574. Adaptable vibration monitoring in rotor systems

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Abstract. In the event of optimization of monitoring and diagnostics procedures, the data collection periodicity should be altered with respect to technical condition, specific identified defect and information on its development. This research work presents the methodology and algorithm of adaptive vibration monitoring and diagnostics of rotor system bearings, which are generated on the basis of analysis of vibration monitoring data archive and the method of modified vibration power spectrum diagnostics.

Keywords: rotor system, bearing, technical state, vibration monitoring, adaptability.

Introduction

Vibration measurements are widely applied in control of condition of rotor systems, equipment or machinery. Regular vibration monitoring and estimation of time-varying changes by taking relevant actions based on the achieved results help extend machine lifetime, avoid accidents or emergencies. These functions are performed by vibration monitoring and diagnostics systems.

Technical condition of rotor systems is frequently related to parameters of bearing vibro-acoustic processes and their alterations [1-4]. Vibration monitoring of rotor system bearings is widely used in practice. It is divided into constant and periodic vibration monitoring. In the first case stationary measurement and analysis systems are used while in the second case mobile and, commonly, modern vibration measurement and analysis devices are applied. In terms of measurement and data collection the process is subject to a regular basis; in the first case the information collection procedure is so frequent that only real-time measurements are relevant [5], which is not the case when considering the second method.

Both monitoring methods (constant and periodic with recorded periodic intervals) are not optimal. The first one is relatively costly and a considerable amount of inexpedient information is processed while the second method is subject to a high-level risk of missing a defect [6]. Therefore research of monitoring process including periodicity, which is dependent on the existing technical condition of the controlled object, is highly significant with respect to science, economy and practice.

Adaptive bearing vibration monitoring using data trend characteristics is analyzed in the monograph [2]. In terms of a concept and idea it was a new attitude towards monitoring as to an optimized procedure but non-considered issues are related to specific defects of rotor systems though the technical condition depends exactly on them. This means that varying measurement intervals did not depend on specific defects impacting different rate of rotor system deterioration.

A diagnostics method when trend characteristics are not applied is familiar [7]. It may be modified and then used in the algorithm of adaptive monitoring measurement interval alterations subject to assessment of specific defects in rotor systems.

This study presents the methodology and algorithm of adaptive vibration monitoring and diagnostics of rotor system bearings, which are generated on the basis of analysis of vibration monitoring data archive and the modified diagnostics method.

Concept and Principles of Adaptive Monitoring

The theory and practice of vibration and diagnostics reveal that these procedures are hardly distinguished; assessment of the object condition is a complex process during which both procedures influence one another. This was clarified when termination of the object functioning has been recently conducted based on technical condition and not according to the schedule of routine servicing or non-sanctioned event. Regardless of the fact that diagnostics may be carried out in the “off-line” mode monitoring data is still used and diagnostics results often require a new part of data of measured magnitudes. In case the amount of the latter is considerably high than a task of data collection periodicity selection may be statistically reasonably be solved as well as a lower probability of inaccurate diagnostics may be expected. This defines measurement uncertainties, the statistic constituent of which becomes irrelevant [6]. Therefore in practice stationary monitoring and diagnostics systems with fixed, quite often, data collection frequencies are common. In this case trends of measured magnitudes may be determined, the technical condition of the object may be forecasted and periodicity of data collection and analysis may be objectively selected. However, trend is integral characteristics of changed technical condition which does not identify a specific defect. The defect may develop abruptly and the technical condition may change radically (cannot be remedied) until the next data collection and analysis moment. The same applies to mobile monitoring systems but upon assessment of their significantly greater periodicity of data collection and analysis a probability of emergency that may occur between the object control moments highly increases. This means that in the event of optimization of monitoring and diagnostics procedures, he data collection periodicity should be altered with respect to technical condition (diagnostics result), specific defect identified and information on its development.

Periodicity of vibration measurements of vibration monitoring and diagnostics systems may be basically changed if the tendencies of the controlled object technical condition change and development are known or if by means of the diagnostics procedure a specific defect with the known symptoms is detected.

Principle of technical condition change tendency. Evaluation of tendencies of vibration magnitude variations provided new possibilities related to objective results and existing condition of the object (for instance, rotor system) as well as reasonable variable interval of vibration measurements, which reduces monitoring costs. When the condition of rotor system is satisfactory the interval may be sufficiently long and constant. If the tendency of vibration variations occurs, and the standard requirements (or allowable vibration levels) do not require rotor system shutdown or repair, the periodicity is subject to reduction so as not to miss the defect and avoid emergency situations between measurements [2]. This is particularly important when monitoring is based on mobile systems.

Today mobile devices used for monitoring (e.g., B&K Vibrotest-60 have a programmable controller tuned with PC software and, connected to PC, can organize a data bank, which is analyzed by a dedicated program. A structural monitoring scheme with such devices is given in Fig. 1.

During a periodical vibration monitoring, the operator defines the aggregates which vibrations are going to be measured; he programs device and then performs measurements and, if necessary, analyses vibration at place. The accumulated measurement and analysis data is transferred to PC, which files them additionally and analyses pursuant to the requirements of ISO 10816 standard.

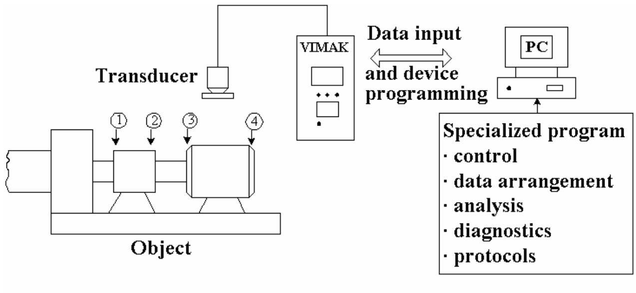

Fig. 1. Monitoring structure with the programmable device

Considering the technical state of rotor systems, optimal monitoring expenses and change tendencies of vibration quantity, it is possible to optimize periodicity of vibration measurements. We will analyze measurement periodicity of a monitoring system depending on vibro-activity of the rotor system bearing node.

When the state of a rotor system is fairly good, measurement periodicity can be constant and period between measurements can be long enough. If the tendencies of vibration change are detected, and standard norms (or permissible vibration levels) not yet require maintenance of the rotor system, in order not to miss the fault and avoid emergency situation between measurements, periodicity must be reduced. Thus, we have two distinctive tendency stages of the parameter change (Fig. 2), where measurement periodicity can be different and objectively grounded. Of course, this is to apply only to relatively slowly-developing faults in rotor systems, which commonly prevail in practice. Essentially, in the first stage ($t < t_2$), the state of the rotor system is stable and a root-mean-square (r.m.s.) values of vibration of bearing nodes do not reach permissible values. In this case, periodical measurements are characterized by (m_i, σ_i^2) and $m_i \approx$ const, $\sigma_i^2 \approx$ const as well as a very slow change of r.m.s. values (a change is described by the equation linear regression), and they are performed with a constant period $T = t_2 - t_1$. In the second stage ($t > t_2$), r.m.s. measurements are distinguished for the fact that $m_i = var$, $\sigma_i^2 = var$, the fault develops considerably quicker and changes of r.m.s. average approximate in a non-linear function.

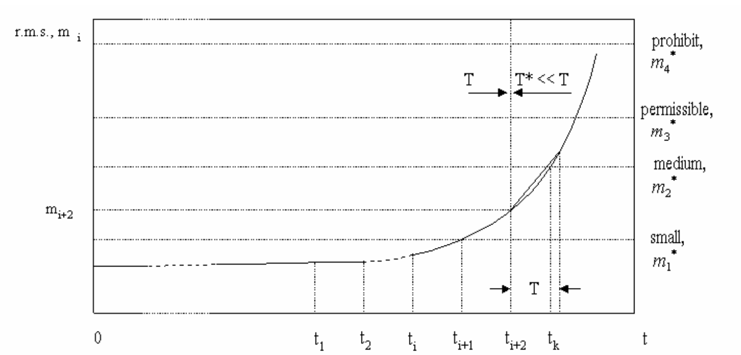

Fig. 2. Change tendency of r.m.s. averages of bearing nodes

Then collection of the data to be monitored is better to be organized with a variable periodicity, using data changing tendencies and r.m.s. levels, evaluating the risk of omission of a sudden change of the technical state and help to avoid the economic consequences.

Investigations indicate that durability of bearings – key elements of a rotor system – depends on different factors and duration of the first stage reaches 5000 ÷ 50000 hours.

Meanwhile, duration of the second stage is considerably shorter, therefore measurement periodicity must be shorter as well.

For this purpose, the following algorithm can be proposed [8]:

1. The accumulated data bank is statistically processed, r.m.s. average m_i and dispersion σ_i^2 are determined (the first data is collected by a priori chosen period, e.g., $T = t_2 - t_1$).

2. If $m_i \approx const$, $\sigma_i^2 \approx const$, tendencies are determined by means of regression analysis, applying linear models, and T remains unchanged. The period is increased in the case if:

$$t^* = \frac{m^* - a}{b} >> T \tag{1}$$

where a and b – linear regression coefficients, m^* - r.m.s. level of a standard or other standard document, the closest by a quantity to the last r.m.s. measurement time moment t_l. In this case, the period T is increased till

$$\mathrm{T} \approx \frac{1}{3}\left(\mathrm{t}^* - \mathrm{t}_l\right)$$

3. If r.m.s. averages m_i, m_{i+1}, m_{i+2} monotonically increase during three successive measurements performed by the period T, and $\sigma_i^2 = var\ (j = i,\ i+1,\ i+2)$, regression analysis models are applied to determine the tendencies (e.g., $m(t) = a + bt + ct^2$), choosing the sample of the last measurements from $(n+3)$ r.m.s. averages, i.e. $(i = 1, n + 3)$ (in practice, $n = 7 \div 12$). In such a way a statistically justified tendency function m(t) is obtained.

4. Then the system of equations is solved:

$$\mathrm{m}(\mathrm{t}) = \mathrm{m}_j^*, \quad \left(\mathrm{j} = \overline{\mathrm{k},\ 4};\ 1 \le \mathrm{k} \le 4\right) \tag{2}$$

where m_j^* - j fixed r.m.s. level of standards or other standard documents, complying with one state of the rotor system bearing nodes (see Fig. 2); k – r.m.s. level closest to m_{i+2} value when $m_{i+2} < m_k^*$.

5. The smallest solution of the system $t_k > t_{i+2}$ is equaled to the period T as follows:

- if $(t_k - t_{i+2}) > T$, the period T remains unchanged;
- if $(t_k - t_{i+2}) \le T$, the period is chosen from the condition:

$$T^* \le \frac{1}{\xi} \cdot \frac{T\left[m_k^* - m(t_{i+2})\right]}{m(t_{i+2} + T) - m(t_{i+2})} \tag{3}$$

where ξ - weight coefficient depending on m_k^* level and evaluating consequences of a false period T^* choice. For instance, when for m_2^* level, we can chose $\xi = 3$, i.e. during two measurements with the period T^*, we will have with some guarantee m_2^* not exceeding r.m.s. With increase of a parameter k, ξ should naturally increase as well.

This algorithm is straightforwardly implemented in a specialized data analysis program of mobile monitoring device.

Principle of variation of technical condition vector. Technical condition of the object is defined by vector $\mathbf{G} = \{X_j\}^T$, $j=1,...,m$, and its elements are generalized m defect coordinates q_j. Vector $\mathbf{G}$ depends on object performance mode $\mathbf{G}_o$ (as well as on defects that occurred after assembly or during the process as well as were eliminated and on the repair quality) and operation $\mathbf{G}(t)$ components. Mathematical model of the technical condition change may be composed on the basis of the sensitivity theory [9]. It may be written down as follows:

$$\mathbf{G} = \mathbf{G}_0 + \mathbf{G}(t) = \mathbf{G}(n_0, p_0) + \sum_{j=1}^{m} \frac{\partial \mathbf{G}}{\partial q_j} \Delta q_j(t) \tag{4}$$

- when $\mathbf{G}_0 = \mathbf{G}\,(n_0, p_0)$ – a component attributed to the object with deterioration of almost zero (new) and operated at nominal rate (n_0) and load mode (p_0);
- $\Delta q_j = X_j$ – object j failure symptom, which is detected when analyzing lifetime of the object when j defect is present during manufacturing ($t = 0$);
- $\partial \mathbf{G}/\partial q_j$ – technical condition vector $\mathbf{G}$ sensitivity in relation to j defect according to corresponding generalized defect characteristics q_j. Here (t) is the defect parameter dependence on time within a certain observed interval.

The concept of adaptive monitoring, which is based on evaluation of technical condition alteration according to the formula (4), requires determining symptoms of identified (known) defects of the monitoring object and deterioration of the technical condition by means of applying the methods of diagnostics. For this reason the statistic analysis of AB *Lietuvos Elektrinė* monitoring system measurement data and numerical modeling of defect detection possibilities were conducted.

Numerical Modeling of Defect Detection

Bearing deterioration model was analyzed based on AB *Lietuvos Elektrinė* periodical monitoring and diagnostics system measurement data collected in the course of eight years. Data is presented in Fig. 3, where black measurement points stand for high-frequency peak noise of rolling bearings and blue curve means general bearing noise (the SPM methodology to assess bearing condition is used). During the analyzed period impermissible (exceeding 35 dB) peak bearing noises were twice detected for pump S-008. In September 2003 and October 2007 the bearings were replaced with the new ones. After replacement the noise decreased to the allowable limit and did not exceed 35 dB. Meanwhile r.m.s. measurements of the same bearings remained stable and did not exceed the allowable limit.

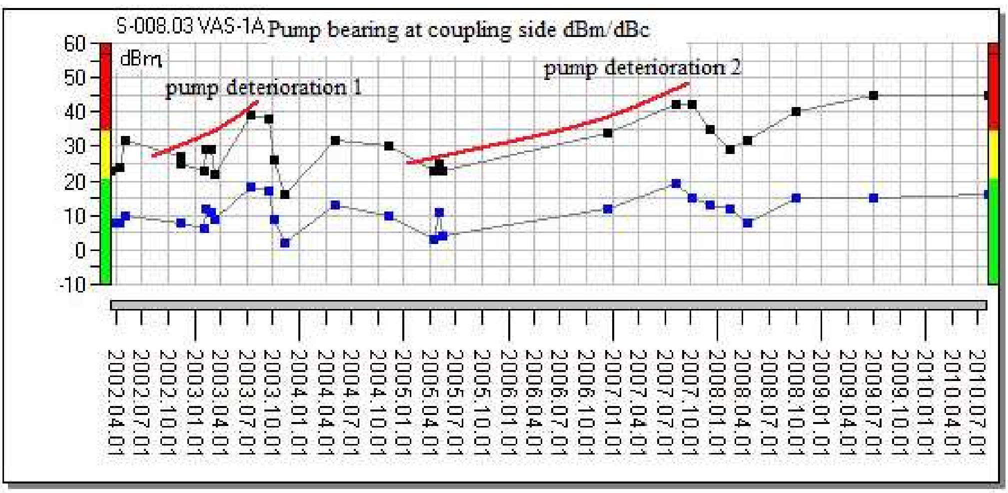

Fig. 3. Noise measurements of pump bearing

In order to conduct numerical modeling of these defects and determine adaptive monitoring periodicity the tendencies and models of bearing deterioration were defined in a form of a regression equation.

Deterioration model of the first defect (September 2003) of the pump bearing:

$$y = 22{,}354e^{0{,}0534x},\ r^2=0.3799. \tag{5}$$

Deterioration model of the second defect (October 2007) of the pump bearing:

$$y = 19{,}758e^{0{,}0646x},\ r^2=0.4319. \tag{6}$$

Here r^2 is a determination coefficient of regression.

Due to modeling of the monitored object technical condition alteration the most common defects of pump electric motors were selected. They are presented in the first vertical column of Table 1: imbalance, shaft misalignment, rotor disturbances, rotor bending, etc. Other columns present spectrum frequencies and additional measurements (f – rotation frequencies) for determination of these defects. The next columns present examples of vibration measurements, which are decomposed by means of FFT (up to 1000 Hz), and r.m.s. measurements. Failure frequencies (f_k) that are attributed to defects (Table 1) are marked in yellow.

Table 1. Failures and their spectrum frequencies and measured r.m.s.

Electric motor defects	Frequencies and additional measurements	<0,2 x f_1 mm/s	(0,33÷0,5) x f_1, mm/s	(0,52÷0,95)xf_1, mm/s	f_1 mm/s	1,5 x f_1 mm/s	2 x f_1 mm/s	3 x f_1 mm/s	(4÷10) x f_1 mm/s	>10 x f_1 mm/s	**V, r.m.s.,** mm/s
Imbalance	f_1=kf, k=1, Measure phase variations	0	0,3	0	2	0,2	0	0	0	0	2,03224
Shaft misalignment	f_1=kn, k=2,3	0	0	0	2	0,5	1	2	0,3	0	3,056141
Rotor disturbances	f_1=kf, k=1 ,2 , 3	0	0,3	0	2	0,2	0	0	2	2	3,482815
Rotor bending	f_1=kf, k=1 ir 3	0	0	0	2	0	2	0	0	0	2,828427
Rolling bearings	f_1=>10f	0	0	0	2	0,5	0	0,4	0,5	2	2,942788
Auto vibration of plain bearings	f_1=(0,33÷0,5)f	0	2	0	2	0,6	1	0,3	0	0	3,074085
Plain bearing lubrication film rupture	f_1=(0,41÷0,49) f	0	2	0	2	0,6	2	1	1,5	0	3,950949
Rotor fractures	f_1<2f,f_1=>10f observe phase variations and allowable limit curves	0	0	0	2	3,5	0	0	0	1	4,153312
Insecure bearing attachment in the bearing housing	f_1=kf, k=0,3; 0,5;	0	3	1	0,5	0	0	0	0	0	3,201562

Every structural failure (defect) has its own characteristics in a form of spectrum constituents f_{sp} [1,2,7]. Upon modernization [7] of description of a defect provided in the study the way each defect is evaluated only in consideration with energy of its characteristic frequencies f_{sp} (yellow color) the relation between vibration spectrum f_{sp}, which exists during failure, and magnitude $V_{r.m.s.}$, which completely defines vibration energy, is received. This way the object defect will be estimated by relative magnitude R:

$$R = \frac{f_{sp}}{V_{r.m.s.}}. \qquad (7)$$

$V_{r.m.s.}$ value is obtained after vibrations are measured at the time. During the initial stage of the defect the components that are characteristic to specific defects (presented in Table 1) occur in vibration spectrum, therefore magnitude f_{sp} is calculated using these vibration components as follows:

$$f_{sp} = \sqrt{\sum s(f_k)^2}. \qquad (8)$$

Here $s(f_k)^2$ is failure components which are marked in yellow in Table 1.

In accordance with Standard ISO 10816 the failure is ignored when vibration amplitude expressed by magnitude $V_{r.m.s.}$ is low and/or does not exceed allowable limits. Unfortunately, the standard criteria did not evaluate vibration magnitude proximity to impermissible limits. When the defect is under development diagnostics additionally requires magnitude R, which assesses failure so as the defect is not missed in the early stage.

According to vibration measurement spectra presented in Table 1 magnitude R which assesses failure is deducted from relatively different frequencies f_k.

Table 2 presents results of magnitude R, which assesses failures by means of adding different frequencies f_k from Table 1. R achieved results marked in yellow are attributed to specific defects.

Table 2. R - defect evaluation in terms of different spectrum constituents

Electric motor defects	$0{,}2xf_1+0{,}43xf_1$	$0{,}2xf_1+0{,}43xf1+f1$	$0{,}2xf1+0{,}43xf1+1{,}5xf_1+2xf_1+2xf_1+3xf_1+10xf_1+>10 \times f_1$	f_1	$1{,}5xf_1+2xf_1$	$2xf_1+3xf_1$	$1{,}5xf_1+2xf_1+3xf_1$	$0{,}2xf_1+0{,}43xf_1+1{,}5xf_1+2xf_1$	$1{,}5xf_1+2xf_1+3xf_1+4 \div 10xf_1+>10 \times f_1$
Imbalance	0,1476	0,995	0,098	0,984	0,098	0	0,096	0,177	0,098
Shaft misalignment	0	0,654	0,749	0,654	0,365	0,732	0,749	0,3658	0,756
Rotor distur-bances	0,0861	0,580	0,577	0,574	0,057	0	0,057	0,103	0,814
Rotor bending	0	0,707	1	0,707	0,707	0,707	0,707	0,707	0,707
Rolling bearings (m coefficient considered)	0	0,679	0,721	0,679	0,169	0,136	0,217	0,169	0,679+m
Auto vibration of plain bearings	0,6506	0,650	0,759	0,651	0,379	0,339	0,391	0,7531	0,3917
Plain bearing lubrication film rupture	0,5062	0,716	0,506	0,506	0,528	0,566	0,586	0,732	0,698
Rotor fractures	0	0,482	0,842	0,4815	0,842	0	0,842	0,843	0,876
Insecure bearing attachment in the bearing housing	0,9370	0,987	0	0,156	0	0	0	0,937	0

When the likelihood is $R \leq 0{,}5$ then defect occurrence is low, meanwhile $0{,}5 \leq R \leq 0{,}8$ implies defect development process, and, finally, if $R \approx 1$ then the defect is progressive and it may endanger further operation of equipment. According to R the periodicity of measurement is modified in real time based on dependence, which is given in Fig. 4.

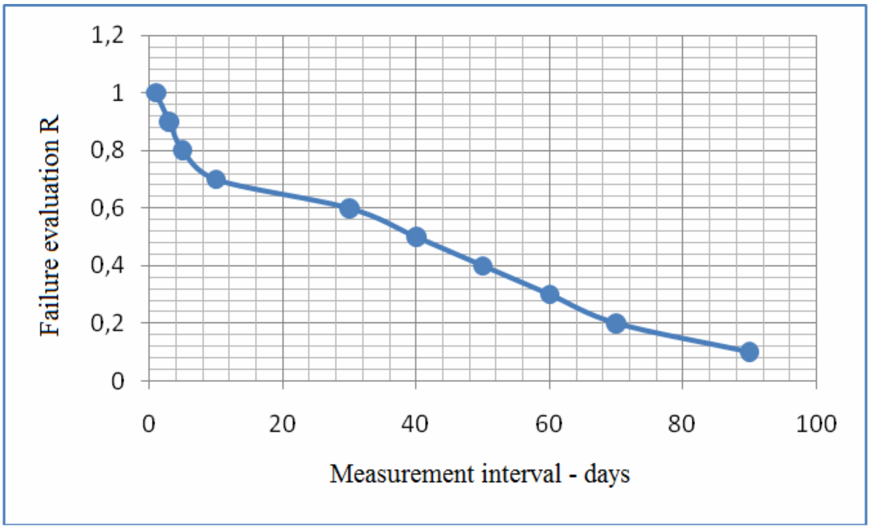

Fig. 4. Measurement (time) interval correction curve

Recognition of bearing failures in early stages requires additional measurements and evaluations:

a) Rolling bearings are subject to additional evaluation of the bearing spectrum high-frequency constituents, i.e. magnitude dBm (bearing noise) measured in relative units applying SPM method. For this reason coefficient m is introduced, which depends on a specific dBm value (when dBm =0÷25, m=0; dBm=25÷35, m=0.1; dBm=35÷40, m=0,2; dBm=40÷50, m=0,4; dBm=50÷70, m=0,5).

b) Plain bearings are subject to using defect spectrum constituents, which are not included in $V_{r.m.s.}$ measured frequency limits, when $R \approx 1$ defect likelihood is increasing, and at 0,5 it is decreasing. It is necessary to conduct vibration spectrum analysis in higher frequencies and evaluate them by determining R.

When performing real-time measurements the efficiency increases, since monitoring system corrects measurement intervals in consideration of defect defining the ratio R as dangerous. Monitoring system corrects measurement intervals according to parameter R; when the defect is minor $R \leq 0{,}5$, the interval between measurements is expanded, and when $R \approx 1$ (or $R > 1$, in the case of rolling bearings) - the ratio is considered dangerous, which corresponds to the fact of defect development, therefore the interval is shortened.

Adaptive Monitoring Algorithm

The obtained results enable proposition of the methodology of adaptive vibration monitoring when the periodicity of data collection depends on technical condition of the object. The procedure of the periodicity of vibration measurements is mapped by the algorithm structure shown in Fig. 5.

Selection of parameters of measured equipment and their ratio with the limit standard values (for example, ISO 10816), and optimization of measurement points constitute the first step in the algorithm of varied measurement periodicity.

To create the periodicity of varied vibration measurement it was required to analyze defects of various types, which are already known in analogous and similar equipment (measurement data bases), and based on the results of practical research the defect recognition features and their limits for equipment of a certain type were determined. If equipment contains rolling bearings then bearing condition is additionally evaluated using SPM coefficient.

According to the defect evaluation criteria and other parameters, the defect severity *R* and assessment of potential hazard are determined. Then the measurement interval is estimated in consideration with the equipment condition, indicated by the curve presented in Fig. 3. In the case when the impermissible (critical) defect is detected, the equipment must be shut down.

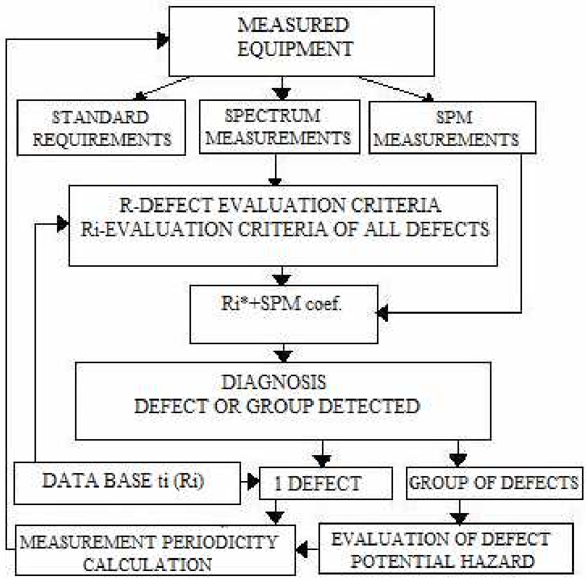

Fig. 5. Algorithm of object adaptive monitoring and diagnostics

Conclusion

Statistical analysis of vibration measurement data bank obtained from AB *Lietuvos Elektrinė* rotor system bearing enabled performing research of correlation between failure and vibration monitoring data, determination of vibration spectrum frequencies characteristic to a specific defect. Furthermore, it was proposed to evaluate the technical condition applying the modified diagnostics method, which allows assessment of developing defects by means of criteria offered by undetectable standards. In terms of identification of developing defects the methodology of adaptive (varied vibration measurement periodicity) monitoring and respective algorithm have been proposed on the basis of spectrum characteristic constituents and their energy ratio with general vibration energy. The research results have led to development of methodology for adaptive monitoring of rotor system bearing, which is more optimal in comparison to the strategy of customary periodic vibration monitoring.

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