The Application of Multifactorial Diagnostic Criteria for Early Vibration Diagnostics of Aircraft Gas Turbine Engine Bearings

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ABSTRACT

The paper proposes basic approaches and results of working out and application of early vibration diagnostics of gas turbine engine bearings using multifactorial diagnostic criteria.

Fatigue spalling, not detected at an early stage on working surfaces of ring raceways and rollers of a turbine bearing subsequently leads to its failure and considerable expenses for regenerative engine repairing. Thus the regular alarm system detecting debris presence in oil due to insufficient sensitivity and selectivity gives an alarm signal too late, at a high stage of damage that excludes the possibility of malfunction elimination without the engine withdrawing from the operation.

The vibrations generated by a bearing at its work in the aircraft GTE structure, mostly, have a very low intensity in relation to the noise level and consequently, for working out of an early and reliable diagnostics, it is necessary on the one hand, to take measures in decreasing the levels of external and internal noise, on the other hand, to develop reliable diagnostic criteria on the basis of multifactorial models, allowing to minimize a zone of uncertainty of diagnostic parameters, to lift their diagnostic sensitivity by taking into account various influencing additional parameters such as shaft speed, ambient temperature, etc.

During the preliminary tests recording of vibrating signals was made in the process of HPT speed deduction after its manual drive up to speed 1.5 Hz. Thus to decrease the level of not informative noises and vibrations, the immovability of all shafts except HPT rotor, and also shafts and gears in a gearbox was provided. Therefore special assembling of an experimental engine was made for real conditions modelling with bearings in various stages of damage. The subsequent data processing was made for the revealing of diagnostic vibration parameters sensitive to the damage presence and the stage of its development [5,7,9]. Frequency range for data processing was defined using traditional approaches [1,2]. Besides transfer functions from the bearing to accelerometer on an external flange of HPT casing have been defined [1,3,6]. The additional diagnostic parameter was detected by the calculation based on a ratio between values of measured diagnostic parameters. As a diagnostic criteria of the bearing condition were used the combinations of 4 specified diagnostic parameters values. The diagnostics was carried out on the aircraft under operating conditions. Below the detailed information on the basic approaches stages and results of working out and practical use are presented.

1. THE METHODS OF DIAGNOSTIC RESEARCH

The subject of diagnostics was fatigue spalling detection on the HPT bearing ring raceways and rollers on the aircraft engine in operation conditions. It was important to provide damage detection at the very early stage in order to avoid failure and expenses for regenerative engine repairing.

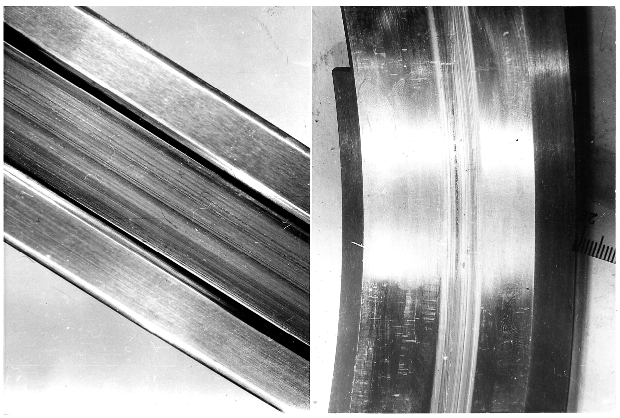

Figure 1. Early and medium stage of bearing ring raceways damage examples.

In order to make necessary testing the regular serial engine was assembled with the HPT bearings in a different stages of ring raceways and rollers fatigue spalling from absence to high stage of damage as follows: new bearing, bearing after full cycle of operation but in a good condition, early stage of damage, medium stage of damage, high stage of damage.

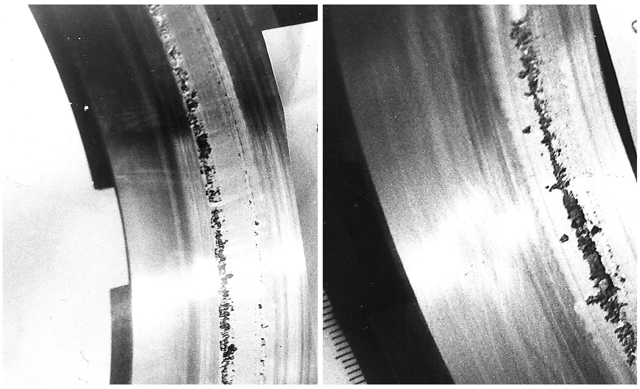

Figure 2. The high stage of bearing ring raceways damage examples.

Several bearings in each of mentioned stages were tested. On Figures 1 and 2 the view of mentioned defects have been presented. Accelerometer for bearing vibrations measurement was located on external surface of a lower part of HPT casing flange. In order to minimize noise it was decided to provide measurements when gearbox and all engine shafts with exception of HP shaft blocked. HP shaft was rotated manually using special tool. Rotation was provided until 1,5 Hz shaft speed achieved. After that tool was removed and rotor begin gradually decreasing of its speed until stop. Recording of vibration signal was automatically starting and finishing within preset rotation speed range with duration about 10 seconds. The main stages of diagnostic researches were based on following principles of bearings work. Vibration signals generated during rotation of HP shaft on its bearings usually including frequencies which are defined by:

- design data, geometrical sizes of the elements of the bearing; quantity of rolling elements;
- shaft speed;
- defects of the bearing parts [1,2].

Vibration signal energy sharing along frequency axis depends on:

- properties of channels of vibrations passage of from the bearing to accelerometer [10-13],
- condition of the bearing and deviations at its manufacturing and quality of bearing support assembling.

The basic bearing frequencies from which formed vibration signals during shaft rotation are: frequencies of rolling elements generating due to a contact with an external and internal rings, frequency of rotation of a separator, frequency of rotation of rollers [1,2]. In case of damage of the bearing the multiple informational harmonics of the basic frequencies added to a bearing casing spectrum of vibrations [5,6]. Intensity of multiple harmonics is in most cases defined by degree of defects development in the bearings. Vibration signals energy distribution on these frequencies is connected with shock interaction of rollers and rings .

Local small fatigue spalling on rollers and surfaces of rings generates periodic pulse signals but large multizone fatigue spalling of rings leading to excitation of more broadband vibrations in the more wide range of frequencies [7,13].

Vibration on this frequencies lead to excitation of a resonant vibrations of the bearing case support which also are informative for bearing diagnostics. Natural frequencies can be defined by means of transfer function calculation during shock excitation of a bearing support. As the result of research works requested frequency range of raw vibration signal was defined as including main bearing and multiple defects forcing frequencies calculated according to a well-known formulas [1,2] and natural frequency of HPT casing defined from a transfer function between bearing and accelerometer places of location. Finally mentioned range was stated within 10 to 1750 Hz. Vibration parameter to be measured – acceleration. Measurement dynamic range was selected within 0,3 to 50 mg. Vibration signals were recorded automatically on a portable digital data processing system.

2. DIAGNOSTIC SYMPTOMS DETECTION

As the basic tool in processing of the received data for definition of diagnostic symptoms were used methods of

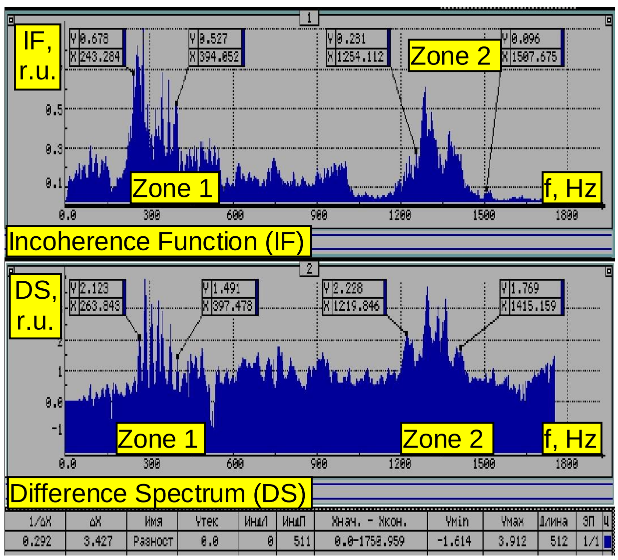

Figure 3. Example 1 of distinction analisys between signals.

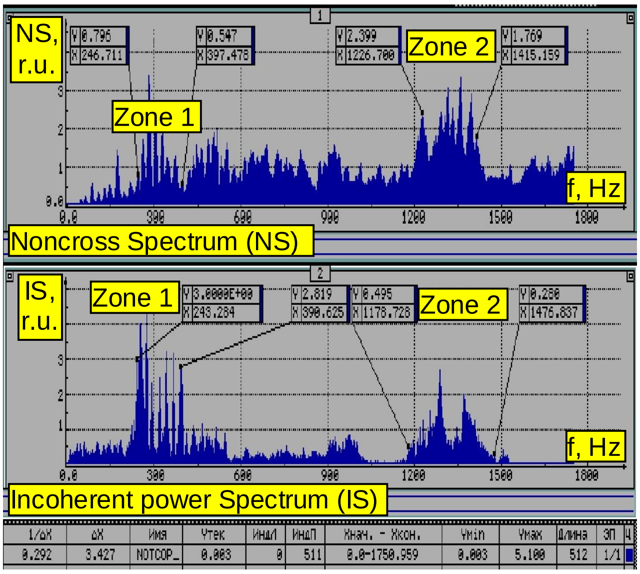

Figure 4. Example 2 of distinction analisys between signals.

the comparative analysis allowing to reveal zones of the maximum distinction between signals received from the bearings in a various stage from good condition to having the maximum damage.

These methods are as follows: incoherence function, difference spectrum, noncross spectrum, incoherent power spectrum. All of them based of FFT [3,4].

The view of mentioned calculation results have been presented on the Figures 3 and 4. Thus as a result of

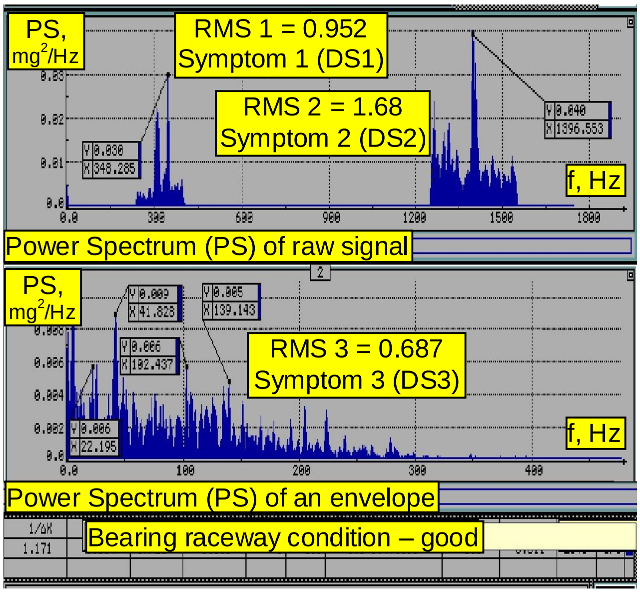

Figure 5. Example 1 of diagnostic data processing results.

mentioned investigations at the first stage of research on 18 different condition bearings within diagnostic signals spectrums diagnostic zones 1, 2 and 3 were considered in a

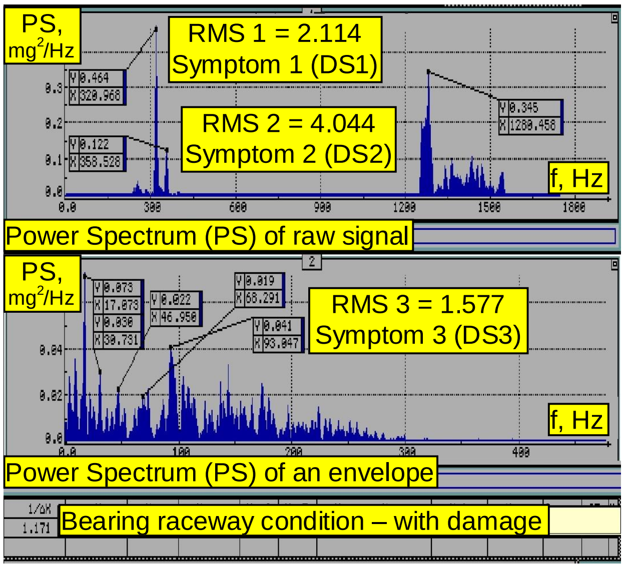

Figure 6. Example 2 of diagnostic data processing results.

range of frequencies of forced vibrations 320 ±80 Hz; and in a range of resonance vibrations of a support 1400 ±150 Hz; discrete components in a spectrum of envelope in a range 20…400 Hz.

Examples of mentioned data processing results presented on a Figures 5 and 6. Three different diagnostic symptoms have been detected after follows steps conducting:

1-st step - power spectra receiving;

2-nd step - spectra multiplying on two different rectangular windows with the side borders equal to the frequencies defined as diagnostic zones 1 and 2 mentioned earlier;

3-rd step - calculation of RMS 1 & 2 for zones 1 and 2;

4-th step - filtering of a raw signal within range of diagnostic zone 2;

5-th step - enveloping of filtered signal and power spectra receiving;

6-th step – RMS 3 calculation.

RMS 1, 2, 3 considered as a set of diagnostic simptoms 1, 2, 3.

3. APPROACHES TO DEVELOPMENT OF MULTIFACTORIAL DIAGNOSTIC CRITERIA

During previous research works it was discovered that ambient conditions as temperature and noise have strong influence on the results and must be fixed before going further. Temperature values were taken from onboard system and corrective coefficients were calculated using statistical data. It allow to bring values of measured vibrations to a normal temperature +20ºC. External noise increase deviation of vibration level up to 15…30%. To fix this problem it was decided to measure signal of engine silence before and after main measurement, to make comparison and if difference is over 15% all measurements are to be repeated. Also it was decided to make main measurements 3 times and if difference between values of symptoms more than 15 % the last measurement must be repeated. It was decided to calculate an average level of each symptom and to use further only this value. And after all this actions were undertaken and all data base was recalculated received results presented on Figure 7.

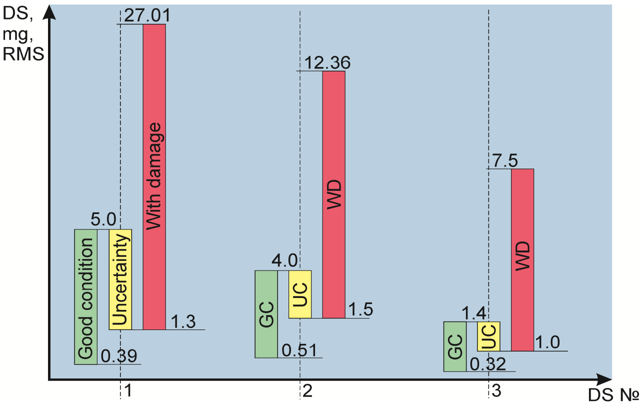

Figure 7. Distribution of symptoms values depending on bearings condition .

According to Figure 7 each of defined diagnostic symptoms still has its zone of uncertainty. That mean that using of alone symptom does not exclude big probability of false diagnose. So it was necessary to minimize possible errors to acceptable levels of probability less than 2,5 %.

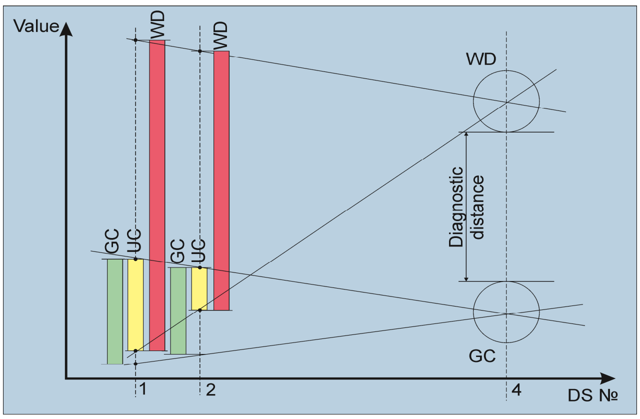

Figure 8. The principle of DS4 calculation.

In this case using of multifactorial diagnostic criteria is an acceptable solution. It was decided to use algorithm of additional diagnostic symptom DS4 calculation using the ratio between the absolute values of diagnostic symptoms DS1 and DS2. As it is demonstrated on Figure 8 the calculated values of DS4 have large "diagnostic distance" and uncertainty zone is absent. Using statistical and logical approaches it become possible to evaluate bearing condition in appropriation to the values of diagnostic symptoms. This gave possibility to provide more accurate diagnostics using four symptoms.

According to the diagram on Figure 9 and Table 1 it became possible to classify bearing condition by using the interval of symptoms values and intervals combinations.

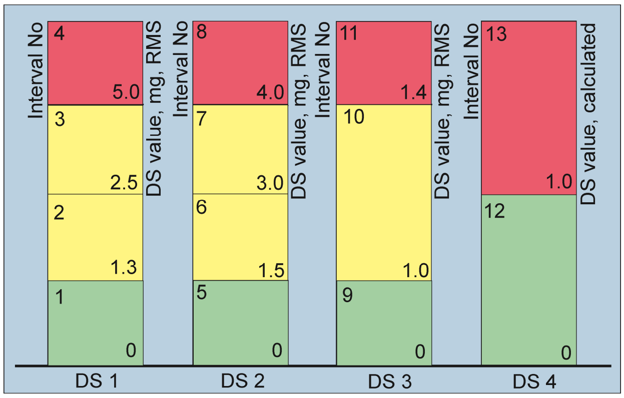

Figure 9. Diagram for defining the intervals of DS1…DS4.

Uncertainty zones DS1 and DS2 in the diagram were divided on two parts. Interval borders were defined using statistical data of 28 measurements on the aircrafts.

Table 1. Appropriation of intervals combinations and bearing condition

Intervals combinations	**Condition status**
(1,5,9) (1,6,9) (1,5,10,12) (2,5,9) (2,6,9)	1 Condition good
(1,5,10,13) (1,5,11) (1,6,10,12) (1,6,11) (1,7,9) (1,7,10,12) (1,8,9) (2,5,10,12) (2,6,10,12) (2,7,9) (2,7,10,12) (3,5,9) (3,5,10,12) (3,6,9) (3,6,10,12) (3,7,9) (4,5,10,12) (4,6,9) (4,6,10,12)	2 Early stage of damage
(1,6,10,13) (1,7,10,13) (1,8,10,12) (2,5,10,13) (2,5,11) (2,6,11) (2,7,10,13) (2,8,9) (2,8,10,12) (3,5,10,13) (3,6,10,13) (3,7,10,12) (3,8,9) (4,5,10,13) (4,7,10,12) (1,7,11) (1,8,10,13) (1,8,11) (2,6,10,13) (2,7,11) (2,8,10,13) (2,8,11) (3,5,11) (3,6,11) (3,8,10,12) (4,5,11) (4,6,10,13) (4,6,11)	3 Minimal damage
(3,7,10,13) (3,8,10,13) (3,7,11) (3,8,11) (4,7,10,13) (4,7,11) (4,8,10,12) (4,8,10,13)	4 Medium damage
(4,8,11)	5 Maximum damage
(4,5,9) (4,7,9) (4,8,9)	6 Incorrect measurement

All mentioned approaches have been realized by using portable automatic expert system which provided described algorithms and minimize probability of mistakes. During diagnostic works on more than 80 engines no false diagnosis done. Using experience received during research works and statistics of damage appearing there were defined and recommended time intervals for regular inspection. For the engines with HPT bearing classified after first inspection as:
- good condition (status 1) inspection to be provided each 300…500 operation hours;
- early stage of damage (status 2) – each 100…300 operation hours;
- minimal stage of damage (status 3) – each 50…100 operation hours;
- medium stage of damage (status 4) – 25…50 operation hours allowed to fly back with additional control of debris presence in the oil and bearing must be changed in the base airport;
- maximum stage of damage (status 5) – operation is strictly forbidden, bearing must be changed on a new one on the place where damage was detected;

4. CONCLUSION

Bearings used on the aircraft engines are a very difficult object for diagnostics because of extremely low vibration levels which they are generating during work. There are some additional factors which also making this task even more complex. They are: external noise, ambient temperature change, shaft rotation speed deviation. Deviation of diagnostic signals levels is the reason of uncertainty in use of measured values. During the works presented in this paper this obstacles were fixed by using described approaches such as: minimizing engine noise by using manual shaft rotation, automatic selection of shaft speed range for data recording, using corrections for noise deduction and temperature compensation, using of measured and calculated diagnostic symptoms, using multifactorial diagnostic criteria for final decision about bearing condition. Mentioned approach shows its high reliability in providing diagnosis and allowed to continue aircrafts operation under periodical inspection.

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BIOGRAPHIES

Adamenko Vladimir at 1975 graduated Technical University in Zaporozye, Ukraine with electricity engineer diploma. Work at JSC Motor Sich as an engineer and later Head of Department of Vibrations and Diagnostics until 2000. Main topics of his work were different research and investigation projects, development of different methods of diagnostics. During this time have about 30 papers on different international and local conferences, received 28 certificates about inventions. From 2000 and for today work for Meggitt SA, Switzerland as a Country Director in Ukraine. Continue contacts and cooperation with Motor Sich on different technical and scientific projects as an expert and consultant.

Drokin Igor at 1999 graduated Technical University in Zaporozye, Ukraine with radiotechnics engineer diploma. Work at JSC Motor Sich as an engineer and later Head of Testing Department. Main topics of his work are different research and investigation projects, development of different methods of aircraft engines testing. During this time have 6 papers on different international conferences. Continue to work for diagnostic methods development.