \tag{6}$$

where: D_w – diameter of the inner race of rolling bearing, d_k – diameter of the rolling element

Having substituted numerical values for upper bearing of a gearbox WR-24: D_w = 232 mm, d_k = 47.55 the value p_{sN} = 0.355 might be obtained. It means that the loading on the monitored bearing is lower than the loading on the bearing with rated rolling coefficient. It is owing to the positive influence of the vibration and hydro-dynamical forces induced by the lubricating oil, as well to the beneficial distribution of clearance deviations.

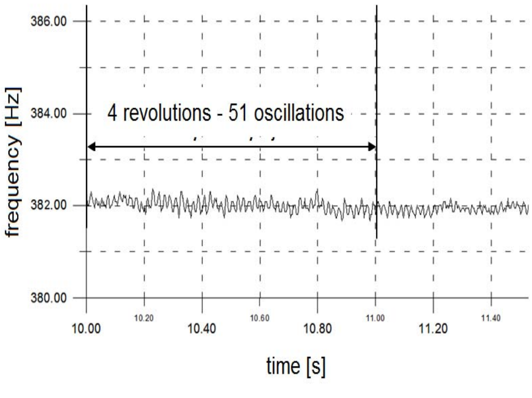

Fig. 6. Frequency deviation, damaged bearing

In the case of a damaged bearing, the oscillation rate is much higher – for every 4 revolutions 51 oscillations can be observed. Therefore, the p_s coefficient is equal to 0.799, which significantly exceeds the nominal value and signifies a severe load on bearing element.

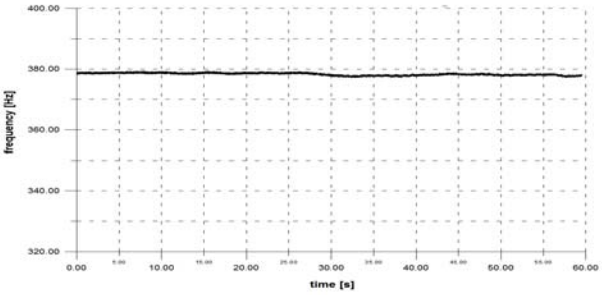

Fig. 7. Long term measurement, undamaged bearing

During prolonged-time measurement additional information about the bearing load severity has been collected. The measured frequency level is stable in the case of undamaged bearing (Figure 7), whereas in the case of damaged bearings, periods of monotonic angular frequency decrease (in the order of 1.4%) are observed (Figure 8). The authors suggest that such behaviour indicates a complex increase of bearing torque. Damaged bearing was dismantled from a helicopter and closely examined. Surface measurement confirmed a significant wear of bearing faces (Fig. 9) [1, 11].

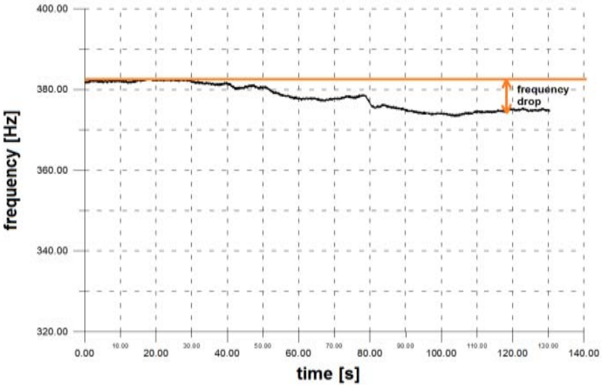

Fig. 8. Long term measurement, damaged bearing

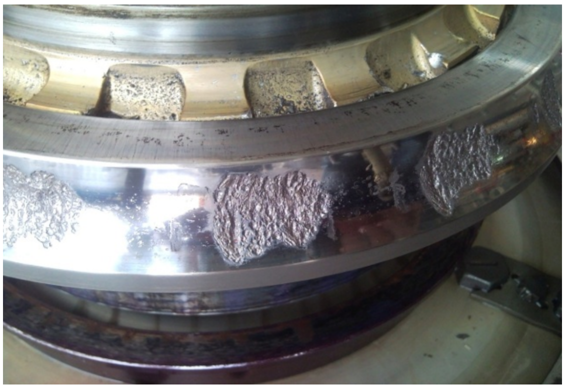

Fig. 9. Inner race of the upper (main) bearing of Mi-24 gearbox – damaged bearing

The anti-torque of this bearing is so high that it caused the rupture of fit of bearing inner race on the shaft, which is proved by the circumferential crack – Fig. 10, detail 1. Deep exfoliations evenly placed on bearing inner race circumference – visible on Fig. 9 - indicate long-term operation in state of inner resonance. It is also proved by the shape and height of characteristic sets of damaged bearing ("negative pattern") – Fig. 11 – in relation to properly working bearing ("positive pattern") – Fig 12. For the pattern of damaged bearing in a resonance state the height of characteristic set is reduced, but a characteristic set of A_2 set, reflecting the properties of this subset, disintegrates into two subsets: A_{21} and A_{22}.

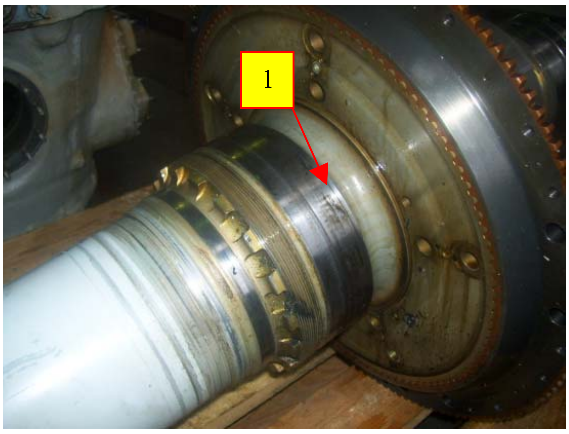

Fig. 10. Surface wear on gearbox shaft caused by inner bearing race interference: 1 – peripheral scars

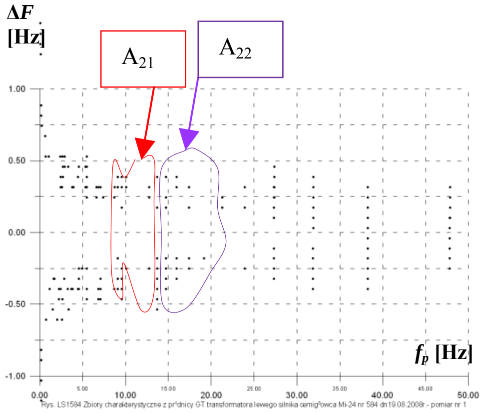

Fig. 11. Characteristic sets acquired for powerplant of "negative pattern" of a Mi-24 helicopter – characteristic sets of upper (main) bearing A_2 divided into two subsets: A_{21} and A_{22}

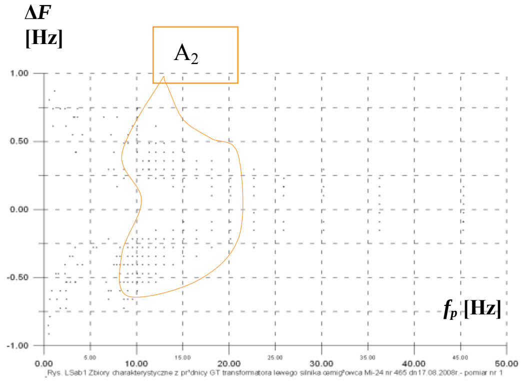

Fig. 12. Characteristic sets acquired for powerplant of "positive pattern" of a Mi-24 helicopter – characteristic set upper (main) bearing A_2 not divided

As it is known from the literature [8], exfoliations of the inner race result in the increase of stresses and surface wear . To make matters worse, products of exfoliation contaminate a lubricating oil, what substantially intensifies the wearing process of a rolling bearing. Marks of a moving bearing ring induced by the rupture of fit of a bearing inner ring might have indicated a high level of destruction of this bearing, which resembles changing operational mode from rolling to sliding – usually it signifies a catastrophic state.

4. DAMAGE OF GENERATOR POWER SYSTEM HELICOPTER GEARBOX

Generator power gearbox distributes mechanical energy of a power unit into generators that are indispensable for a proper functioning of a helicopter i.a. it drives on-board generators. An example of such kind of a gearbox was depicted on fig. 13. Thanks to FAM-C it is possible to detect anomalies of intertooth clearances in an early stage – Fig. 14, before they will pose a threat to helicopter operations.

In general, it is believed that processes leading to the break-off of gear wheel teeth have a rapid, sudden character – fig 15 – and detecting the early stage of excessive wear is difficult.

Processes leading to gear teeth break-off have a rapid, sudden character, what makes that detecting damage build-up is difficult. To reliably monitor and detect the gear tooth defect onset and growth, a systematic monitoring of the inter-tooth clearances is necessary.

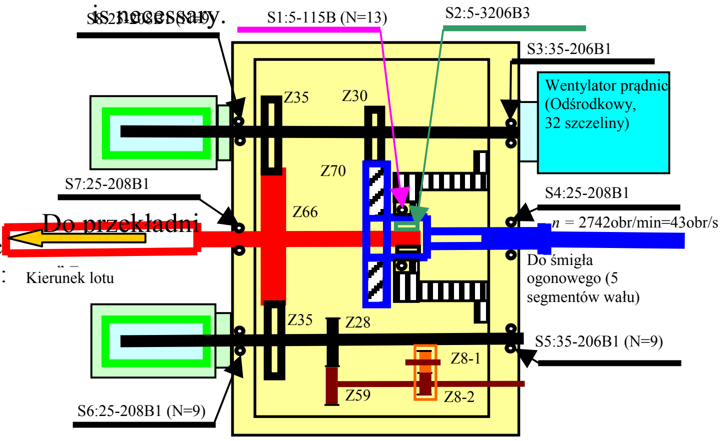

Fig. 13. Surface wear on gearbox shaft caused by the interference of inner bearing race

Because of the interaction of bearing clearances and shaft eccentricity, aliasing effects enable detection of radial clearances in the order below 10% of pitch diameter.

Such signals can be clearly observed in FAM-C measurements, despite some theoretical considerations suggesting that they shouldn't be visible, because the Nyquist condition is not met [6, 11]. If one takes into account that FAM-C method, has its first sampling (conversion of modulation of angular speed frequency into modulation of frequency in generator-converter) synchronized with a mechanical process (with an initial diagnostic signal), as well as the jitter arising out of own oscillations of the transmission system of signal from mechanical kinematic link to generator - converter, then it turns out that it is fully possible.

Such signals can clearly be observed in the FAM-C measurements, despite some theoretical considerations [11]. FAM-C diagnostic symptoms for gear radial clearance increase are shown on figure 8. Series of significant frequency deviation impulse spikes has been recorded during FAM-C measurements of the generator power gearbox of a Mi-24 helicopter. Characteristic frequency deviation impulses, seen on figure 14, showcase unevenness of inter-tooth clearance distribution. Experience of authors in the field of measurements suggests that presence of such impulses is a prognostic of dynamical break-off of several gear teeth [11]. Example of such damage, observed during Polish air force's mission in Afghanistan is presented on figure 15.

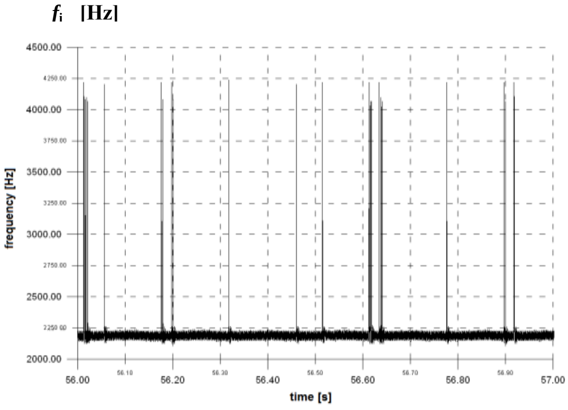

Fig. 14. Multiple spikes indicating the increase of radial clearance in helicopter generator power gearbox

Fig. 15. Damage of gear of generator power gearbox – multiple tooth break-off is noticed

The first two teeth, fig. 15, were breached out as a result of their prolonged undercutting caused by systematic increase in the instantaneous speed of the gear wheel in the same angular position. Breaking the remaining teeth was the result of a dynamic impact.

An interesting phenomenon was observed on few generator power gearboxes before the above mentioned impulses were generated. Namely, modulations of instantaneous frequency on frequency waveform in time function were noted – Fig. 16. Probably it is due to the geometry of impact of propulsion, received from WR-24 main transmission. These modulations are repeated in periods equal to the period of the full revolution of a Z30 gear wheel (Fig. 13), resulting in undercutting of its tooth pair in one and the same angular location. At the same time, after the increased run – it is possible to detect deep undercuttings on slopes of run - Fig. 17. It indicates increased circumferential clearances – it was proved by observations after disassembling both a generator and a generator power gearbox. In figure 18, detail 2, severly worn-out teeth (approximately 50%) on splines of a sleeve might be noticed – Fig. 19. Furthermore, this sleeve (Fig. 18, detail 1) represents a rotation axis of Z30 and Z35 gear wheel – Fig. 13. Due to this fact, on outer splines of generator shaft, substantial material defects are recognized.

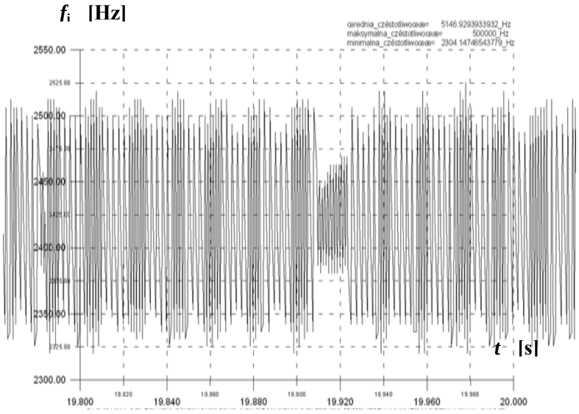

Fig. 16. Frequency waveform in time function with visible modulations

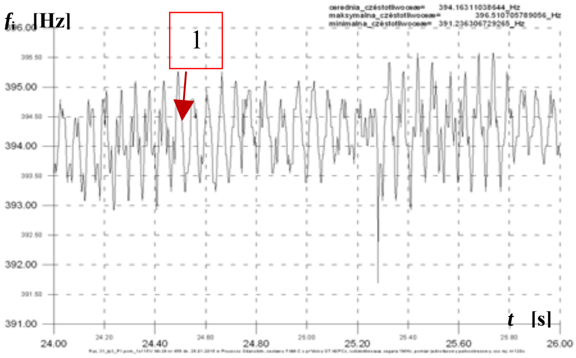

Fig. 17. Frequency waveform in time function with visible undercuttings on edges: 1 - undercutting

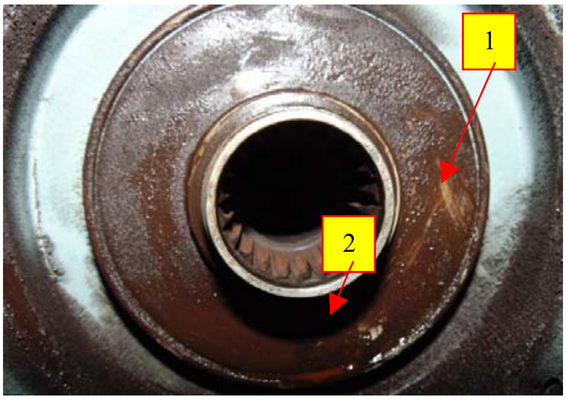

Fig. 18. The sleeve of generator shaft propulsion – visible splines located inside the sleeve are distinguished by symptoms of severe wearing (approx. 50%) – a sleeve is also a shaft on which the Z30 gear wheel is mounted: 1 – generator driver sleeve with inner spline teeth, 2 - splines

On generator shaft – Fig. 19 there are visible material defects on tooth contact edge (detail 1) and visible reduction of tooth crest width. Sizes of wearing might be measurably assessed under field conditions by using a slide caliper – Fig. 20.

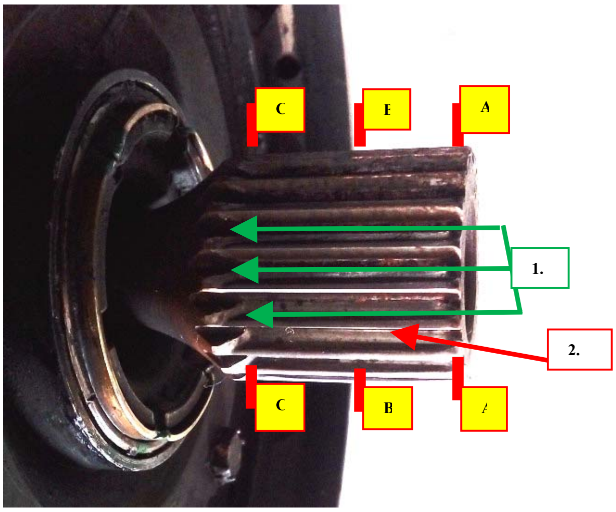

Fig. 19. Worn-out (inner) splines of generator transmission shaft: 1. – material defects on tooth contact edges, 2. – reduction of tooth thickness (defect above 50%), A-A, B-B, C-C – planes of measuring splines (by using a slide caliper)

The measurement shall be conducted in three planes – Fig. 19, detail A-A, B-B, C-C. Such measurement enables to evaluate the shape of wear and therefore also to assess a geometry of motion of both elements relative to each other. Measurement results were presented in tabel 1, in which particular measurements (Table 1, No. 1÷20) and average measurements (Table 1, level „Śra”) were demonstrated.

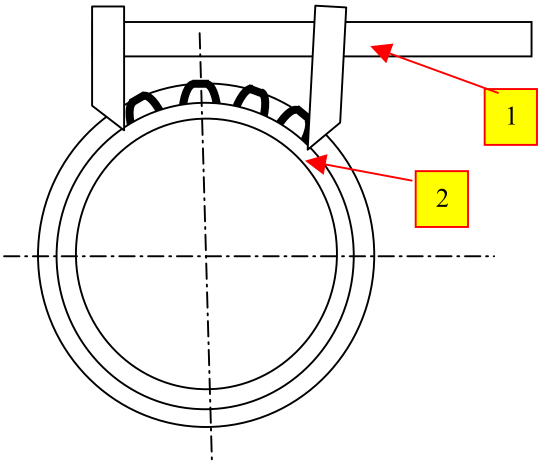

Fig. 20. Way of measuring the inner splines wear of generator transmission shaft applying a slide caliper: 1 – caliper, 2 – measured spline shaft generator

Tabel 1. An exemplary measurement of inner splines (20 teeth) of left generator shaft – negative pattern

lp	***Planes* A-A**	***Planes* B-B**	***Planes* C-C**
-	**mm**	**mm**	**mm**
1	15.1	14.8	15.3
2	15.0	14.8	15.3
3	15.0	14.8	15.3
4	14.9	14.8	15.3
5	14.8	15.0	15.3
6	14.8	15.0	15.2
7	14.9	15.2	15.1
8	15.0	15.3	15.2
9	14.9	15.2	15.1
10	15.0	15.2	15.0
11	15.1	15.2	15.1
12	15.1	15.3	15.1
13	15.2	15.4	15.2
14	15.1	15.3	15.2
15	15.2	15.2	15.3
16	15.2	15.2	15.2
17	15.2	15.1	15.3
18	15.1	15.0	15.3
19	15.1	15.0	15.3
20	15.2	15.0	15.3
arithmetic mean	**15.05**	**15.09**	**15.22**
total mean	**15.12**		
measurement in compliance with technical requirements	**Min 15.53 mm** **Nominal: 16.4 mm**		
δ [%]	**-0.46**	**-0.19**	**+0.67**

According to technical requirements a measured value for a spline shaft meeting normative requirements shall not be less than 15.53, and for a brand new spline shaft it amounts to 16.4 mm. From data collected in tabel 1 it is explicitly clear that a shaft is characterized by wear above standards and that it should be replaced as soon as possibile. Demonstrated data allow also to reproduce the geometry of splined connection (driver sleeve relative to generator shaft) during its motion.

On the basis of data provided in tabel 1 – a relative deviation value of δ [%] from the averaged measurement result (ŚrO) – suggests a conical character of generator shaft motion relative to drive sleeve – Fig. 21. It is possible thanks to increased radial clearances of bearing S3:35-206B1 (Fig. 13), what will ensure an angular deviation of rotation axis of drive sleeve (Fig. 21, detail A-B) from rotation axis of generator shaft (Fig. 21, detail C-D).

In this way it turned out that the measurement of wear of a generator spline shaft might be a source of information about technical condition of a gear wheel pair (Z30, Z70). Thus, the shaft of the generally available generator – systematically disassembled during periodic maintenance for the purpose of conducting overhaul works – by appropriately selected and analysed simple measurements, might be a source of diagnostic information about the technical condition of generator power gearbox.

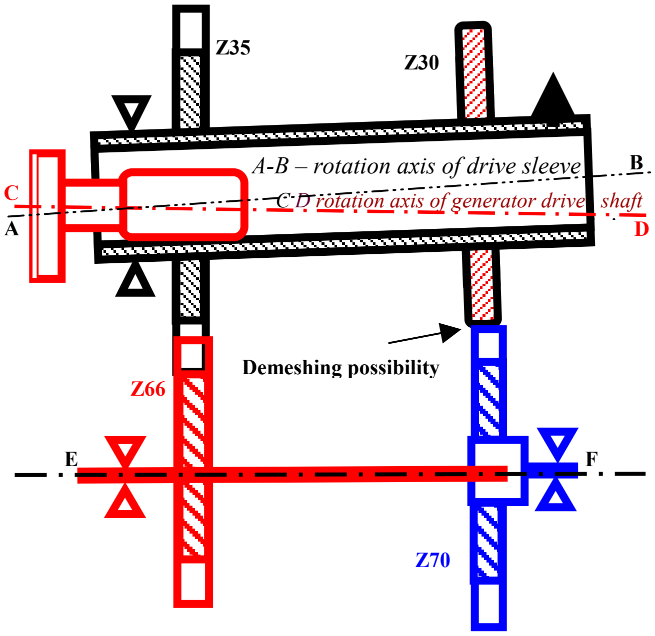

Fig. 12. Geometry of mating elements situated inside the generator power gearbox by a skew location of a drive sleeve relative to rotation axis of generator shaft: A-B – rotation axis of drive sleeve (constituting also a rotation axis of Z35 and Z30 gear wheels), C-D – rotation axis of generator drive shaft, E-F – rotation axis of Z66 and Z70 gear wheel; The C-D axis is parallel to the E-F axis, The A-B axis misaligned with respect to the C-D axis, F – vector of force leading to misalignment.

5. SUMMARY

The article illustrates some aspects of an innovative method developed 20 years ago in the Air Force Institute of Technology, designated by the authors with a FAM-C symbol. This abbreviation signifies the following: FM – frequency modulation, AC –alternating current. In this method it is not indispensable to drill holes to install sensors as in all other diagnostic methods. In the FAM-C method a permanent on-board generator was used. This generator has been utilized on power units since the beginning of military aviation. Not to mention that it eliminated the costs of producing and assembling a sensor. More importantly, FAM-C is based on using frequency modulation (FM) and voltage phase, which remain constant irrespective of the distance from primary modulation source. Owing to this, a diagnostic apparatus might be connected in any distance from places that pose a danger for diagnostician. A third and more important method? Not advantage? is an incredible resolution and accuracy of representation of spectrum of frequency modulations from certain mechanical subassemblies. This method easily detects resonances of subassemblies and presents many kinematic pairs on one plane of rectangular coordinates.

Firstly, the article portrayed (2. General description of FAM-C method) rules, on which FAM-C is based – using an initial signal, conversion through generator, calculating time increments between consecutive zero crossings of generator output voltage and forming sets that are characteristic after detecting a signal.

The following two chapters covered diagnosing of two different element types, applying the FAM-C method, each one located in a different helicopter mechanical assembly:

a) rolling bearing in a main gearbox driving a helicopter rotor – it is the most severely overloaded mechanical subassembly in a helicopter,
b) gear wheels in generator power gearbox in tail rotor power unit. This gearbox, however less overloaded than a), when being defected it might result in preventing a directional control of a helicopter, what in practice ends in breaking the helicopter fuselage.

In case a) the ability of the FAM-C method to detect and metrically determine the progress state of resonance of rolling bearing was described.

In case b) the ability of the FAM-C method to detect few problems associated with the operation of gear wheels assembly and their destruction was illustrated:

- synchronous inner modulations causing the excessive wear of teeth pair in the same angular location – long-term operation of gearbox by such impact might result in undercutting the base of these two teeth, which usually contributes to their break-off,
- discovering increased intertooth clearances for any pair of gear wheels,
- detecting skewing of shafts a rotation axis of gearbox gear wheels.

5. CONCLUSION

The FAM-C method of electric generator signal analysis might be used to detect an early stage of wear of helicopter transmission system. The method may be applied to many types of rotating components, such as rolling bearings or gear wheels.

A special feature of FAM-C that distinguishes it from other diagnostic methods of mechanical power units is a fact that it doesn't require any additional sensors. The role of a sensor is played by a strange element of power unit structure – an on-board energy generator or tachometer generator. It is equipped with information concerning damaged mechanical subassemblies. Having appropriately picked up the voltage signal of such generator–converter and adequately detected the signal, many defects of different mechanical subsassemblies might be witnessed at the same time. It might be illustrated on one plane of rectangular coordinates.

It should be noted that there are also some ergonomic benefits of this method – measuring system might be connected to any point of electric network of an aircraft, e.g. far away from dangerous spots, such as a tail rotor, hot elements of engines etc, by measuring parameters of subassemblies located in any distance from electrical connection. It is due to the fact that the FAM-C method is based on using frequency modulation (FM) and voltage phase, which remain constant irrespective of the distance from the initial source of their creating, in contrast to amplitude modulation, where with the increase of distance, the modulation is subject to damping, then the FM remains unchanged.

The FAM-C method has a digital character of conversion of initial signal (modulations of angular speed of mechanical subassemblies into an electric signal). Thus, it is easier to conduct automation of the process of analysing data – it is easier to prepare software for diagnostic testers. Currently, numerical algorithms are being developed by the authors that will enable to detect and assess the degree of wear and damage of system elements in an automated manner.

Currently, the FAM-C method is based on the analyst's experience and comparison with reference damage patterns noticed in the past measurements and inspections. However, the works target at the possibility to select initial diagnostic thresholds on the basis of design data of a certain type of mechanical power unit. It could save a lot of time and money spent currently on several months of monitoring the aircrafts applying FAM-C during its operation, time-consuming dismantles and verifications of mechanical subassemblies.

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dr inż. **Andrzej GĘBURA** – absolwent Wojskowej Akademii Technicznej na kierunku elektromechanika specjalność osprzęt lotniczy, w latach 1973-1978. 1998 obronił rozprawę doktorską w Instytucie Technicznym Wojsk Lotniczych. Autor 106 publikacji w tym 2 monografii naukowych. Specjalizuje się w badaniach lotniczych układów elektroenergetycznych oraz w diagnozowaniu mechanicznych zespołów napędowych wojskowych statków powietrznych. Wielokrotnie uczestniczył w badaniach awarii i katastrof lotniczych.