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DIAGNOSTIC TESTERS OPERATING ON THE BASIS OF THE FAM-C METHOD

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Summary

The article discusses the design and principles of operation of three diagnostic testers constructed by the authors of this study, intended for three, different aircraft propulsion units. These design have one common way of processing the original diagnostic signal - they use one FAM-C method. This method is based on natural processing of the rotational speed fluctuations of individual kinematic cells of the propulsion unit, by the on-board generator into frequency modulations. The method, thanks to its properties, is extremely beneficial for the automatic digital diagnostic processing. The tester can be connected at any, convenient for the crew, location of the power grid, away from dangerous zones of the aircraft.

Keywords: frequency modulation, diagnostic tester, propulsion unit, diagnosis, military aircraft, overrunning coupling, rolling bearing, tooth breakout, gear wheel, flight safety, on-board generator.

TESTERY DIAGNOSTYCZNE DZIAŁAJĄCE W OPARCIU O METODĘ FAM-C

Streszczenie

W artykule omówiono konstrukcję i zasadę działania trzech testerów diagnostycznych skonstruowanych przez autorów niniejszego opracowania przeznaczonych do trzech różnych lotniczych zespołów napędowych. Konstrukcje te łączy jeden wspólny sposób przetwarzania pierwotnego sygnału diagnostycznego – wykorzystują one metodę FAM-C. Metoda ta bazuje na naturalnym przetwarzaniu wahań prędkości obrotowej poszczególnych ogniw kinematycznych zespołu napędowego przez prądnicę pokładową na modulacje częstotliwości. Metoda dzięki swym szczególnym właściwościom jest wyjątkowo korzystna dla cyfrowego automatycznego przetwarzania diagnostycznego. Tester może być przyłączony w dowolnym, dogodnym dla obsługi miejscu sieci elektroenergetycznej, z daleka od niebezpiecznych stref statku powietrznego.

Słowa kluczowe: modulacja częstotliwości, tester diagnostyczny, zespół napędowy, diagnoza, wojskowy statek powietrzny, sprzęgło jednokierunkowe, łożysko toczne, wyłamanie zęba, koło zębate, bezpieczeństwo lotu, prądnica pokładowa, modulacja częstotliwości napięcia wyjściowego prądnicy.

1. INTRODUCTION

Previous operational experience confirm that the exhaustion of an aircraft service life cannot be clearly associated with it not being fit for further, reliable flights. Not always, the exhaustion of the service life result with the loss of technical performance of flying object and exceeding the assumed reliability value [26]. That is why, currently, maintenance according to the service life resource is put aside, and more and more often maintenance according to the technical condition is used. However, it requires efficient diagnostic measures. One of such measures is the ground diagnostic tester or the HUMS system [7]. The aviation technology know to authors utilizes mainly vibro-acoustic methods to test the technical condition of the propulsion unit, in terms of detecting worn components: rolling bearings, gears, shaft coupling defects, couplings, etc. [3, 7, 13]. In order to supplement system defect, the authors of that method suggested an alternative one, marked FAM-C [4-5], using the output signal of the generator connected to a particular propulsion unit.

The testing consists of observing an induced response of the device or system, in order to identify its properties [3, 7, 11, 16, 21]. The literature in the field of technical diagnostics over the last decade, saw the appearance of many papers suggesting the possibility of using different methods to detect damage through tracking the changes of the time waveform shape and the location of bands of system response frequency harmonics. Because the determination of actual forces and torques dynamically impacting a propulsion unit is almost impossible, different methods were suggested, which enable analysis of the technical conditions of a particular propulsion unit, practically without data - Gabor distribution, Wayner-Viller distribution and many others are applied. These considerations have rather theoretical-mathematical nature, only partially documented on real objects (mainly laboratory) with the use of the vibro-acoustic technique. The authors of this article adopted a completely different strategy of testing aviation propulsion units - first they implemented to operation instruments of their own design, allowing the use of the output signal of an on-board generator for diagnostic purposes [4-5], then they collected abundant research material from real propulsion units [13] and in the end, developed diagnostic testers facilitating locating and defining wear of particular sub-assemblies. The diagnostic testers developed by the authors and presented in this article, test the correctness of operation of mechanical nodes of aircraft and helicopters. They are characterised by a similar manner of use – they are connected to the on-board generator, mechanically coupled with the propulsion unit. The measurements takes place at a fixed rated speed of the engine, at which the movement dynamics of individual components is observed. Used here is the phenomenon of synchronous reflection of rotational speed fluctuation onto frequency modulations of the generator's voltage. Diagnostic information about the technical condition of mechanical bundles of the propulsion unit are obtained using the FAM-C method.

It is a method of the TTM *(tip timing method)* group [25] - an indirect measurement of the rotational speed and movements of rotating elements (e.g. compressor blades) in a classic method is performed with the use of electromagnetic, optical, microwave, capacitive, eddy current sensors [13, 25]. On a similar principle, torque meters have been designed since the beginning of the 1970s. Despite the fact that the FAM-C method [13], developed over an expended period of time independently from the listed one, it should be put in that group, since it utilizes the TOA principle described by Campbell. Unlike the classic TTM, the FAM-C method [4-5] does not require a sensor being installed - its function is taken over by the regular AC generator. Each pole shoe of such a generator is used as a reluctance sensor and "observes" the movement of rotor grooves. Than to a uniform distribution of pole shoes and their number different in relation to the number of rotor grooves, a kind of a vernier is formed [13]. It increases the accuracy of the momentary value measurement, which enables the detection of fast transient processes, theoretically undetectable at a given number of pole shoes or grooves. Therefore, thanks to the use of the generator as a diagnostic transducer, a network of sensors necessary in previously used vibro-acoustic methods were disposed of. The noise floor of the initial diagnostic signal also decreased and reduced was the way the measurement is impacted by defects and errors of the sensor and the manner and location of its installation. Thanks to many advantages, the FAM-C method is competitive, even for the related TTM methods. In addition, the used by the authors, simple analysis algorithms for data collected from the tested propulsion unit, make the FAM-C method very beneficial for digital measurement-analysis equipment, which the ground-based diagnostic testers are. The user of such a tester obtains first solid results (determination of diagnostic classes of mechanical sub-assemblies of the tested propulsion unit) already after 60÷120 s from the start of the test. Of waveform, only the preliminary sub-assembly mechanical wear classification with sort-term forecast is obtained.

2. GENERAL DESCRIPTION OF THE OPERATION AND DESIGN OF TESTERS USING THE FAM-C METHOD

As mentioned in the introduction, the FAM-C method uses synchronous processing of the diagnostic signal (fluctuations in the angular velocity of individual kinematic pairs of the tested propulsion unit) into a discreet-frequency system of characteristic sets (fig. 1). Each kinematic pair generates a certain spectrum of angular velocity vibrations with some rated frequency, referred to in the literature (in the scope of telecommunication) as sub-carrier frequency. Many such spectres reach the rotor of the generator. The angular velocity deviation spectra are summed up and the transformation into the electrical signal of the AC takes place here. At the same time, all these spectra obtain a "carrier" frequency - it is the rated generator frequency. At this point, the angular velocity spectra gain a considerable resistance to disruptions. At the same time, the frequency-phase modulations of the angular velocity of particular kinetic pair become frequency-phase modulations of the electrical waveform. Electrical frequency-phase modulations are not subject to damping in the power grid of an aircraft. In the same parameter form they can be received at any point in the power grid. Such an electrical signal, frequency modulated by the on-board generator is resistant to interference. After its detection in the tester, the modulating component is recovered. This component constitutes a digital-discreet reflection of the initial diagnostic signal. This signal, after an appropriate (automatic) analysis can be presented in the form of characteristic sets (fig. 1). The tester automatically compares parameters (i.a. height) of such sets with a reference set. Such characteristic sets can be easily transposed into an electronic automatic signalling system. Each of the characteristic set reflects the dynamics of another kinetic pair. The position on the abscissa axis informs about the rate velocity of a given kinetic pair, which greatly simplifies their identification issues. Usually, a few of such sets can be observed simultaneously. That is why, it is possible to monitor many sub-assemblies and the relations going on between them. There, this is how the idea of concurrent processing is implemented [15].

Usually, the measurement chain of a tester is connected to one generator and has a defined observation band of mechanical sub-assemblies of a given mechanical propulsion set. In multi-channel testers, where each of the channels is connected to another generator, it is possible to monitor virtually all mechanical sub-assemblies of a particular propulsion unit.

Thanks to the advantages of the FAM-C method, it became possible to monitor aviation sub-assemblies packed in small volumes, such as gearboxes - identification of individual, damaged kinetic pairs with traditional methods, e.g. vibro-acoustic, causes many difficulties [7, 21, 23-24]. The FAM-C method easily identifies and defines the degree of wear of such kinetic pairs as rolling bearings, gear backlash, shaft crossing, etc. [9-13].

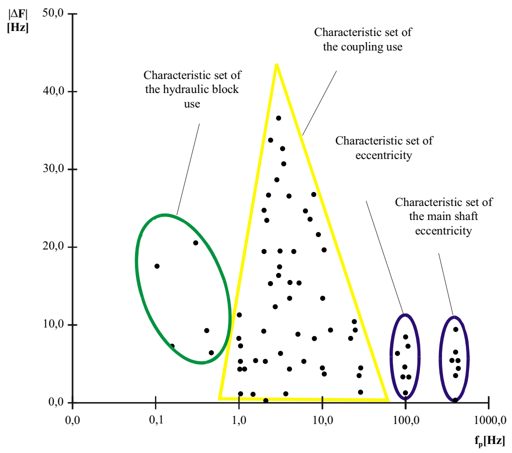

Fig. 1. Characteristic sets on a plane (f_p, ΔF) for typical damages of the aircraft propulsion box

A diagram of a single-channel DIA-KSA-CM tester is shown in fig. 2 [13].

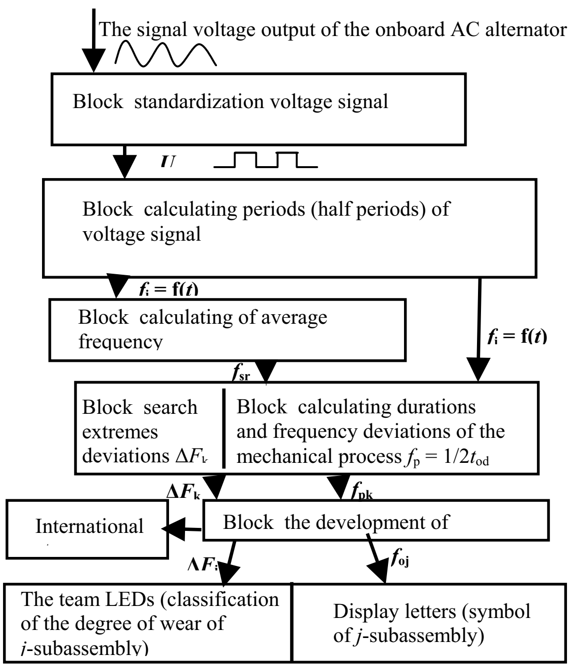

Fig. 2. Functional-block diagram for the DIA-KSA-CM tester

The block of voltage signal standardization is at the input. This is where the threading of voltage component takes place, allowing the matching of the input signal to the TTL level (3.3 V). Thanks to that, the level of noises decreases. Then, the spot frequency is measured with the indirect method. In order to obtain characteristic sets it is necessary to calculate the average frequency. Then, characteristic sets are created virtually - in the block of searching for deviation extremes and the block of calculating deviation durations. The next step is the automatic comparison of heights of characteristic sets obtained from the measurement with a set of reference parameters – it is performed by the block determining diagnostic signals. The final stage is the archiving of the data and its visualization for the user. The data is archived through saving the data in the internal memory. Visualization is in the form of signalling diagnostic classification of the most worn mechanical sub-assemblies, together with the identification (assigning to particular mechanical sub-assemblies). Transferring data from the internal memory to a stationary data base of the user allows long-term tracking of the wear trends for particular nodes of an aircraft. Whereas, the signalling of the diagnostic classification of particular sub-assemblies allows immediate decision of the user on authorizing a helicopter or plane for flight or, in justified cases, suspending flights and undertaking remedial measures: replacement of a sub-assembly or the whole propulsion unit. [13].

The diagnostic tester DIA-KSA-CM (put into operation) is used to determine the degree of wear of overrunning couplings of the KS2-A gearbox units and the degree of air-lock of the hydraulic block of the generator GP-21-3PS in a MiG29 aircraft. The measurement procedure is simple: connecting a tester to an electrical connector, switching on the engine to rated speed "small throttle" and pressing the "START" button (fig. 3) [13].

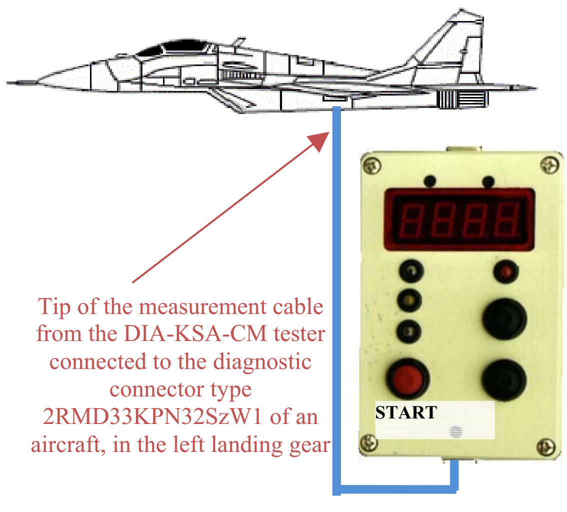

Fig. 3. Manner of connecting a DIA-KSA-CM diagnostic tester to a MiG-29 aircraft

The tester carries out a single-phase measurement of the frequency modulation of the GŻ-30 on-board power generator's output voltage [13]. The tester is characterized by considerable ergonomics and is easy to use. A preliminary test result, in the form of individual characteristic sets' height measurements is displayed after a one-minute test. The internal storage capacity of the diagnostic tester is 100 entries. In order to facilitate the control over the internal memory filling, when 50 tests are completed, after turning the power on (prior to the next test), the display will show double lines (= = = =), and after 75 tests – triple (≡ ≡≡ ≡), while after 100 test, "FULL' will appear. These markers disappear after copying the information saved in the internal memory of the tester to a computer [13].

3. DIAGNOSTIC TESTER DIA-SO3

The DIA-SO3 tester is a compact and miniaturized version of the previously used computer set for measurements with the FAM-C and FDM-A methods. It is used to determine the current condition of bearing supports in SO-3/3W engines of the TS-11 Iskra aircraft. Two measurement channels can be distinguished in it (fig. 4÷6):

a) measurements in the DC channel - measurement of FM parameters of the output voltage pulsation component of the GSR-ST-6000WT DC generator,

b) measurements in the AC channel - measurement of FM parameters of the output voltage of the D-10/2 tachometer generator.

Tie-in locations for the measurement system of the tester to the electrical system of the TS-11 plane were presented in Fig. 4 and 7. Each of the measurement channels consists of:

1. block of the input voltage signal standardization;
2. block measuring the time increment between successive passages of the input voltage waveforms $u = f(t)$ through the reference level (block calculating durations of successive periods or semi-periods, fig. 4);
3. blocks of image formation;
   - waveform of spot frequency $f_i = f(t)$,
   - characteristic sets in a plane $\Delta F = f(f_p)$;
4. block of calculating 27 quantifiable parameters from imaging: $f_i = f(t)$, $\Delta F = f(f_p)$, fig. 6;
5. block comparing measured values (27 quantifiable parameters) with limit levels - determination of the wear class for each parameter, fig. 6;
6. block determining a diagnostic decision, fig. 5:
   - weighing function blocks,
   - block determining the wear model type classification;
7. blocks of internal memory - for storage;
   - measurement data,
   - results of the diagnostic process;
8. light elements - indicators;
   - displaying wear type of individual bearing supports, fig. 5,
   - signalling the degree of wear of bearing supports, fig. 6;
9. blocks of developing diagnostic forecast for a particular wear model - block of comparing (comparison) of the parameters selected for a given model and the relations obtained on the basis of measurements with reference levels and relations, fig. 6.

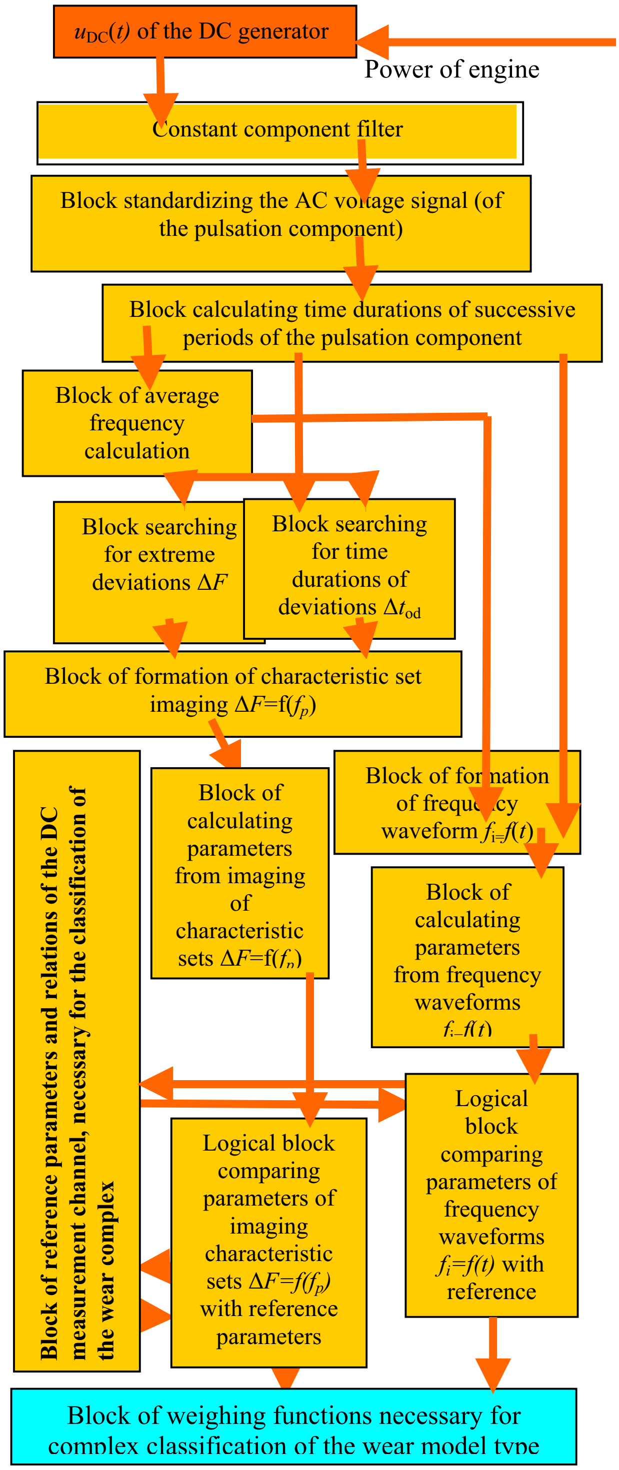

Fig. 4. A block diagram of a logic structure of the field tester for short-term diagnosis of bearing supports of SO-3/3W engines – DC measurements canal.

DIA-SO3 diagnostic tester displayed against a silhouette of the TS-11 Iskra plane in the background is presented in fig. 7. The simplicity of connecting the tester to the measured structure and its minor dimensions can be seen. It is a particularly valuable feature in military operation, in conditions of a common time deficit. As mentioned, the DIA-SO3 tester is used to determine the current degree of wear of bearing supports for the SO-3/3W engines of the TS-11 Iskra aircraft [8, 18, 20].

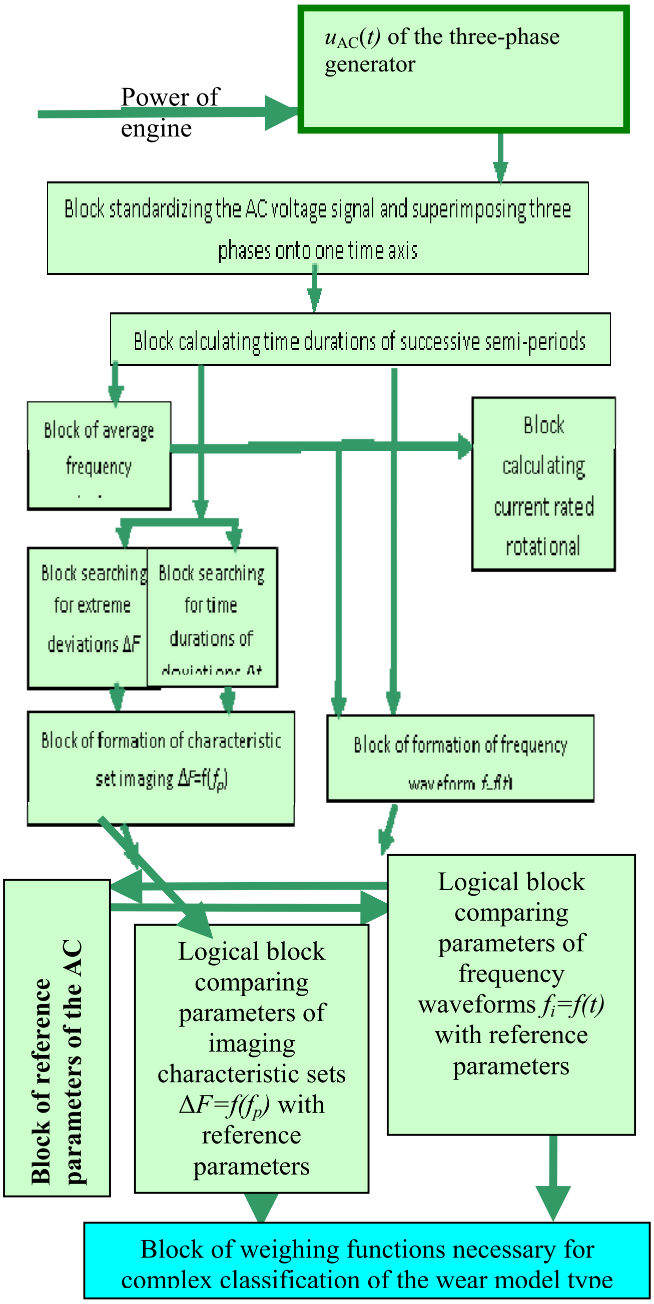

Fig. 5. A block diagram of a logic structure of the field tester for short-term diagnosis of bearing supports of SO-3/3W engines – AC measurements canal

The tester recognizes four wear models (fig. 5):

- increased reactance [8,19],
- rolling elements clamped between races [9],
- increased radial backlashes taking into account the resonant aspect [11],
- increased longitudinal backlashes [10].

In this case, the FAM-C method would introduce complexity and precision in monitoring mechanical nodes of a mechanical propulsion unit, at slight gradual expansion of the measurement network. In 2014, the tester won a Silver Medal at the 63. International Exhibition of Invention, Research and New Technologies BRUSSELS INNOVA 2014 and a gold medal at the 66. International Exhibition "Ideas, Inventions, New Products" iENA 2014 in Nuremberg.

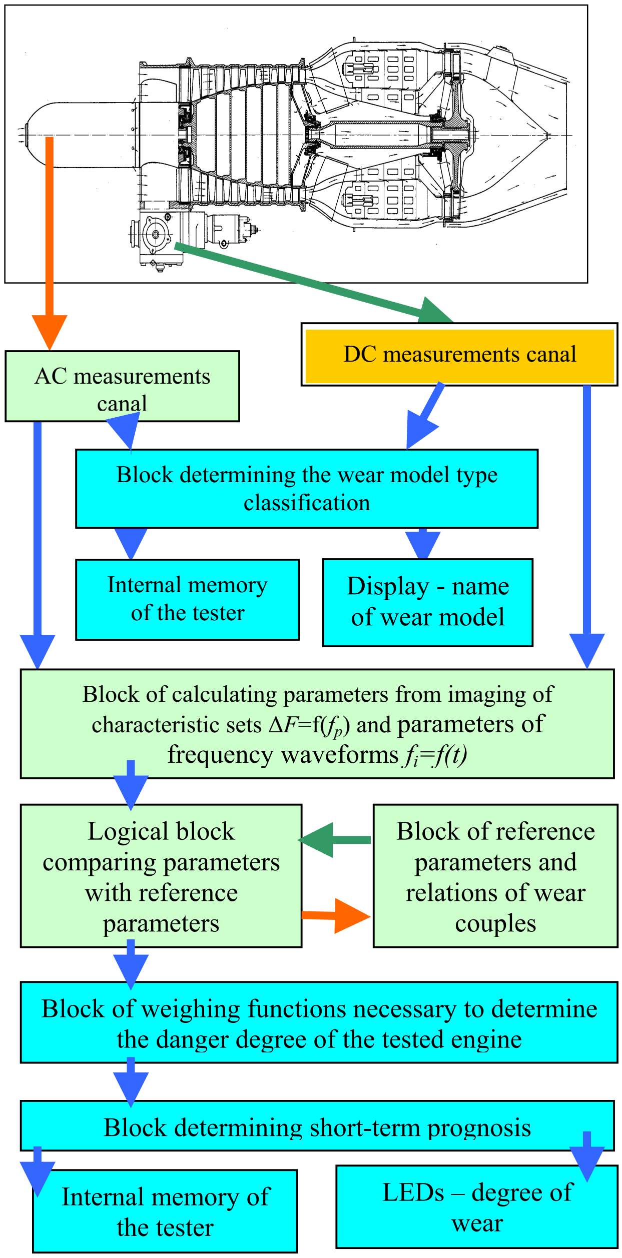

Fig. 6. A block diagram of a logic structure of the field tester for short-term diagnosis of bearing supports of SO-3 engines – part. 3. Drawing up a diagnostic forecast

Fig. 7. TS-11 Iskra aircraft with a connected diagnostic tester DIA-SO3:1–diagnostic tester DIA-SO3, 2 – 28V DC socket (nose cone part of the fuselage) – tie-in location for a DC measurement channel of the DIA-SO3 tester circuit, 2a – electrical cable connecting the 28V socket and the tester, 3 – tachometer connector (dashboard in the second cabin) – tie-in location of the AC measurement channel (three-phase) to the DIA-SO3 tester, 3a – electrical cable connecting the tachometer connector with the tester

4. DIAGNOSTIC TESTER DIA-MI24

The electronic tester DIA-Mi24 (fig. 8 and 9) is desgned to perform measurements and analyse the technical condition of sub-assemblies of the power transmission unit of the Mi-24 helicopter, on the basis of measurements of on-board generator voltage frequency modulations. Until now, a first working model of the tester was constructed for measurements and data acquisition. Also, first laboratory tests associated with the correctness of operation of that unit were carried out. FAM-C measurements in a Mi-24 helicopter can be simultaneously carried out in three measurement channels:

1) in a single-phase channel 1x115 V, 400 Hz,
2) in a three-phase channel 3x36 V, 400 Hz (optionally 3x200 V, 400 Hz) of the output voltage of GT-40PCz6 generator (3x200 V, 400 Hz) after decreasing the voltage by the on-board three-phase transformer,
3) in a three-phase channel 3x47 V, 800 Hz of the pilot exciter GT-40PCz6.

The manner of connecting a DIA-Mi24 tester to the power grid of the helicopter is presented in fig. 9. In the only constructed and currently tested design, there is one DC and two three-phase systems. At the same time, it needs to be noted that the three-phase system has the feature to perform a single-phase measurement simultaneously with a three-phase measurement. Therefore, the DIA-Mi24 diagnostic tester may comprehensively measure all voltages of on GT-40PCz6 generator - carry out FAM-C measurement:

- single-phase (f_N = 400 Hz tj. $f_{śr}$ = 400 Hz),
- three-phase from three-phase output terminals (f_N = 400 Hz i.e. $f_{śr}$ = 1200 Hz),
  three-phase from the internalpilotexciter (f_N = 800 Hz i.e. $f_{śr}$ = 2400 Hz).

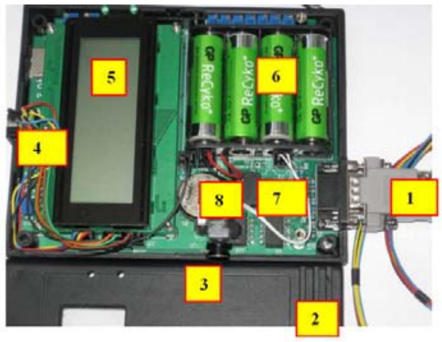

Fig. 8. Model of the semi-automatic DIA-Mi24 tester: 1 – bundle of external electrical cables intended for connection to terminals of on-board generators, 2 – housing, 3 – power switch, 4 – connector for the 12V DC power supply for charging internal power batteries, 5 – display screen, 6 – internal power batteries, 7 – electronic board with microprocessor, 8 – memory backup battery

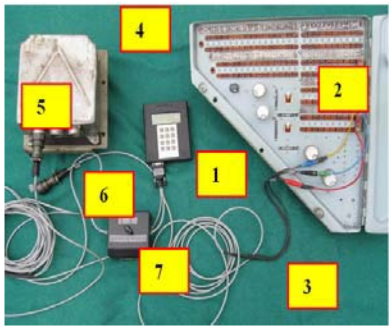

Fig. 9. A DIA-Mi24 connected to Mi24 helicopter's electrical infrastructure sub-assemblies 1 – DIA-Mi24 tester, 2 – AC switchboard of the Mi-24 helicopter, 3 – three-phase electrical bundle connecting the electrical circuits of the helicopter 3x36 V, 400 Hz with the DIA Mi24 tester (channel A+B), 4 – voltage regulator of the on-board generator no. 1 (tie-in location of the diagnostic tester), 5 – reception connector for the pilot exciter voltage signal from the voltage regulator of generator no. 1, 6 – reception connector for the pilot exciter voltage signal from the voltage regulator of generator no. 2, 7 – pilot exciter measurement chain switch (pilot exciter no. 1 – pilot exciter no. 2)

The DC channel is not currently used - its application is planned for the measurements on-board the W-3 Sokół helicopters (one DC generator WG-75Ja and a three-phase generator with an earthed zero GT-40PCz6). Currently, the DIA-Mi24 diagnostic tester, in the automatic alarm mode, diagnoses the sub-systems:

– overrunning coupling,
– main shaft (helicopter rotor),
– upper bearing of the WR-24 transmission,
– gearbox units (SNA)

and allows gathering data necessary for expert evaluation of the remaining power transmission nodes of the helicopter.

Fig. 8 shows the appearance of the PCB along with elements. It is a system combining high computational capabilities (32-bit processor with a 168 MHz clock), high storage capacity, a large set of peripherals (SPI, USART, TIMER-s, etc.), minor energy consumption (ca. 90 mA) and a small cost. In order to minimize the power demand, individual elements of the device are designed to be switched off, depending on the currently performed functions (switching on measurement channels only for the period of the measurement, switching off LCD display illumination, etc.). The keyboard used in the device allows for entering data (keys 0÷9), controlling menu selection cursors (up-down arrows), as well as direct selection of functions (mode) of the device (F1-F5). In total, the keyboard has 12 keys. The data collected during the measurements is saved on a micro SD card, which, after being taken out from the device, can be read on a PC. The used LCD display allows to display four lines of 20 characters each. A display of such size is sufficient to clearly depict the device's mode of operation and to present measurement and calculation results. The software of the device shall enable gathering measurement data and analysis of the data according to the algorithms designed for individual aircraft. The calculation result will be the determination of the degree of wear of the tested elements. The device was designed to be placed in a plastic housing, with dimensions of about 143x120mm (fig. 9). So, this is a small device, comparable with a pocket universal meter, which fits in a technician's palm.

5. SUMMARY

This study presented three diagnostic testers intended for monitoring the selected elements of the propulsion unit of different aircraft types:

- DIA-KSAM – diagnosing damage of the overrunning coupling and the degree of air-lock of the hydraulic block in a MiG29 plane,
- DIA-SO3 – diagnosing the technical conditions of rolling bearings of bearing supports in a turbojet, single-shaft SO-3 engine in a TS-11 Iskra plane,
- DIA-Mi24 – diagnosing rolling bearings, technical conditions of gear and other transmission sub-assemblies of the Mi-24 helicopter.

The described testers were created as a result of the progress in learning the wear mechanisms of a propulsion unit and reflecting these processes in imaging provided by a natural transducer, which is the on-board generator. As a result, already today, the authors may attempt to develop diagnostic testers for virtually any mechanical propulsion units equipped with a generator (coupled with a mechanical propulsion unit). Gradual improvement of the tester technology gives hope that the described testers can be - after further modifications - used as a permanent element of the on-board diagnostic infrastructure. From here on, it is only one step of the HUMS system.

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