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APPLICATION OF VIBRATION PASSPORT TECHNOLOGY FOR CONDITION MONITORING OF HELICOPTER ENGINES

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ABSTRACT

This paper considers the problem of vibration monitoring of helicopter engines. Sensitivity of existing systems is limited because of limited frequency range usually used. High frequency vibration modelling could provide the development of vibration diagnostics of helicopter engines. Non-linear effects cause time and frequency instability of vibration components. The model of turbomachine vibration, which accounts pulse nature of blade-vane aerodynamic interactions, is discussed. Non-linear effects follow above interactions and sophisticate structure of casing vibration spectra. Discussed spatial model considers peripheral location of accelerometer and spatial distribution of pulse impact sources in a turbomachine. The paper briefly describes vibration passport techniques and its structure. The paper presents also first application of VP based diagnostic system for helicopter engine, including its main features and architecture. Results of experiments illustrate VP technology effectiveness on the test bench and in trial operation on helicopters. Conclusions outline main benefits of VP technology.

1. INTRODUCTION

Vibration measurement is widely used for condition monitoring of turbomachines however, existing diagnostic systems traditionally operate within frequency range of rotational speed. Practically all operating systems that provide vibration monitoring of gas turbine engines traditionally consider the rotor as the main source of vibration, therefore these systems measure vibration within low frequency range. Running modernization of hard- and software for vibration measurement and analysis provided higher accuracy and reliability of systems operation; however, its diagnostic abilities fall behind. Inertial rotor and construction of aviation engines makes typical systems insensible to small failures of rotor components.

To provide both: flight safety and time/costs saving an aircraft operator is forced to apply more condition-based maintenance (CBM) and less preventive periodic maintenance works. However, to provide CBM, the system must be sensitive enough to detect latent failures timely and to monitor operational condition of an engine.

2. ACTUAL ISSUE OF TURBOMACHINE VIBRATION DIAGNOSTICS

To improve diagnostic system sensitivity it is necessary to expand frequency and amplitude ranges of measured vibration. Experimental researches [1] showed that if to provide 120dB of dynamic range and to expand frequency band to ultra-sound, the vibration diagnostic system may become sensitive to even small changes of engines units functionality. Modern vibration monitoring systems for new engines contain embedded accelerometers that have wider range. However, majority of existing helicopter engines are equipped by accelerometers for measurement of rotor vibration only or have no vibration control at all. The only opportunity to place accelerometer at already designed engine is to mount it on the outer casing of the engine. One of engine’s attachment fittings or one of cargo ends (hooks) may be chosen as a place for accelerometer mounting. Therefore, to be applicable for the particular type of helicopter engine the newly created diagnostic system must be simply handled and easy mounted equipment for vibration measurement.

Sensitive accelerometer mounted on outer casing of the engine generates complicated vibration signal [2]. Such signal contains plenty of information that needs to be interpreted using sophisticated model of engine vibration. The model must account all interactions between engine's units but not rotor-stator only. As a sample, figure 1 shows low-frequency band of vibration spectrum, which was measured by accelerometer on the outer casing of the free turbine of medium-size turbo-shaft engine.

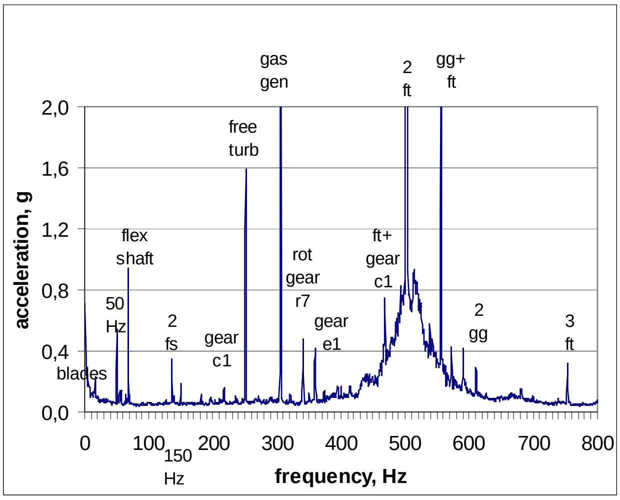


Figure 1. Spectrum of vibration measured on the free turbine casing

Rotors of gas generator and free turbine generate components *gg* and *ft* at frequencies equal to its rotational speed. However, casing vibration may contain many other components generated by engine, main rotor, gearbox, transmission, etc. To identify such components and to relate them with operating units the proper model of vibration is needed. To illustrate the sample brief list of identified components of above spectrum is presented below:

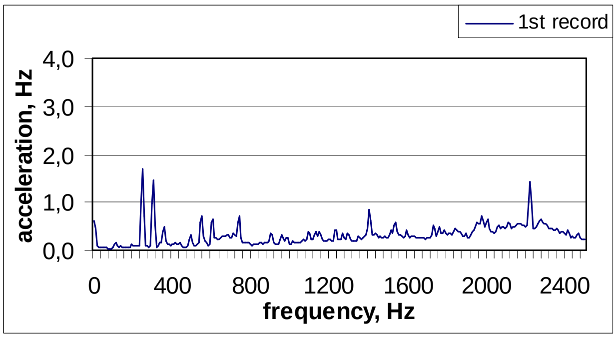
- engine:
  - gas generator (*gg*) and its multiples (*2gg*),
  - free turbine (*ft*) and its multiples (*2ft*, *3ft*, *4ft*, *6ft*),
  - flexible shaft of fuel control unit (*flex shaft*), and its multiples (*2fs*);
  - intermediate gear of flexible shaft (*gear c1*) and its multiple (*4g c1*, *5g c1*);
  - gear of free turbine tacho probe (*tacho*),
  - central gear (*e1*);
- main rotor gears:
  - gear Nr.7 (*rot gear r7*),
  - gear Nr.6 (*rot gear r6*);
- main rotor – blades passing (*blades*), which generated by rotating blade wakes.

There are also components born by non-linear interaction of units, which frequencies are equal to sum or difference between reference frequencies, like:

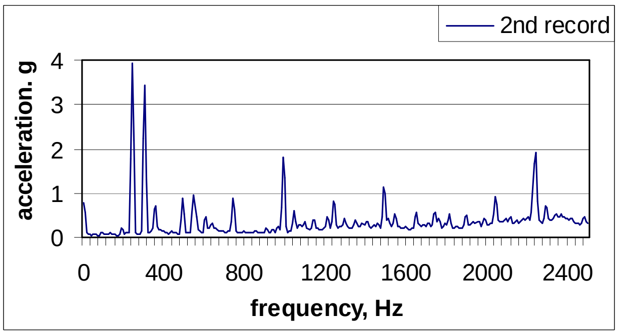
- gas generator and free turbine – (*gg+ft*), (*gg+2ft*), (*gg+5ft*), (*6ft-gg*);
- free turbine and intermediate gear (*ft+gear c1*).

Vibration components at such mixed frequencies may appear in case if there are mechanical non-linear interactions, effecting as a modulation in radio engineering. In addition to above-mentioned narrow-band components there are also wide-band components looking like "hills" (500 Hz and 870 Hz in figure 1), which spectrum width could spread from tenths to hundreds Hz. Typically resonances of stator elements cause such components in low-frequency band.

Sophisticated frequency structure of vibration is coupled by instability in time (figure 2).



a)



b)

Figure 2. Vibration spectra (low-frequency range) of two consequent records: a)- 1st record; b) – 2nd – record two months later.

While testing the engine on a test bench two vibration records (in the same operating mode) followed with two-month interruption. In low-frequency range, both spectra have similar structures, though amplitude of components varied. As low-frequency components have stable behavior, they become good indicators for diagnostic purposes. However, these components opportunities are limited; because small-scaled failures of blades, vanes, teeth and bearings reflect in high-frequency vibration range mainly.

Research of casing vibration in high-frequency domain displayed its unstable behavior and the problem of wide-band components identification. As figure 3 illustrates, wide-band components of high-frequency casing vibration may vary its allocation in spectrum. In high-frequency range, indicated harmonics of 1st and 2nd free turbine cascades kept its positions in spectra. However, frequency distribution of random or so-called "noise" vibration in spectra had modified. This fact is most evident in the case of wide-band component, which in first record had its maximum at 14400 Hz but in second one, the maximum had moved to 15300 Hz.

Above-mentioned instability of casing vibration in time and frequency domains requires detailed vibration modeling, which may describe deterministic and random components.

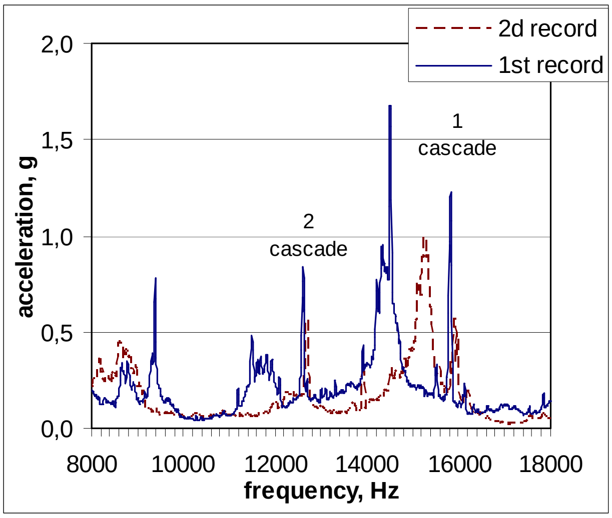


Figure 3. Vibration spectra (high-frequency range) of two consequent records

3. SPATIAL PULSE MODEL OF VIBRATION

The model of vibration must describe relations between operating engine units and vibration measured on the engine's casing. The model considers basic types of excitation and sources. There are mechanical interactions, for instance between rotor and stator or in bearings and gears. Interaction between blades and vanes is a typical sample of aerodynamic one. Sources of vibration in turbomachine may be considered as concentrated or distributed ones.

Compressor and turbine vanes, which interact with upstream blade wakes, present the group of multiple *distributed and correlated* sources. Deformation waves, propagating to an accelerometer via stator elements, transmit vane's excitation. Therefore, guide vanes are typical distributed sources of high-frequency vibration. To outline mutual spacing of distributed sources and peripherally located accelerometer the term "spatial" is used for casing vibration model. Single blade/vane interaction is very short in time because of high rotation speed and small width of blades and vanes. That is why its simulation has "pulse" nature [3], which reflects on casing vibration model.

There are main assumptions and conclusions of spatial pulse model of turbomachine vibration below.

1) The separate pulse of casing vibration is the response to the impact from a single vane actuated by a blade wake.
2) Pulse series modulated by upstream flow and blades irregularity present variable aerodynamic forces acting to vane.
3) An actual order of blades and vanes interaction is not sequential and interaction sequence depends on the ratio between blade and vane numbers. The functional describing relation between sequential blade/vane interaction and its actual order in time is analogue of the *code modulation* in radio engineering.
4) Force pulses, generated by different vanes, come to casing accelerometer by different paths, which depend on the vane allocation in relation to the accelerometer's position. Different signal paths modify delays and damping ratios of pulses measured by accelerometer. Phase and amplitude modulation of typical pulses describes above influence.
5) The casing accelerometer interprets responses to excitation of guide vanes as the united pulse series. In frequency domain, the carrier frequency of actual interaction is located in the ultra-sound range, but extremely wide modulation zone reaches low frequencies. Therefore, peripheral location of

an accelerometer expands the range of high-frequency vibration to the sound band, where a typical instrument can measure vibration.

The spatial model allowed to explain the nature of local maximums of random vibration in spectra, which are independent of rotational speed and do not belong to mechanical resonances. This newly discovered physical effect of instable distortion of casing vibration was called “echo” [2].

Other group of vibration sources is mechanical interactions of rotor and stator parts, for instance gears or bearings. Any interaction transmits its impact through unit’s bearings. Consideration of source status depends on its scale and distance from an accelerometer. For instance, rolling balls of large rotor bearing, which is located close to the accelerometer, may generate pulse impacts distributed around inner casing. Therefore, each rolling ball should be considered as a separate source for the accelerometer, but complete bearing looks like a set of rotating distributed sources. Opposite, a small bearing of remote gear would act as the concentrated source of excitation.

All mechanical interactions generate variable forces having wide-spectrum structure however, higher frequency components passing well-damped bearing decay more intensively than low frequencies. In other words, typical turbomachine bearing acts as a low-pass mechanical filter. That is why an accelerometer located on an outer casing perceives mainly low-frequency vibration from a remote source.

By this way, the spatial vibration model of turbomachine describes two basic types of casing vibration sources, which have its dominant frequency zones. Remote sources form mainly low-frequency vibration, presented in spectra by harmonics of rotating units and components, caused by mechanical resonances. Distributed sources generate dominantly high-frequency vibration zone by mean of multiple modulation mechanisms. This fact explains presence of intensive random components in high-frequency domain as well as its instable behavior.

4. VIBRATION PASSPORT TECHNOLOGY

Vibration passport (VP) technology appears to be integral solution for turbomachine vibration diagnostics. VP technology involves the combination of high-frequency casing vibration model, engine vibration measurement and analysis techniques, diagnostic signs detection and evaluation, as well as evaluation of current condition of turbomachine units.

4.1. VP approach

VP approach bases on the comparison between actual operational condition of the turbomachine and its initial (reference) status. Such approach uses techniques based on main assumptions:

- vibration of operating turbomachine vary under exposure of operating mode, modification of a turbomachine’s condition, and random factors;
- the operational condition of the turbomachine unit may be characterized by a set of components of three-dimensional (3D) vibration spectrum, which is related to this unit's operation by corresponding physical model;
- deviation of vibration components from its initial status play a role of elementary indicators of the condition modification in case if influence of operational mode and random factors is damped or reduced enough;
- condition evaluation of each particular turbomachine’s unit is available provided by consideration of other correlated units.

VP techniques require extended frequency and dynamic ranges of vibration signal measurement and analysis. Frequency range should overlap sound band (20…20000 Hz) and dynamic range must exceed 100 dB. To reduce an influence of machine operating mode as well as random factors, VP techniques use special methods and procedures of vibration measurement, recording, data processing and diagnostic methods.

4.2. VP structure

Any type of turbomachines may have its *typical* VP, which is the set of formulas for calculation of elementary and aggregate parameters. Engine’s typical VP could contain few hundreds of *elementary* parameters, which are corresponded to spectrum components of vibration. VP models relate the variation of elementary parameters to changes of geometric, aerodynamic or other features of the corresponding unit's structure or its operation. Each *aggregate* parameter, based on calculation of few elementary ones, describes the operational condition of a particular engine's unit, for example gas generator or its component only, like compressor stage, or a single gear. Each aggregate parameter of typical VP has allowable and emergency limits that originate from tests and trial data.

The *individual* VP describes condition of one particular engine of that type. The individual VP of the engine contains the number of sheets determined by the number of vibration checks. The structure of each VP sheet repeats the typical VP and reflects the actual condition of the machine at the check moment. Each elementary parameter of individual VP measures the relative deviation of actual vibration component value from its value at the start of this engine operation. The individual VP originates at first vibration check, when initially measured values of vibration components would complete the zero sheet of individual VP or *an etalon*. The next vibration measurement would provide first sheet of individual VP and so on. Aggregate parameters of an individual VP play conclusive role for monitoring or diagnostics of each engine's unit.

4.3. VP system architecture

The simplest version of VP system may work as autonomous, which serves few engines at one area. Such system has the local independent database (DB) for the limited engines number. In other case, the distributed system for whole fleet of such engines may exist, where the DB of diagnostic centre interacts with distributed local VP systems (figure 4).

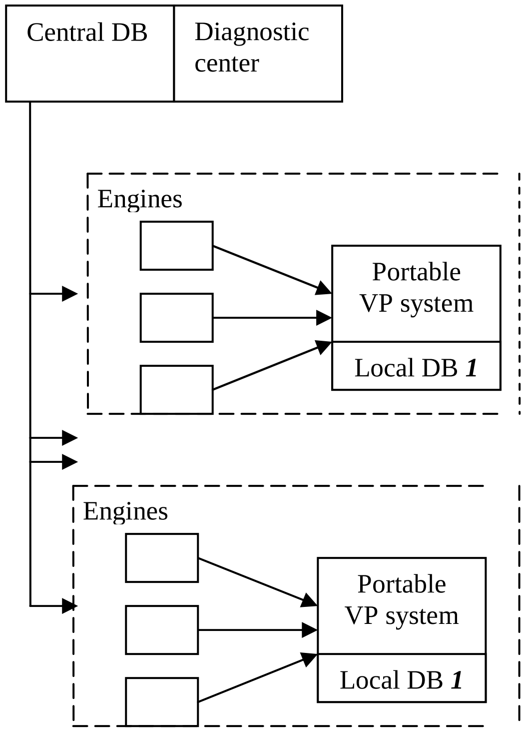


Figure 4. Architecture of VP systems interaction.

The diagnostic centre of a manufacturer or leading MRO may centralise local systems that operate in different companies. Such centre could provide bilateral connections via internet with end users of system sets. Working within centralized system each local system reports regularly collected data that provides statistics for the development of system's diagnostic facilities. Backward the centre sends necessary corrections of permissible and emergency margins as well as system's software updating.

4.4. VP application to helicopter turbo shaft engine

Widely used Russian helicopter engine TV3-117 became the first object of VP technology application. The vibration monitoring and diagnostic system in its trial version measures 350 elementary vibration parameters to monitor technical condition of the gas generator and the power turbine, as well as its bearings, gearbox and important aggregates, including oil and fuel pumps.

The system operates as portable set of land-based equipment providing vibration measurements during engine's operation test after technical maintenance. The pilot sample of the system is in trial use in large helicopter company now. Pilot system includes four accelerometers for two engines, cables and preamplifiers set, and 12-channel input module connected to PC in the ruggedized case. Easy-to-mount brackets provide quick accelerometers mounting to the front engine attachment (figure 5a) and to the cargo hook on the power turbine bearing housing (figure 5b). The ruggedized case places in cargo/passenger cabin (figure 5c).

a)

b)

c)

Figure 5. Portable VMD system located on a helicopter:
a) and b) –accelerometers mounted by special brackets: on the front engine-to-fuselage attachment (a), and on the load hook (b); c) – portable set in a passenger cabin.

The technician mounts accelerometers on the both engines before operation check and removes after the check finished. After manual starting, the software of the system provides automatic registration of vibration data, its processing and VP parameters calculation. Calculated VP parameters form the new sheet of the VP. After that, the system generates report on current condition of the engine as well as its forecast until next test. The system is autonomous and has no connection to engine or helicopter board control systems. Batteries or helicopter DC source (cargo cabin located) provides power supply of the system. After evaluation of the object's condition and forecast, the system automatically generates diagnostic report.

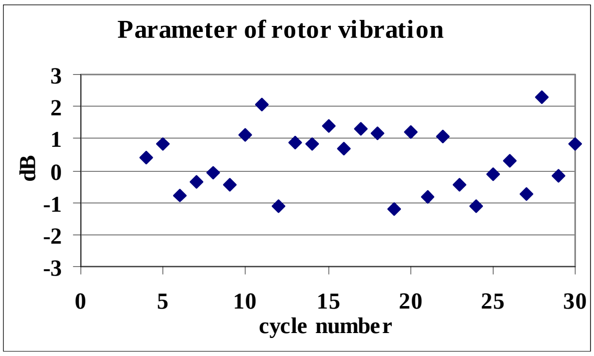
5. EFFECTIVENESS OF VP SYSTEM FOR CONDITION MONITORING

Wide program of experiments and trial operation provided versatile verification of basic assumptions of the spatial model and proved effectiveness of most usable VP parameters. There are some illustrations below to demonstrate effectiveness of VP techniques.

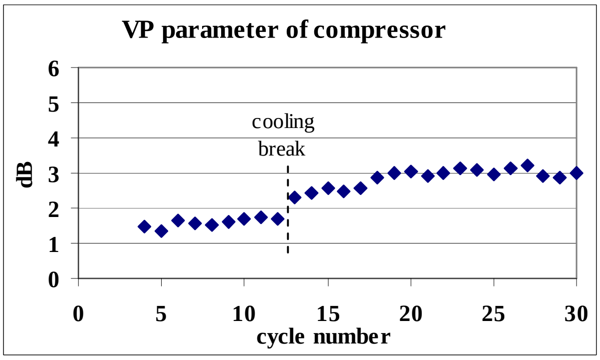
5.1. Good-order engine

The program of serial cycles of engine test on the bench provided iteration of the tested engine's condition. The series of thirty start-stop cycles of the good working order engine had to show whether VP parameter of compressor status might reflect modification of its actual operational condition caused by slight running in. The effectiveness of VP compressor parameter is easy to illustrate by comparison with commonly used "rotor vibration" parameter, which is measured at rotational speed and typically used for indication of aircraft engine vibration. For more convenience, diagrams of both parameters are presented in relative scale (dB) as variation from its initial value.

Rotor vibration (figure 6a) was unstable and varied from one start to another. So-called paratypic factors, as assemble of different operational and occasional factors, cause such fluctuation of vibration level. The scatter between vibration levels of two next cycles exceeded 3 dB and there no any tendency in rotor vibration evolution. Opposite, VP parameter of compressor demonstrated clear tendency of running-in process (up to 18^{th} …20^{th} cycles), and then showed stable behaviour at about 3dB level (figure 6b). One-hour break for oil cooling (after 12^{th} cycle) interrupted the tendency line that demonstrates sensitivity of the parameter to operational condition as well.



a)

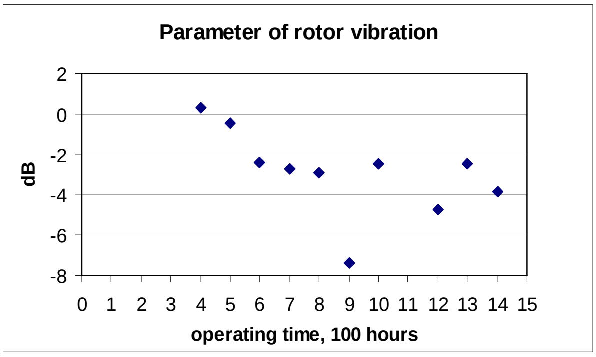


b)

Figure 6. Vibration parameters evolution to test cycle number: a) - parameter of rotor vibration; b) – VP parameter of compressor.

5.2. Engine endurance test

The endurance test on the bench of the same type engine had modified the engine's condition more essentially. The parameter of rotor vibration had no definite tendency (figure 7a). Firstly, it dropped sequentially, then it scattered with variation up to 5 dB.



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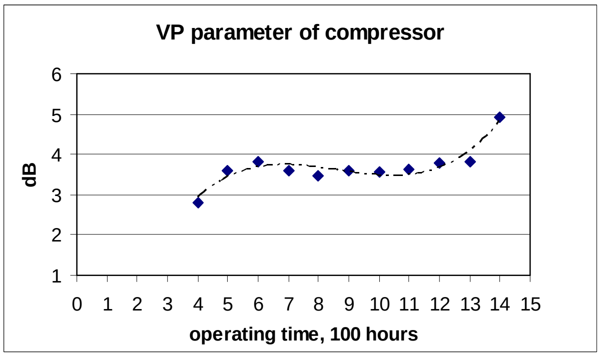

b)

Figure 7. Vibration parameters evolution to operating life: a) - parameter of rotor vibration; b) – VP parameter of compressor.

VP parameter of compressor (figure 7b) shows clear tendency in evolution to operating time and grew from 3 dB to 5 dB. There were defined three stages in this parameter's evolution during endurance test: running-in up to 500 hours, stable operation from 500 up to 1200…1300 hours and further growth after.
Both above engine tests on a bench demonstrated capability of VP parameter for health monitoring of a compressor as an engine's unit.

5.3. Trial operation on helicopter

Trial operation of portable VP system has proved stable relation of VP parameters to modification of engine units' condition. There were eight vibration checks during engine's operating life on the helicopter (figure 8).

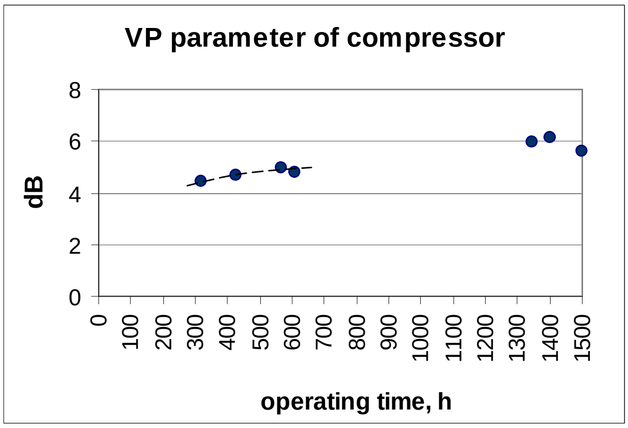

Figure 8. Evolution of VP parameter of compressor to operating life.

After creation of the VP etalon at about 200 hours of engine's operating life, four checks at 319, 427, 565 and 610 hours showed slight growth of the parameter. At the end of operating life, limited by 1500 hours, another three vibration checks demonstrated parameter's climb up to 6 dB. Based on the testing experience on the test bench (figures 6b and 7b) it is possible to suppose that during uncontrolled stage the parameter grows smoothly also, scattering within narrow limits.

Both experiments and trial operation:

- illustrated benefits of VP based monitoring system in comparison with typical vibration systems operating on helicopters,
- demonstrated effectiveness of VP system for monitoring of turbomachine's condition during its operation life.

6. CONCLUSIONS

Newly developed spatial pulse model describes all main components of casing vibration, generated by aerodynamic interactions as well as by bearings and gears. The spatial model substantiates the diagnostic basis of VP techniques, whereas state-of-the-art hard and software provided technical basis for portable field operating system. Based on physical models of vibration and on the new approach to vibration measurement and processing, the VP technology had been developed for monitoring and diagnostics of turbomachine's condition. Pilot samples of the VP based monitoring and diagnostic system had been created for helicopter jet engine. The program of experimental verification and trial operation of the pilot systems has validated some of VP parameters as effective tools for monitoring and diagnostics.

Application of VP technology based system does not require any upgrading or engineering changes of existing aircraft engines. Main benefits of such system are the capability to provide monitoring and diagnostics of operating aircraft engines in field conditions by on-land vibration checks with minimal time and cost expenditures.

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