THE DIAGNOSTIC OF TECHNICAL CONDITION OF TURBINE ENGINE'S BEARING BY MEANS OF METHOD OF ALTERNATOR FREQUENCY MODULATION

Andrzej Gębura, Tomasz Tokarski

Instytut Techniczny Wojsk Lotniczych
ul. Księcia Bolesława 6, 01-494 Warszawa, skr. poczt. 96
tel. 0-22 - 6856510
e-mail: andrzej.gebura@itwl.pl

Abstract

The paper has been intended to discuss an application of a diagnostic method based on measurements and analyses of frequency modulation.

The method has been developed at Instytut Techniczny Wojsk Lotniczych – ITWL (Air Force Institute of Technology, Warszawa, Poland). It has been based on measurements of pulse-frequency modulation of a DC generator or that of an AC alternator. The method has been intended to determine the usual wear-and-tear of a subassembly under examination and to locate defects, both of them in the course of normal operation of an aircraft power plant. The diagnostic system is connected to any terminal supplied with DC[1] or AC[2] voltage.

Results of performance tests of the turbine engine have been presented. An airborne D.C. generator and a three-phase rate A.C. alternator were used as generators-observers.

Subsequent stages of the wear-and-tear of rolling bearings, the turbine unbalance, and the misalignment were observed while taking measurements during both flight and bench tests. What was observed first was some increase in the amplitude of braking the bearing induced by the increasing resistance to motion due to the wear-and-tear of the bearing's components. Then, the amplitude was observed to decrease due to the wearing-in of the bearing's components. At the beginning of operation, the rolling-friction coefficient was 0.4, then this value kept increasing with time until some rapid decrease beyond any mathematical meaning. This decrease resulted from the extension of radial clearances.

Such being the case, the bearing's operation had to be stopped to avoid intense destructive effects.

***Key words**: distortion, frequency, modulation, characteristic set, power-plant diagnosing*

1. Introduction

Power plants often suffer premature wear-and-tear, which means complications to the operational-use/maintenance schedule and sometimes even a real hazard to human life.

Most maintenance systems in Poland have been based on calendar/hourly-rated schedules. In case of repairs/overhauls within such systems, it quite often appears that a given power plant under treatment doesn't, in fact, require any renewal and can be operated further on to the benefit of its operator. The on-condition maintenance enables, with reliable technical means and methods employed, the monitoring of any item's health/maintenance status and the withdrawing it from operation as soon as the recorded symptoms prove the object may be hazardous.

In the Author's opinion, the presented FAM-C method can become a precious tool of the interference-free monitoring of health/maintenance status of power plants for example turbine

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[1] The method has been labelled 'FDM-A' (F - frequency, M - modulation, D - direct current, A - level of the method's advance)

[2] The method has been labelled 'FAM-C' (F - frequency, M - modulation, A - alternating current, C - level of the method's advance, here: C means that the system finds application as an automatic tester)

engine's ball bearings. Some applications discussed further on have already proved some maintenance-dedicated advantages of this method. These are as follows:

- no need to use any sensors – a regular built-in alternator assembly plays this role,
- measurements can be taken at any point of the electric network, even far away from the object under examination,
- easy automation of the diagnostic process,
- high speed of acquiring diagnostic information.

The FAM-C method has been based on measuring the alternator's frequency modulation. It has been used for many years in aviation to diagnose, e.g.: one-way clutches, motor-generator sets, gear boxes, etc.

2. Description of the FAM-C diagnostic method

The method was thoroughly described in [2,6÷13]. However for better understanding the subject's context some its more important elements are highlighted below.

With every assembling or wear fault e.g. skew of transmission splined couplings, a modulation of the output rotational speed is associated. Period of the modulation is proved to be a characteristic parameter for the fault type and rated rotational speed of a given kinematic pair. Where as the modulation amplitude is proportional to size of a given fault. The modulation effects are transferred through the transmission system to the rotor of the alternator. The aircraft alternator, being a synchronous machine, reflects changes of the instantaneous angular speed as a modulation of the output voltage frequency. By measuring the time increments between successive zero-level crossing points and applying the inverses of their doubled values on the plane of the rectangular coordinates (t , f_i) a set can be obtained which reflects, in a discrete way, a course of speed changes of the alternator's rotor. Two parameters can be assigned to every i-th deviation, as follows:

- the deviation time Δt_i,
- the deviation amplitude ΔF_i.

The deviation time Δt_i can be replaced with the process frequency fp according to the formula:

$$f_{pi} = 1/(2\Delta t_i) \tag{1}$$

Every such deviation can be represented on the plane (f_p , ΔF). During many investigations it was observed that the set of such points tends to gather into clusters. They were called the characteristic sets as they characterised wear state of particular subassemblies.

It was observed that they had different shapes, heights and locations relative to the abscissa axis. It was also stated that the greater the fault magnitude the greater height of a given cluster, $\{/\Delta F_{\max}+\Delta F_{\min}/\}$, and the bound accommodated by the cluster relative to the abscissa axis 0-fp was characteristic for a given subassembly type. During many applications of the method it was stated that the representations realised in the form of the characteristic sets have been applicable for a thoroughly recognised object, i.e. that of known relations between change of magnitude of a mechanical fault and that of depth of modulation amplitude. Use of such representations has many advantages:

- easiness of diagnostic process automation,
- easiness of observation, on one plane, of arbitrarily long time courses, which is especially important in the case of occurrence of stochastic signals,
- easiness of pulse component separation out of highly modulated signals, free from drawbacks of partial Fourier's analysis.

However, in spite of the advantages of the representation method in question, its use is not recommended for the objects not recognised in the earlier given sense, and direct using the functional courses f_i = f(t) is instead advised for diagnostic purposes. The experienced diagnostician is able to make use of it effectively for assessment of technical state of an object, however in a more time consuming way.

3. Description of the diagnose object as well as the meter circuit

The single-shaft turbine engine has been an object of examinination (Fig. 1). The motion shaft has been sectional (compresor's shaft turbine's shaft) and connected in the centre by means of a splined coupling. It has been supported on three rolling bearins. The fore bearing had 12 rolling components. The central (midle) and rear bearings had 22 components. Their charcteristic sets have been easily distingnished by means of FAM-C method. The central bearing is pressed into a spring sleeve, which is fastoned by its splines with engine frame. Sometimes during engine's overhauls the traces of bearing's circut rotation in the sleeve (slides) become visible. The craks of the sleeve also occur.

The internal bearing's ring is pressed on the compressor's pin. The tear of that point is in danger of crash, because it causes the tear of link with the power turbine – stops drives of pomps and other units nesessary for running of engine. The point is submitted multivector stresses. Skews often arise in that point. They introduce dynamic load. Additional forces arise in that point.They are caused by bearing's assembly errors and radial clearances. Distinct levels under small radial clerance of the central support are dangerous from point of view of the pin's loads – strong loads occur and bend the pin. Slides of internal ring of the bearing on the pin are the most threatening operating conditions. They cause dynamic excesses and increase the level of thermal field.

Considering engine construction it is very important to secure the bearing mountings to be coaxial. Theoreticaly, all three bearings should be in one axis with small tolerance. Changes in the coaxial geometry lead to troubles in bearing operation.

Condition of the bearing separator, which separates bearing's rolling components, is very important component of every bearing. Smothness of bearing montion ensures corrctness of reeling rolling components.

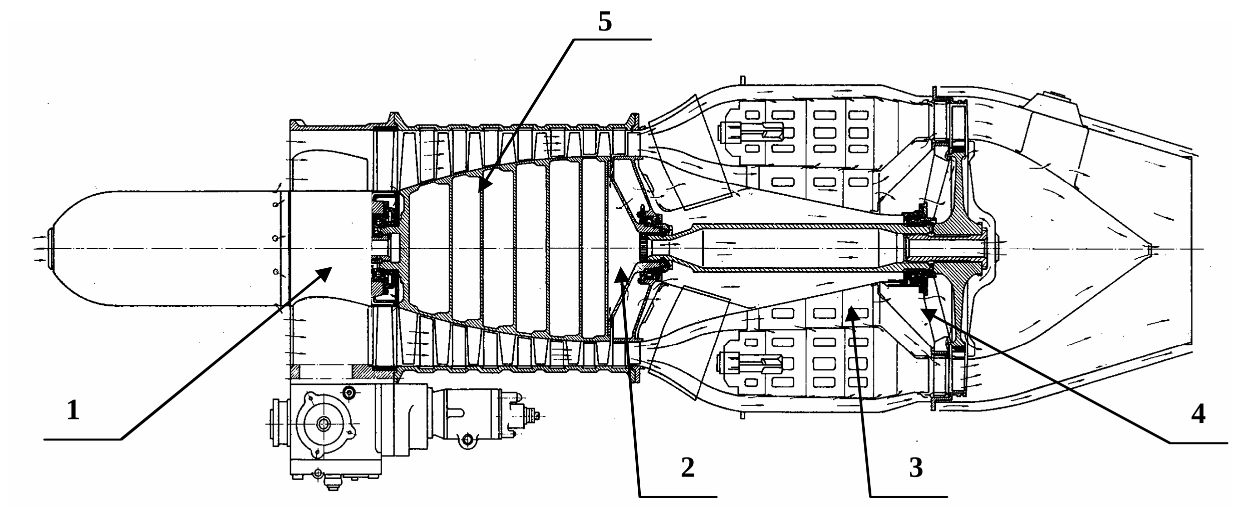

Fig. 1. Investigated turbine engine: 1 – fore bearing, 2 – central bearing, the point of coupling both parts of the shaft (turbine's shaft, compressor' shaft), 3 – rear bearing, 4 – turbine, 5 - compressor

The investigation has been executed differently – Fig.. 2. Signals from the genrator DC and the three-phase rate generator AC have been used for the investigation. Both channels have been complementary to one another.

The three-phase rate generator AC "has afforded" information about faults relevant to the slowly unstable processes:

a) technical condition of the gear box,
b) unbalance of the main motion shaft (with compressor and turbine) as well as the size of the radial clerance in bearing support (Fig. 3),
c) skew of the main shft – it can be evaluated, if skew of the compressor's shaft increases. It can be also evaluated, if the skew does not exceed permissible value specified by manufacturer of the bearing,
d) crack of the sleeve fastering the control bearing.

Generator DC "has afforded" information about fast – changing processes. The fallowing can be observed and diagnosed:
a) the main shaft co-operation with the vibration damper of the lateral vibration (central support) - Fig. 5,
b) extended friction force of the force bearing caused by longitudinal montion of the compressor's shaft ($h \geq 12\cdot$, $p_s \geq 0{,}4$),
c) blocking of the front bearing separator – 12 th harmonic of the rotational speed of the main shaft appers (h=12),
d) blocking of the central bearing separator – 22 nd harmonic of the rotational speed of the main shaft appers (h=22) - Fig. 6,
e) total level of the wear of the wear of the bearing kinematic pair.

4. Succeeding typical stages of the wear of bearings by means of FAM-C method

According to the bibliography there are three succeeding stages of the wear of bearing [5]: noisy, vibrating, thermal.

In the subject engine bearing separator is covered with the galvanic layer of silver. In the first period of operating (i.e. noisy) spalling of the silver follows. In this cause more heavy operation of bearings is observed. This height of characteristic sets (Fig. 3) of bearings systematical increases – Fig. 4. The coefficient[3] of reeling of the central bearing, which is determined from the proportion of total band with frequency of *N* harmonic (where *N* – number of rolling components, also increases during this time – bearing separator rotates with difficulty.

In the second stage – vibrating – the height of characteristic sets systematically decreases – in view of coming to an end of spalling of galvanic layer and rinsing out previous spalling products by circulation of lubricating oil. The coefficient of reeling also decreases. In this stage considerable clerances in the bearing occur. The process of wear goes on, but the wear is a result of dynamic forces influencing moveable components of the bearing in the environment of increasing clerances. During the investigation value of the reeling coefficient below mathematical sense has been mentioned. It can mean, that not all-rolling components of the bearing reel themselves on the bearing race. In the stage of vibrating wear cracks of the sleeve which fastens the external bearing race with the engine's frame. This crac has been detected in the circuit of the three-phase rate generator by means of the first harmonic of the main shaft for all rotational speeds, except the speed approximate maximal decreases almost – 10 times – Fig. 7. Sometimes symptoms of a mechanical resonance occur characteristic set or sets decrease of their frequency band. Sometimes the height of characteristic set increases – so-called mechanical quality factor of a kinematics pair increases (Fig. 3 – point 2). This stages, as it appears from experiences of authors, sometimes signal advanced level of kinematics pair destruction (Fig. 7).

[3] the bearing factor – a proportion of an average angular velocity of the main symmetry axis of the bearing component and a velocity of the main shaft

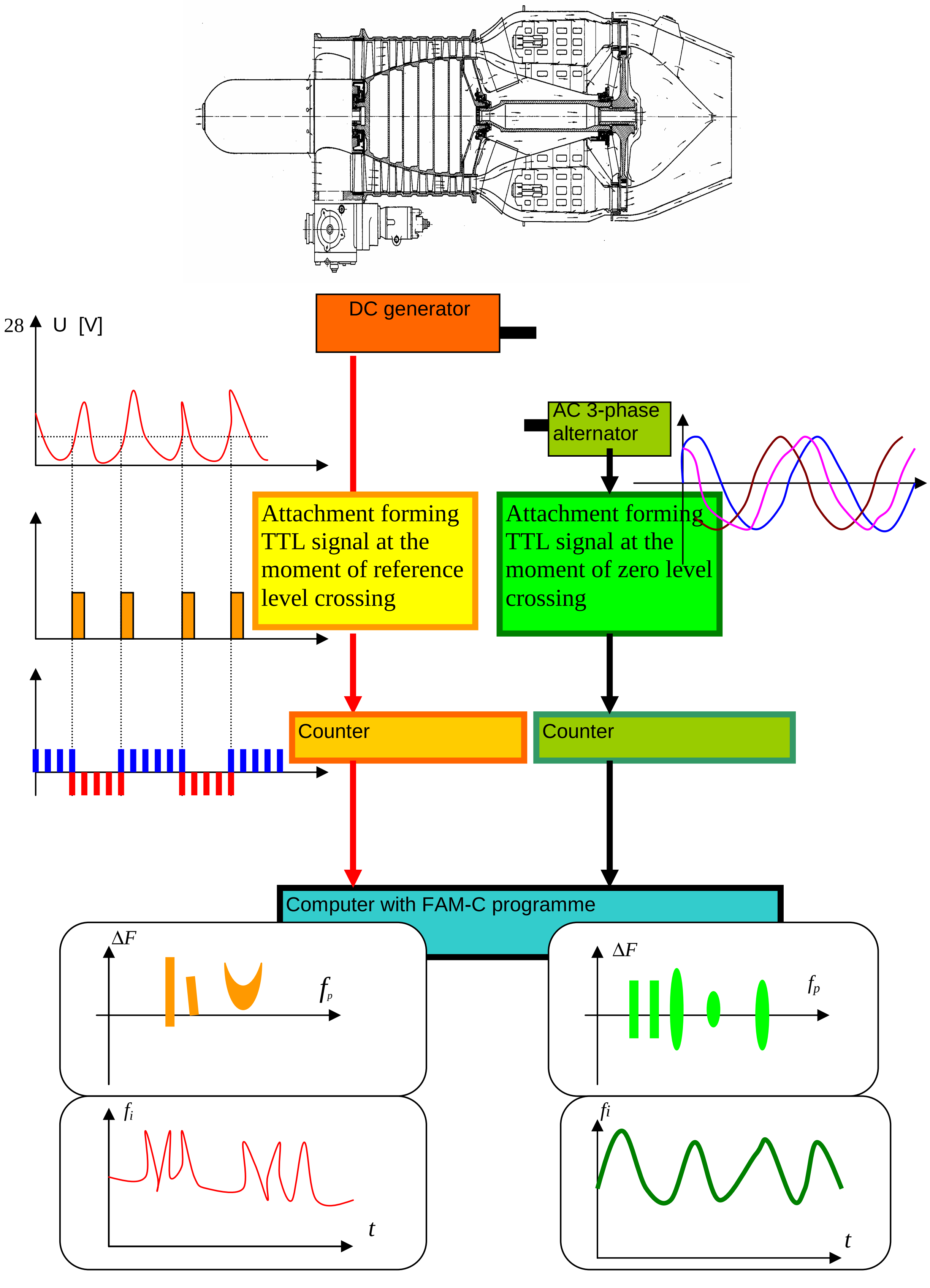

Fig. 2. The method of gaining of diagnostic signal from the engine investigated by means of FAM-C method

During intensifying of occurrence of rolling components reeling along the bearing race, total disappearance of rotation of most rolling components – the stage of thermal wear begins. Considerable amount of heat emits in the bearing. By now oil circulation does not secure an off take of heat in the bearing. As a result of increased temperature a reduction of strengths of material structure of bearing's components follows (e.g. intensive working of window width in the bearing separator even an interruption of separation – Fig. 7). Groups of pulses which number is proportional to number of interrupted windows are generated. The shape and parameters of generated groups are repeated. As a result of direct action of rolling components, groups of pulses can be observed in alternating current channel for a momentary frequency in time f_i = f (t). Simultaneously a pulsation amplitude increased from level about 10% to 160%. As a result of increased temperature a thermal deformation of central bearing's ring follows. The bearing loses a clamp on the pin and slides. Using FAM-C method in a direct current DC generator channel, an angle of those slides as well as their frequency can be precisely defined. To this and a duration as well as a repeat time of dissipated pulses of the momentary frequency in time f_i = f (t).

5. Assembly errors observing by means of FAM-C method

Assembly errors of bearing supports should be distinguished independently on wear processes. They can influence acceleration or deceleration of the duration of particular wear stages. Errors are as follows:

- radial clearances particular bearings,
- increased backlashes,
- coaxial error of three bearing supports – Fig.8,
- unbalance error of the turbine or the compressor,
- ovalization error of the bearing mounting,
- skew error of couplings of both parts of shafts,
- perpendicularity error of the compressor pin,

Increased radial clearances appear as a increase of the characteristic set amplitude (presentation of ΔF = f(f_p) central bearing for the channel generator. The increase of circuit clearances in the channel of AC generator appear as a particular undercuts of diagram f_i = f(t).

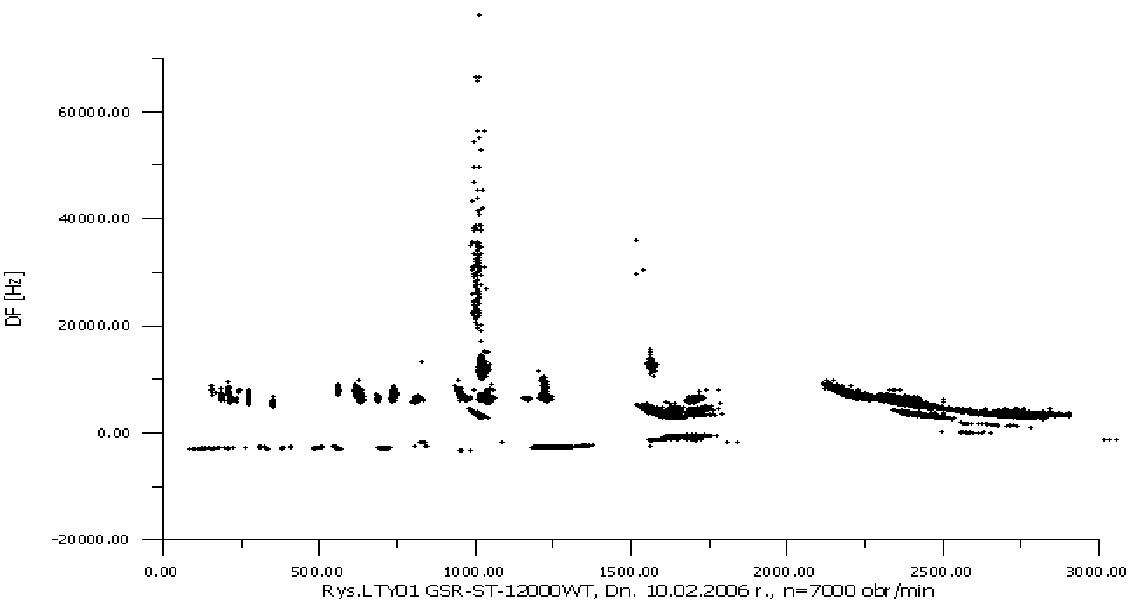

Fig. 3 Characteristic sets obtained from DC generator channel

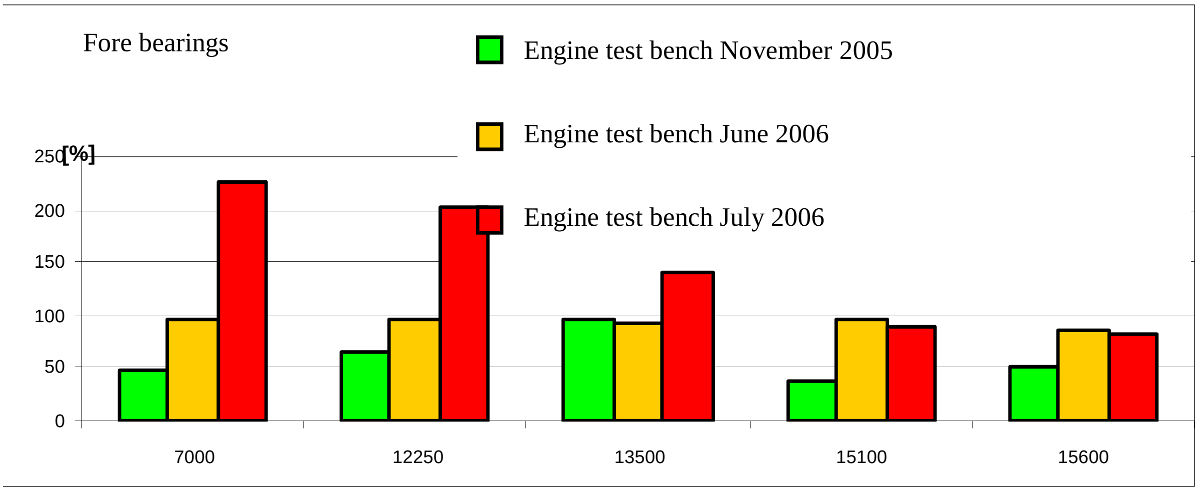

Fig. 4. The graph of the characteristic set height of the fore bearing for three succeeding observation periods of the rolling bearing in the stage of noise wear

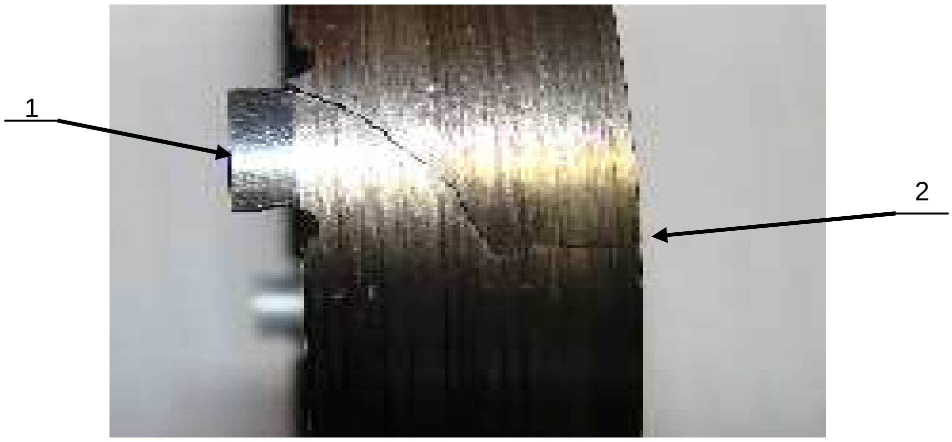

Fig. 5. The cracked sleeve fastening the internal bearing race to the engine frame:
1 – the component protecting the sleeve against rotation, 2 – the point of sleeve crack

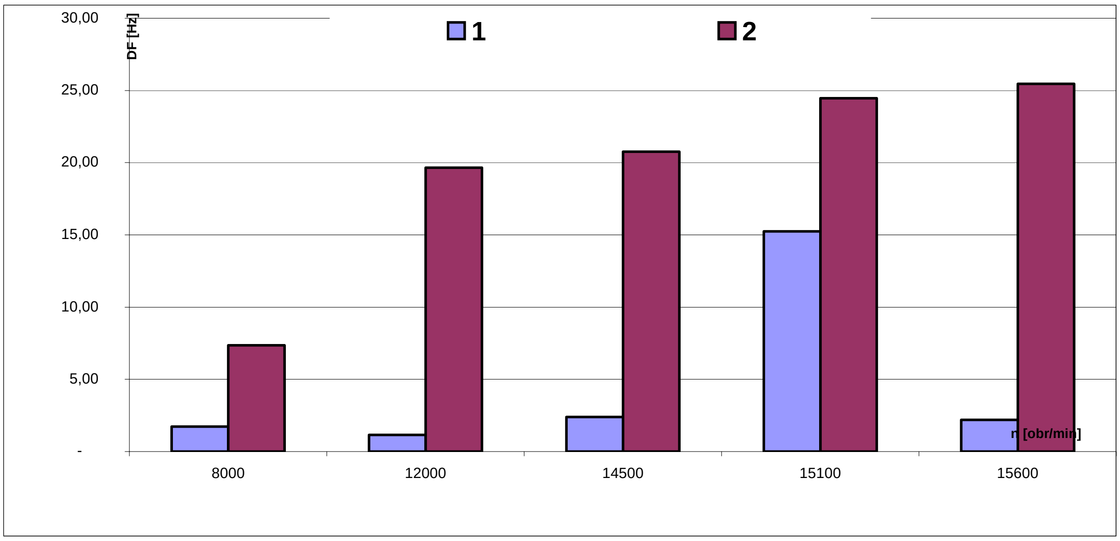

Fig. 6 Changes of the characteristic sets height of the first harmonic after the crack of the sleeve fastening internal bearing race to the engine frame: 1 – after the crack of the sleeve, 2 – before the crack of the sleeve

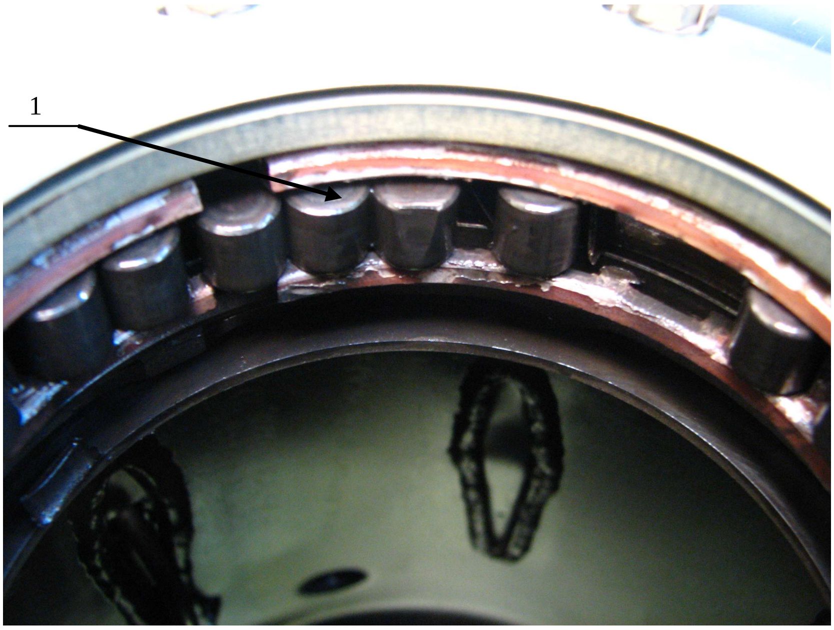

Fig. 7. The damaged central bearing diagnosed by means of FAM-C method:
1- interrupted ring of the spacer-separator

Generally all characteristics of reeling coefficient are inversely proportional to rotational speed. Increased hydrodynamic forces can easily explain it with decrease resistance of rolling friction. Long- drown observations supported by mechanical measurements have enabled a statement, that if minimum appears on the reeling characteristic, considerable value of non-coaxial bearing supports occurs.

An unbalance error of the turbine or the compressor appears as a increase of the characteristic set amplitude in the channel of AC generator (presentation ΔF = f(f_p) first harmonic of rotational speed of the main shaft as well as an extension of the band width). If the error of an ovalization of the bearing mounting appears the characteristic set disintegrates as a two vertical characteristic sets. A skew of the coupling of both shaft parts appears as a increase of the characteristic sets height of the first subharmonic.

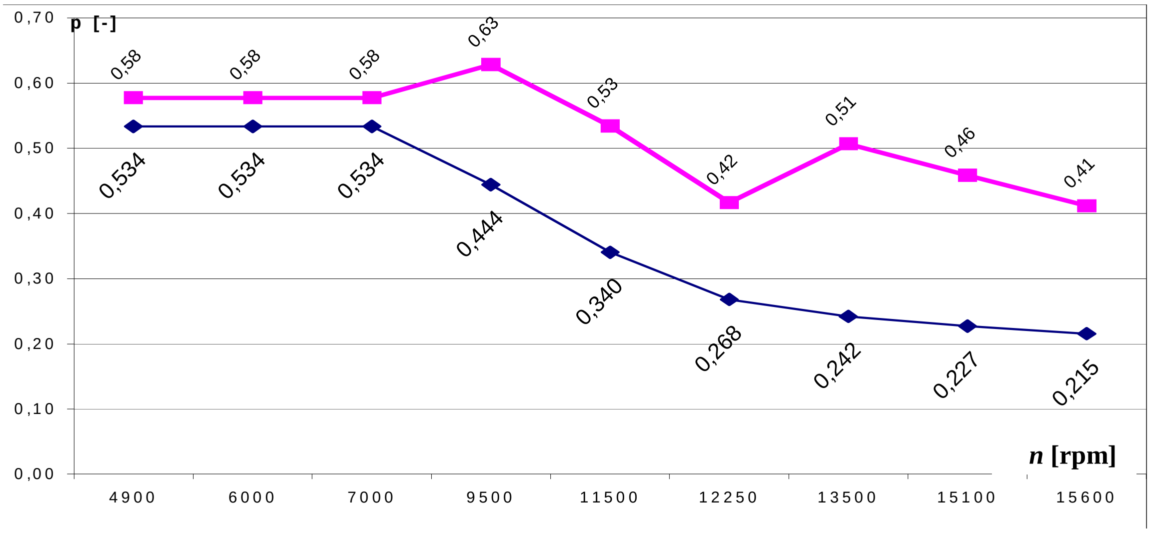

Fig. 8. Diagram of the coefficient changes of reeling of central support bearing:

- *top diagram – under negative coaxial,*
- *bottom diagram under positive coaxial.*

A perpendicularity error of the compressor's pin can be determined by means of a measurement of amplitude modulation depth on the presentation f_i= f(t).

Summary

In the paper theory and application of the diagnostic FAM-C method have been described. This method is based on analysis of frequency modulation parameters of output voltage used for diagnosis of technical condition of turbine engines bearing supports. The application of FAM-C method enables prior detection of subassembly failure, before the failure is danger for flight safety. It is possible to detect various assembly errors as well as monitor of wears effects occurring in bearing supports.

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