ADVANCED VIBRATION TECHNIQUE FOR MONITORING OF HELICOPTER BEARINGS

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Abstract

The paper is dedicated to rolling bearings vibration diagnostics. Main problems of currently used diagnostic methods are discussed. There is a discussion of research study and trial applications of new adaptive technique that allows high credibly assessment of technical condition of bearings and its components. It is briefly described the basic model of bearing operation and new approach to its condition evaluation using operational transfer function. There are consideration of results of research study on laboratory test bench, trial applications for diagnosis of helicopter's bearings and other industrial aggregates. Main benefits of the adaptive technique are considered.

1. INTRODUCTION

Rolling bearing are obligatory units of practically all rotary mechanisms taking up all static and dynamic loads from a rotor. However, its operational condition could be complicated by abnormal loading, lubricating or elevated temperatures. So technical condition of bearings often limits workability of the whole machine.

To increase lifetime and reliability of rotary mechanisms as well as to reduce maintenance costs it is necessary to monitor bearings technical condition during all its life cycle. Vibration methods of bearings monitoring and diagnostics became the most popular in last decades. The reason was that vibration signals reflect most of mechanism operation aspects including technical condition of bearings. The theory and practices of vibration signal analysis are developed very well up to moment providing adequate information about technical condition of bearings [1,2]. Actual diagnostic techniques apply mean-square values, peak/noise ratio, spectral density peaks and spectrum of an envelope. However; considering aviation machines efficiency of above methods is still low and main problems of these methods are:

- vibration path from a bearing to a sensor is complex and extrinsic vibration sources may mask bearing signals, so useful signal is lost in the noise;
- application of any actual method to each bearing of specific machine requires tests of operating machine and high-skill expertise to achieve reliable diagnosis.

2. MODELING OF BEARING VIBRATION SIGNAL

The new technique, called *adaptive,* settle above problems using new approach for extraction of useful bearing vibration components from common vibration signal. Accountable phase ratios between rotating elements of a bearing that is rollers, inner ring and cage (separator) provide this extraction. Adaptive technique [3] uses physical model that based on conventional idea of pulse-mode interaction between rollers/balls and bearing rings. Members and order of bearing interaction are illustrated by figure 1.

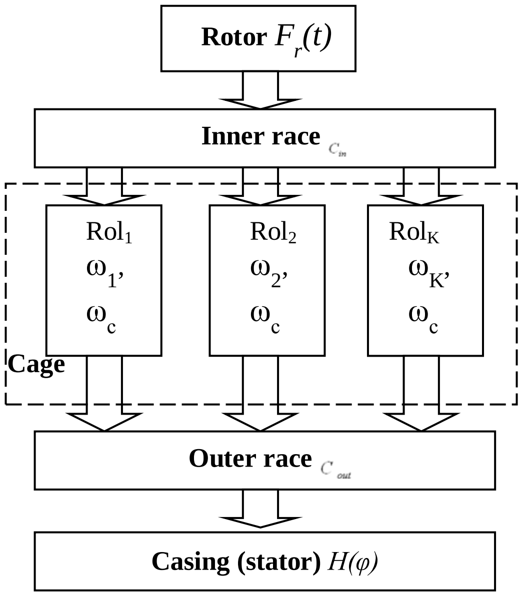


Figure 1. Bearings component interaction chart

Rotor through inner ring affects balls by inertial dynamic forces $F_r(t)$ caused by both rotating unbalance and housing response. Rotating balls transfer these quasi-periodical forces to outer ring and then to a casing. All balls/rollers (*Rol_1, Rol_2,…,Rol_K*) rotate together with cage (separator) around the rotor axis. By the way, each of them is spinning at its own rate ($\omega_1, \omega_2, \ldots, \omega_K$). Surfaces of ball races are not ideal as its shape has geometric fluctuations and roughness. Rolling of uneven balls along rings' races with own unevenness generates impulse forces acting to a rotor and a stator both. Such impulse interaction has random mode and looked as a continuous sequence of micro-impacts. However, quasi-periodical motion of rotating components modulates this random process that creates opportunity for extraction of useful information. Specialty is that though all balls interact with outer ring concurrently, only two of them participate in transmittance of rotor loads to an outer ring (in single-row bearing).

Any fault appearing in a bearing increases unevenness of ball or rings races so the main task of diagnostics is in such unevenness evaluation. Irregularity distribution in relation to phase $C(\varphi) = 1 + \Delta C(\varphi)$ is called irregularity profile and is used for race irregularity measurement of each component. Phase of component (ball, inner or outer race) revolution in its rotation is an argument of this function. Irregularity fluctuates by ΔC around 1, which means ideally even race.

Sensor on a casing, measuring momentary vibration, may be described by the expression (1) that is mathematical model of vibration signal

$$(1) \quad a(t) = \sum_{k=1}^{K} \left\{ \begin{array}{l} H(\varphi_k) * P_r(\omega_r t + \varphi_0^r) * f_k[K\omega_c, \Delta r] * \\ * C_{in}(\varphi) * C_{out}(\varphi) * C_k^{rol}(\varphi) + \\ + H(\varphi_k) * F_{rol}^k(m_k, \omega_c) * C_{out}(\varphi) * C_k^{rol}(\varphi) \end{array} \right\}$$

where

$H(\varphi_k)$ - stator transfer function between contact point of ball *k* and outer ring, from one side, and sensor on a casing, from other side;

P_r - rotor inertial force transmitted through inner ring to balls;

ω_r - rotation speed of a rotor,

$f_k[K\omega_c, \Delta r]$ - lumbering function that is subject of balls quantity K, cage turning rate ω_c and radial clearance Δr;

$C_{in}(\varphi) = \left|1 + \Delta C_{in}(\omega_{in} t + \varphi_0^c)\right|$ - inner ring (ball race) irregularity;

$C_{out}(\varphi) = \left|1 + \Delta C_{out}(\omega_{out} t + \varphi_0^c)\right|$ - outer ring (ball race) irregularity;

$C_k^{rol}(\varphi) = \left[1 + \Delta C_k^{rol}(\omega_{rol}^k t + \varphi_0^{krol})\right]^2$ - race irregularity of ball No *k*;

F_{rol}^k - inertial force of ball No *k* to outer ring;

m_k - mass of ball No *k*;

ω_{rol}^k - turn rate of ball No *k*;

$\varphi_0^{r,c,krol}$ - initial phase of any bearing component.

Two augends of (1) describe two types of inertial forces generated when bearing operates:

- Rotor forces transferred by inner ring to outer ring, and
- Inertial forces of balls rotating with a cage.

For most of bearings the rotor forces multiple exceed the forces created by balls, so the first augend plays main role. That is why further consideration will be related for this part of equation only.

$$(1a) \quad a'(t) = \sum_{k=1}^{K} \left\{ \begin{array}{l} H(\varphi_k) * P_r(\omega_r t + \varphi_0^r) * f_k[K\omega_c, \Delta r] * \\ * C_{in}(\varphi) * C_{out}(\varphi) * C_k^{rol}(\varphi) \end{array} \right\}$$

Applying above model to consideration of actual bearing vibration it is necessary to keep in mind that rotor forces are transferred to a stator at any time alternately by pair of balls (in single-row) only. Such pair of balls called “loaded”. Weak own centrifugal forces acting to other balls and radial clearance do not facilitate sufficient contact and these balls (unloaded) slide. Such sliding reduces turn rate of unloaded balls that breakes a cage and its rotation speed slightly decreses. Occasional sliding of unloaded balls creates uncertainty of its phases that means any re-contacting between specified points of the ball and the ring will happen with arbitrary phase. Such uncertainty is the main source of occasional component of vibration.

Transfer function $H(\varphi_k)$ is determined by mass-elastic properties of the stator and independent to bearing operation (1a). Rotor generated forces $P_r(\omega_r t + \varphi_0^r)$ are considered as quasi-periodical. Lumbering function $f_k[K\omega_c, \Delta r]$ depends of cage turn rate (related by kinematic with rotor speed), phase angle between balls (determined by balls quantity *K*) and radial clearance in the bearing. This non-linear function transposes dynamic rotor forces to higher frequency zone (Kf_r). By this, the product of first three multipliers is quasi-deterministic and it is not related to race irregularities.

Occasional component of vibration is generated by interaction of balls and rings irregularities under rotor forces influence. Three multipliers in square brackets (1a) describe this component. The profile of irregularity $\Delta C(\varphi)$ is a random function however; rotation periodically repeats occasional micro-impulses and modulates them by turn rate of cage, inner ring and balls.

Non-linear interaction between balls and rings may be presented as multi-factor transfer function of a bearing

$$(2) \quad MF(t) = f_k[K\omega_c, \Delta r] * C_{in}(\varphi) * C_{out}(\varphi) * C_k^{rol}(\varphi) .$$

This function transforms dynamic forces induced by a rotor to the sequence of occasional micro-impulses modulated by quasi-periodical motion of an inner ring, a cage and balls. *MF*-function depends of bearing's kinematics, radial clearance and technical condition of its components, including balls, a cage and ring races. This function is not related to rotor's motion and forces as well as to stator transfer function.

Replacing multinomial (product of ball races irregularity profiles) in (1a) by *MF(t)* from (2) we could found bearing transfer function

$$\overline{MF}(t) \approx \frac{\bar{a}(t)}{\sum_{k=1}^{K}\left\{H(\varphi_k) * \bar{P}_r(\omega_r t + \varphi_0^r)\right\}} \qquad (3)$$

Equation (3) shows that *MF*-function could be calculated as division of vibration signal measured vector on a casing to the product of this casing transfer function and rotor force time vector.

Such approach could be used for practical cases for determination of bearing ball race irregularities using measured data as:

- vibration vectors *A(N)* and rotation speed signal vector *T(N)* in digital form (*N* samples length),
- bearing construction data (type, ball quantity and diameter, ball races diameters).

Using above noted data it is possible to calculate ratio of bearing components' turn rate and order *K* of modulating function $f_k\left[K\omega_c, \Delta r\right]$. Then time vector of rotor forces and casing (stator) transfer function should be found. For this purpose iteration approach may be applied to reduce uncertainty. At first, momentary acceleration values measured in three orthogonal directions form time vector of magnitudes. Then synchronized averaging is applied to the vector of magnitudes. Averaged vector acts as the divisor for *MF*-function vector calculation, which length *N* will be the same as raw data vector *A(N)*.

Using energy parameters of *MF* transfer function it is possible to estimate technical condition of a bearing at whole. Any reason that causes growth of micro-impulses intensity will increase *MF* function values. However, *MF*-function cannot detect the source of bearing operation abnormality, for instance, radial clearance increased or inner ring race is damaged. Further *MF*-function processing provides evaluation of each bearing component condition separately. Newly developed Spatial Time Domain Distribution (STDD) provides such separate assessment based on *MF*-function vector and using calculation routines originating from (2). Parameters needed for STDD are based from one side on the specific bearing kinematics and from other side on the knowledge about motion specialties of bearing components in depend of operation mode, lubricating, damaging, etc. To obtain such knowledge extensive experimental program was carried out. Specially constructed test rig and high speed camera been used to research kinematics of operating bearings in different operation modes and technical states.

Above considered approach including estimation of bearing's transfer function and STDD has provided some important advantages in contrast with typical diagnostic methods of bearings.

Adaptive technique becomes universal for technical condition evaluation of any bearing independently to a type, size, rotation speed and operation mode. This feature appears because condition parameters of adaptive technique are based on assessment of rotor loads transferring quality but not on vibration amplitudes. As irregularity parameters of adaptive technique have relative scale, they are compatible for bearings of different types. This means that parameters' statistics is common for most of bearings types, and being collected for one type may be applied to other types with similar faults.

Adaptive technique has low sensitivity to noise generated by other vibration sources, including frequency components that are multiple for rotation speeds of bearing components. Due to accounting of ball's and cage's motion specialties and utilizing of wide frequency range vibration external sources cannot mask diagnostic signs of bearing faults. Based on that adaptive technique it does not require preliminary tests in contrast to conventional methods of bearing diagnostics. Such methods need preliminary research and tests of the object in wide range of its operational modes in order to choose optimal frequency zone for specific bearing in specific aggregate.

Above mentioned benefits of adaptive technique provide reliable diagnostics of complicated aggregates and machines, where are no opportunities to locate a sensor close to a bearing, but there are plenty of external sources of vibration. Such benefits are important especially for gear-boxes, turbo-machines, piston engines, pumps and other machines that widely applied in aviation. By adaptive technique it is possible to monitor condition of multiple bearings of the machine using only one vibration sensor that is mounted on machine's exterior part.

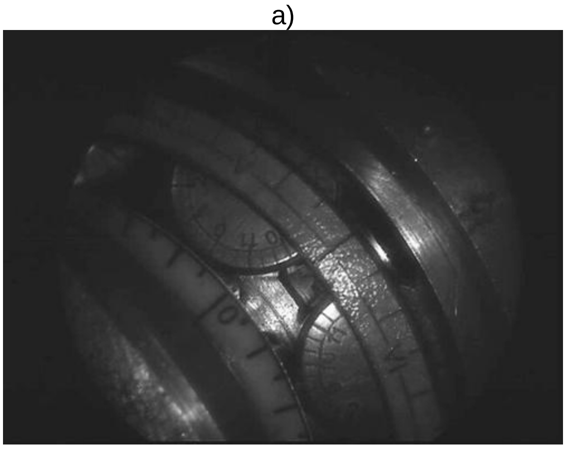
Effectiveness of adaptive technique was tested in different research studies and trial applications. Bearings of aviation engines, drive train, main rotor and swash plate have been tested in healthy and faulty conditions. Also adaptive technique was applied to a wide variety of industrial bearings. Some results are briefly considered below.

3. TESTS AND TRIAL APPLICATIONS OF ADAPTIVE TECHNIQUE

3.1. Laboratory test rig

Laboratory test rig was used for the technique approval (figure 2). This facility includes electric drive, mechanical part and high-speed camera. Electric drive provides operation of the rotor on two supports in wide range of rotation speed. Mechanical part provides variable conditions of tested bearing operation. High-speed camera (up to 150000 frames/s) allows measuring parameters of cage and balls motion.

a)



b)

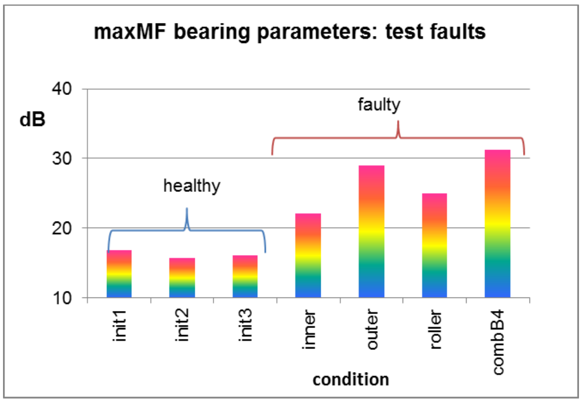
Figure 2.
Experimental test rig for bearing research:
a)- common view; b)- typical frame of high speed camera.

Research study has the task to approve effectiveness of adaptive technique to detect healthy or faulty states of operating bearing as well as states of its components separately. Here below brief results of this study are considered. Three single-row ball bearings had been consequently tested. Each bearing was tested in healthy and faulty states alternately. Test faults have been made by local damages of inner or outer ring races as well as one of balls. There were 7 technical states of one type bearings:

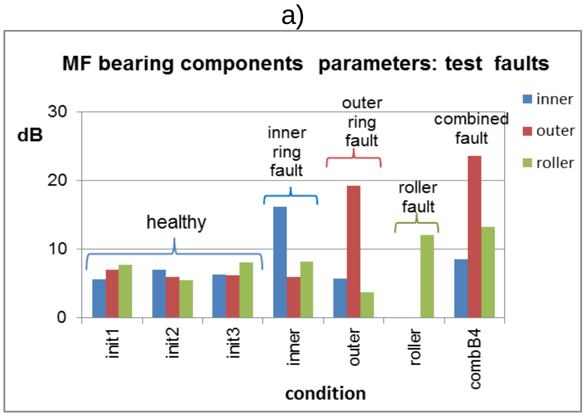
- healthy state of each of three same type bearings (*init1, init2, init3*);
- local damage as a notch crossing inner ring race: depth 0.5mm, width 1mm, length 3mm (*inner*);
- local damage as a notch crossing outer ring race: depth 0.5mm, width 1mm, length 3mm (*outer*);
- damage of one ball as milling with depth 0.8mm (*roller*);
- combined fault: inner and outer races as well as one ball are damaged (*combB4*).

3.1.1. Diagnostic abilities of MF parameters

Diagnostic parameters were calculated using adaptive technique and are presented on figure 3.



a)



b)

Figure 3.
MF parameters diagram of bearing condition:
a – *maxMF* parameter for bearing states; b – *MF* parameters of bearing's components.

Figure 3a illustrates in dB scale evaluation of *maxMF* parameter to bearing state modification. This most simple parameter calculates maximum value of transfer function in each state. Bearings in healthy conditions have its *maxMF* in range 15,8...16,9dB. Faulted inner race of 1st bearing caused 6dB growth of the parameter. Outer race fault had affected stronger 13dB, but ball's fault influenced a bit less - 9dB. So, *maxMF* parameter certainly separates faulted conditions of a bearing from healthy ones.

The set of parameters *innerMF*, *outerMF* and *rollerMF* was used to diagnose each component of bearings separately. Diagram on figure 3b characterizes race's condition of inner, outer rings and balls. Parameters of healthy components vary between 5dB and 8dB. Each type of fault caused growth of corresponding parameter. Damaged inner ring of the 1st bearing raised *innerMF*'s value up to 16,8dB that means 10dB (3 times) increase. Same scale fault of the 2nd bearing outer race caused *outerMF* growth up to 19,5dB that is 12 dB higher than initial value. Smaller growth of *rollerMF* - to 12,1dB was observed when the 3rd bearing ball was damaged. Such weak response to ball's fault is stipulated by balls motion specialties considered earlier in this paper.

It should be noticed that *MF*-component parameters responding to "its" fault almost do not react to other faults. Combined fault caused much greater growth of the parameters with *outerMF* dominating. This fact illustrates transfer function non-linear dependency of factors combination. In this case decisive influence has radial clearance variation created by interaction of all three faults in one bearing. Such interaction amplifies balls interaction with outer ring but attenuates it with inner one.

Thus, the set of *MF-parameters* provides reliable detection of bearing faults at its early stages, even if a fault appears on one of the components only. The most important benefit of adaptive technique is that it allows assessment of the bearing condition without any background. Keeping in mind compatibility of *MF*-parameters for most of bearing types, it means any bearing could be diagnosed by single measurement. Based on results of the laboratory study the threshold of healthy state the level of 6-8dB was preliminary accepted for all *MF-parameters* b.

3.1.2. MF parameters for monitoring

MF-parameters may provide accurate monitoring of individual bearing's condition using comparing of current appraisals with initial ones. *MF*-monitoring allows prognosis of life time, maintenance and repair planning. Figure 4 illustrates *MF*-monitoring parameters calculated as difference between faulted and healthy bearings states. The diagram shows definite detection of any fault using *MF*-parameters as the tools for monitoring purpose. Indirect assessment of method error may be estimated by scatter of *MF*-parameters for unharmed component of bearings that varies from -1,8dB to +0,4dB.

So, experimental check of adaptive technique by laboratory tests has proved its ability to diagnose faults of bearing components separately. This technique could be applied to both monitoring of bearing condition and diagnosis of bearings with no "vibration" history of its parameters in initial state.

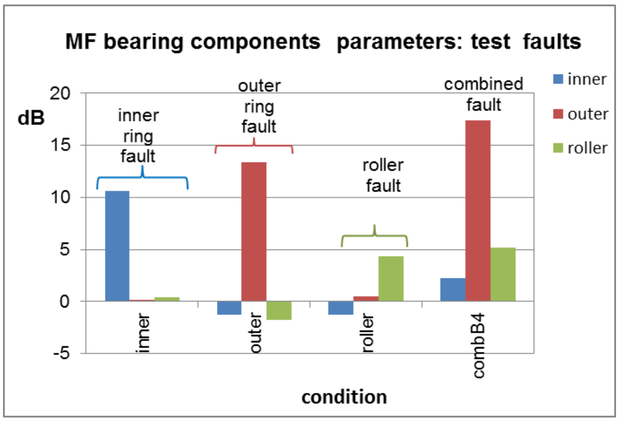


Figure 4.
Diagram: application of *MF*-parameters as monitoring tool.

3.2. Trial applications

3.2.1. Compressor's bearing of aviation jet engine (test bench)

Trial application on aviation jet engine was aimed to check effectiveness of adaptive technique for diagnosis of the bearing that operates in complicated machine with multiple extrinsic sources. Tested aviation turboprop engine is a part of testing bench, where terms of bearings' operation could be approximated to actual ones. The engine operated in "cold" mode being driven by powerful electric motor (figure 5).

Figure 5.
Testing bench for aviation turboprop engine.

To measure vibration signal of front support bearing the 3-axial accelerometer was mounted on intermediate casing of the engine. Preliminary spectral analysis of vibration signal has determined dominating sources of vibration that were: epicyclical 2-stage gear box, gears of lubricating pump, hydraulic, pneumatic and electric systems as well as aerodynamic vibration generated by compressor's blade wakes. After testing in healthy state the engine has been dismantled and the roller bearing of front support was taken out, and its outer ring has been slightly damaged. Initial scale of damage was minimized to small cross scratch aiming to find lower threshold of the technique sensitivity. Therefore, initial scratch size has about 0,08mm depth and 1mm width. Then, after testing in the 1st faulty condition the engine has been dismantled again and the scratch has been deepened up to 0,2*2mm. So, the 2nd faulty testing was with more damaged outer ring. For the 3rd faulty test the bearing was more damaged by adding the same scale damage (0,2*2mm) on to the inner ring. Diagram on figure 6 presents testing study results as calculated *MF*-parameters for above considered bearing states.

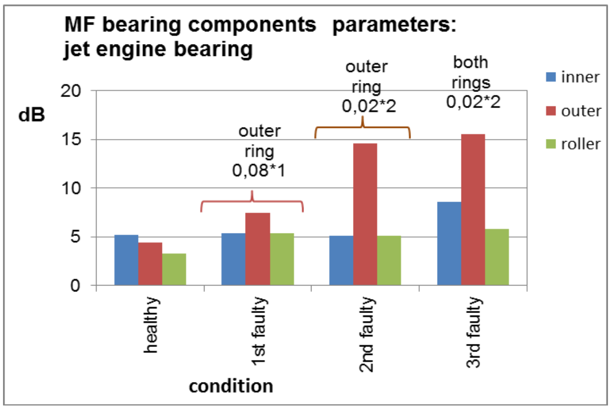


Figure 6.
Diagram: *MF*-parameters evaluation to condition modifications of the turboprop engine's bearing.

Diagram demonstrates that healthy components of this bearing also do not exceed the range 4…6dB, as it was in laboratory study. Visible response of *outerMF*-parameter to smallest scratch was few (7.5dB) but doubling of scratch increased growth of the parameter up to 14.6dB. Such change of the parameter (10dB in comparison to healthy state) to the typical damage scale at early stage could be considered as satisfactory. By the way other bearing parameters did not changed practically.

Further development of damage was simulated by same size fault on inner ring. *OuterMF* almost does not react. *InnerMF* has risen fairly but smaller than outer one because of nonlinear influence of both damaged rings.

3.2.2. Swash plate bearing of helicopter rotor (test bench)

Perspective HUMS projects plan to expand in-flight monitoring to more critical parts of helicopter, including swash plate, where bearings play important role. Helicopter main gear box - rotor test bench was used for test application of adaptive technique for monitoring of the swash plate bearing (figure 7).

Figure 7.
Testing bench for helicopter main gear box and rotor

Rotation speed was measured by laser tachometer accounted reflected signals from marker on the hub. Adaptive technique was applied to data collected from the bearing in healthy (initial) operation state, and then in damaged state. In contrast to many others the swash plate bearing has its outer ring as rotating but inner ring as stationary. Another specialty is very low rotation speed that did not exceeded 240 rpm in the testing session.

Bearing's in its healthy state demonstrated MF-parameter values that conform to levels of healthy bearings discussed earlier in the paper (figure 8).

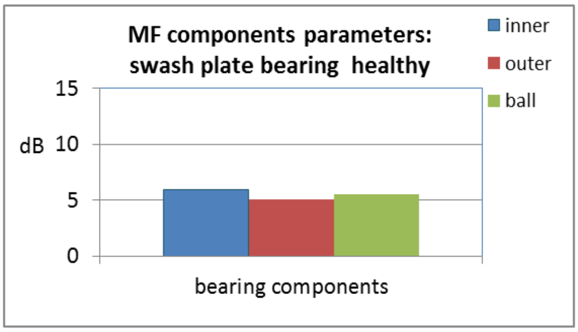


Figure 8.
MF-parameters of swash plate bearing in healthy state.

Cross scratch of 0.15mm depth and 1.5 mm width on the inner ring played role of test damage. On operation in faulty state the bearing responded by enlarged *innerMF* and practically unchanged *outerMF* and *ballMF* (figure 9). MF parameters' monitoring worth is illustrated by figure 10, where innerMF parameter is only sign of a fault but other parameters are changeless.

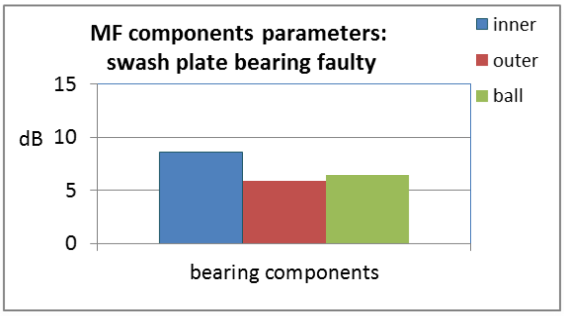


Figure 9.
MF-parameters of swash plate bearing in faulty state.

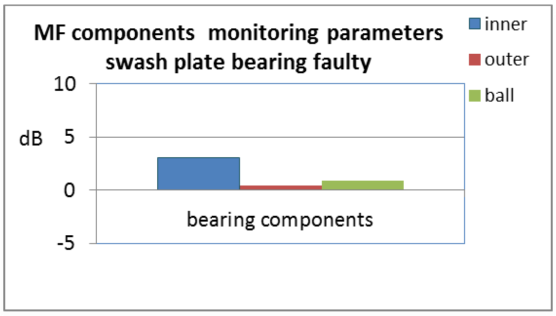


Figure 10.
MF-parameters of swash plate bearing in faulty state.

3.3. Industrial research

One of the most important benefits of adaptive technique is its universality allowing condition monitoring of any bearings within common rating. Aiming to check this feature on natural scale machines and in "field" conditions the extensive research program was developed and realized jointly with some industrial partners. Twelve medium and small size industrial aggregates have been chosen as objects for researches.

For industrial application the technology has been developed that included two basic components: hard- and software for registration of both vibration and rotor-synchronized signals, and original software based on algorithms of adaptive technique. Typical measurement setup for industrial objects is shown on figure 11.

Each 3-axial accelerometer was mounted on a housing of observed bearing in such a way that one axis have been directed along the shaft/rotor axis, and two others in horizontal and vertical directions in cross plane. Laser tachometer was mounted opposite to open part of the shaft, where reflecting markers were pasted. Each 3-axial accelerometer was mounted on a housing of observed bearing in such a way that one axis has been directed along the shaft/rotor axis, and two others in horizontal and vertical directions in cross plane.

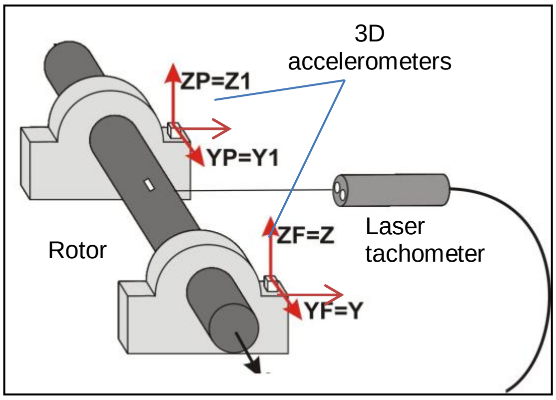


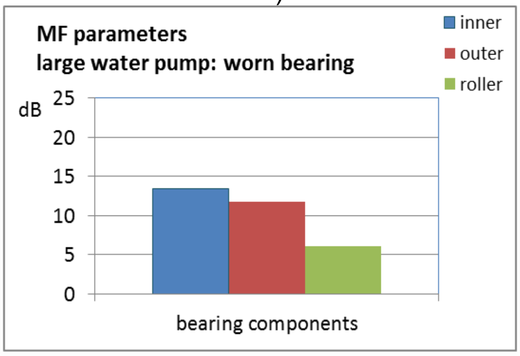
Figure 11.
Measurement setup for vibration and tacho-signals registration

Laser tachometer was mounted opposite to open part of the shaft, where reflecting markers were pasted. Signals from sensors came to multichannel data input module controlled by PC that provided signals registration. There were three stages of research:

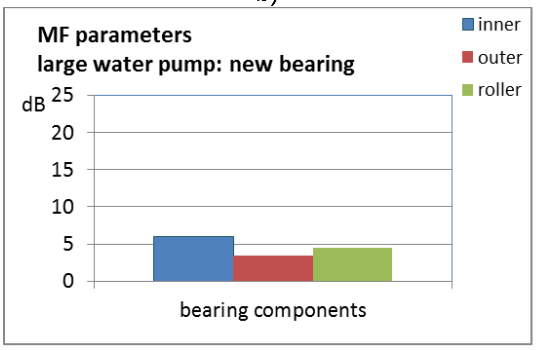
- vibration and rotating speed signals registration of operating aggregates having long running time (2…20 years) and supposed to have technical maintenance in nearest few months;
- disassembling of aggregates within frames of its technical maintenance and taking out observed bearings for further investigation;
- investigation of removed bearings technical condition and it separating in two groups: well or pretty well and intensive deterioration;
- new bearings mounting instead of removed, assembling and adjustment the aggregate and registration of signals of new bearings of same aggregate.

Figure 12 shows the sample of replaced observed bearing and corresponding *MF*-parameters. After 20 years of exploitation this bearing has visible damages, as perhaps traces of impacts and erosion. Two local damages on the race of inner ring (figure 12a) and smaller ones on the outer ring provided 13.4dB *innerMF* and 11.8dB *outerMF* (figure 12b) – both higher than earlier fixed threshold of healthy state. Bearing's balls survived with a good state and its parameter remained as for new ones. Replacement with a new bearing returned *MF*-parameter values of this aggregate to "green" zone – less than 6dB (figure 12c).

a)



b)



c)
Figure 12.
Sample of deteriorated bearing of water pump: a) – local fault; b) – *MF*-parameters of deteriorated bearing; c) – *MF*-parameters of new bearing

In a similar way technical state of bearings of all industrial aggregates has been investigated. As optimal for estimation of whole bearing technical condition was used *comb adaptive* parameter that is derivative of *MF*-parameters for all three components. Diagram on figure 13 demonstrates such parameters effectiveness for condition monitoring of whole bearing. It is clear that all aggregates replaced *worn-out* bearings (red color) have parameter values higher than *new* ones.

Six parameters related to aggregates with light worn (no visible traces) are located from left side of diagram (Sper 50 fan – RU st2 pump). Red *comb adaptive* values of above aggregates few exceed parameter values of new bearing. Right located six parameter values (RU deg pump – Daina motor) relate to bearings with visible traces of wear. These parameter values of old bearing essentially exceed (8 …22dB) related new bearing values of the same aggregates

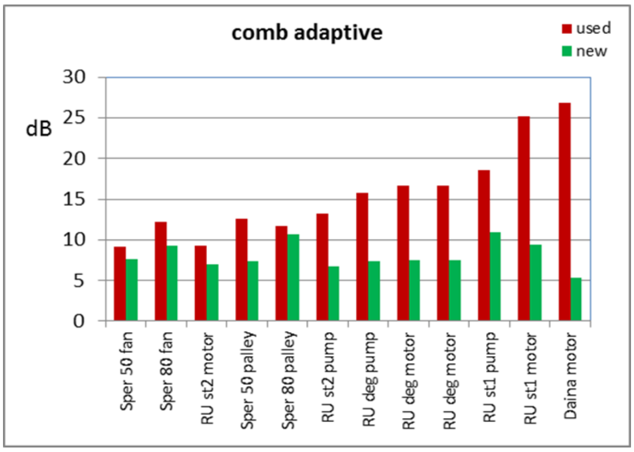


Figure 13.

Diagram: *comb adaptive* parameters for replaced worn-out bearings (red) and new ones (green) on 12 industrial aggregates.

3.4. Efficiency comparison with conventional technique

Bearing monitoring and diagnostics tools are developed by many companies, and one of the leaders in this field is SKF – a leading global supplier of products and services associated with roller bearings. Within the framework of industrial bearings study the SKF-manufactured device CMAS 100-5L was used for assessment the technical state of reference set of bearings. For bearing monitoring this device applies gE (probably acceleration squared) parameter obtained through the envelope detection method. The device generated two kinds of diagnostic messages within measurement process: “Alert” – recommendation to halt the aggregate and investigate it, and “Danger” – the message signalizing about a fault of the bearing. The efficiency of the device (and a technique realized) was evaluated in comparison with actual bearings’ technical state based on investigation using microscope.

Comparing the bearings’ technical state and signal messages of SKF device, one may come to the conclusion that the device has made errors of first kind (false alarm) and second kind (non-detection or missing target). For example, in 12 tests where technically sound bearings were investigated, the device had identified presence of faults or their probability in brand-new bearings, in particular: the device had reported a fault (Danger) three times and prevention signal (Alert) once. Other group of 6 used bearings was investigated where no defects were found (practically healthy state), however the device issued Danger twice and Alert – once. Therefore, the device incorrectly identified technical state of bearings in 7 cases out of 18, i.e., the false alarm percentage of the device made up about 39% accordingly.

One more group included 6 bearings where investigation found substantial faults. For this group the device has made the correct diagnosis thrice: two times by issuing "Alert" and once – "Danger". In regards to the remaining three bearings with substantial defects, the device has even failed to issue the signal "Alert", so it was interpreted as target missing. Therefore, with respect to that group of bearings, the probability of correct identification of their technical state by SKF device constituted 50% only.

The total number of test runs performed by SKF device was 24. Based on the yielded results, 10 errors were recorded, 7 of which were false response with technically sound bearings (error of the 1st kind) and 3 – "target missing" (error of the 2nd kind). These results suggest that the vibration analysis methods used by one of conventional techniques cannot be considered acceptable to ensure reliability of machines, since a high percentage of errors of the first and the second kind leads to unsubstantiated prevention maintenance jobs and uncontrolled failures, which ultimately increases the operating costs for the plant maintenance.

In contrast to conventional method the adaptive technique in the same set of investigated bearings demonstrated essentially higher efficiency. As figure 13 demonstrates, the comb-adaptive parameter of used bearing all the time is higher than of new one in each pair of new and used bearings in the same industrial plant.

The problem of conventional methods is that their parameters depend of structural and operational factors that differ for variety of industrial bearings. As result, two same new bearings in two different industrial plants may show different measures.

4. CONCLUSION

Results of tests and applications considered above demonstrate weighty proofs of adaptive technique's abilities for bearing diagnostics and monitoring, especially for complicated machines and aggregates. Universality of the technique regardless of the type, size, rotation speed and operation mode is based on the fact that transfer function is used for condition assessment of a bearing but not its vibration levels. Relative scale of condition measures (provided by transfer function) makes it compatible for different types of bearings. This was demonstrated by trial applications that show closeness of *MF*-parameters for variously operated bearings. Another benefit is that the technique does not require preliminary research and testing of observed objects. Adaptive technique has high robustness to extrinsic vibration sources that is maintaned by phased syncronization. This approach is based on accounting specialties of rollers/cage motion and on utilizing wide frequency range of vibration that assure technique's application to complicated machines and aggregates.

Research study and trial applications of adaptive technique for bearings diagnosis demonstrate its effectiveness for condition monitoring of bearing during its life cycle as well as for one-time survey of bearing without background of vibration measurements. Perspective technology based on adaptive technique will allow transition to condition-based maintenance of industrial installations, thereby ensuring reduction of unreasonable downtime, cutting down operating costs and improving the reliability and safety at the required level.

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