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## MODEL OF VIBRODIAGNOSTIC PROCEDURE FOR PREDICTIVE MAINTENANCE OF ROTARY MACHINES

**Abstract:** *The paper describes a model of vibrodiagnostic procedure for predictive maintenance of rotating machines, based on experimental tests of real objects. Systematic monitoring of the condition of rotating machines over a longer period of time allows the conclusion of potential irregularities in the operation of the industrial facilities, the detection of vibration sources and the degree of damage to individual components. This way, the conditions for making a vibration map and taking preventive measures for the maintenance of the industrial facilities are fulfilled.*

**Keywords:** technical maintenance, predictive maintenance, vibration, fault detection, rotary machines.

### INTRODUCTION

Technical maintenance of machines represents a set of procedures and activities with the task of preventing the occurrence of failure or downtime, as well restoring the operation of the machine in the shortest possible time and with the least amount of losses in the given environmental conditions and work for an organization. In this way, maintenance becomes a process that enables the management of technical conditions and reliability during the entire life cycle of the technical system.

In the existing production conditions, when certain problems in the maintenance and repair of equipment are planned and predicted, there are three basic methods of technical maintenance in practice [1]:

- operation of the machine until its functional failure,
- intervention and repair based on expert judgment,
- intervention and repair based on the results of diagnostics and assessment of equipment condition.

From the economic point of view, only the last method is considered justified and efficient, and the success of its application is reflected in the following possibilities:

- reduction of the required maintenance time, number of repairs and the number of spare parts by at least two thirds in comparison to the previous two methods,
- reduced number of unexpected failures in a certain period,
- reduction of profit losses because of numerous delays due to unplanned maintenance activities.

The application of this method requires the necessary detailed diagnostics to detect all deficiencies and irregularities that affect the reduction of the life cycle of the equipment before the failure, so that there is time

to plan and prepare the necessary maintenance activities.

Current practice indicates that successful diagnostics of mechanical and electrical equipment is possible in most cases using vibration signals [2], since:

- dynamic forces occur directly at the site of damage, so the machine itself is a vibrating body;
- vibrations contain a maximum of diagnostic information;
- diagnostics can be performed on-site, without disassembling and stopping the machine.

In this way, if the approach to the problem is correct, conventional methods such as temperature control, lubrication analysis, etc. are not necessary and do not have to be carried out, as they can be replaced by unique vibration analysis.

Detailed diagnostics of machines by means of vibrations does not only include the procedure of diagnostics and measurement, data processing with instruments for their analysis, but also includes two obligatory components:

- a database of measurement results over a long period for a large number of machines, with the possibility of access to each data and its subsequent analysis, and
- methods for making diagnostic conclusions.

The basis of a good approach to vibrodiagnostics is the understanding that vibrations themselves are not important but is important to know how the state of the machine changes, that is, how the internal forces in the machine change over time, accelerating damage to individual parts. In this case, changes in forces can be caused by direct changes in the work process or changes in the properties of machine parts.

## PRACTICAL APPROACH TO DETECTION AND IDENTIFICATION OF VIBRATION SOURCES IN ROTARY MACHINES

In practice, there are two concepts regarding the prediction of the state of machine systems that are carried out using vibrations [3]:

1. Vibration monitoring, which includes the detection of changes in the state of vibration of the machine and analysis of the reasons for the changes, and
2. Vibration diagnostics (vibrodiagnostics), when the detection and identification of different types and severity of fails on the tested machines is performed.

The main difference between monitoring and diagnostics is that monitoring does not detect malfunctions and damage in their initial stage of development. The purpose of monitoring is the timely detection of serious faults, bearing in mind that long time before the failure, each small fault is only a part of the fault chain, where any fault in the chain that affects the vibration of the machine can be detected by relatively simple methods (techniques) of analysis of the vibration signal, measured at one or more control points on the machine. In line with this goal, vibration monitoring requires measurements at short intervals so that the rapid and sudden development of certain damages and malfunctions would not go unnoticed. Therefore, it is common to use permanent monitoring systems that perform measurements in a time interval of one or several seconds. One of the user requirements is to reduce the number of measuring channels of these systems, which primarily determines the price of the system. For this reason, the absence of multiple vibration transducers makes it impossible to detect the early stage of malfunction of those parts.

The goal of diagnostics is the detection of the beginning of malfunctions, observation and prediction of their development, and accordingly the development of a machine maintenance plan. However, the problem becomes far more complicated if it is necessary to organize maintenance based on the existing condition of the machine. In that case, it is important to detect all the faults from the very beginning. The fact is that there are no defects in rotary machines that can develop fast, except for hidden defects that occurred in the process of making parts and their assembly. Therefore, the basic features of vibration diagnostics can be expressed as follows [4]:

- It is necessary to perform vibration measurements of each machine part for which there is no specific method for detecting defects in the beginning;
- Diagnosis is more efficient to perform on high-frequency vibrations that can be excited by relatively small forces that develop in the early stage of malfunction.

To present the existing diagnostic methods for different parts of rotary machines, it is necessary to fulfill the main rule of quantitative diagnostics - the condition of the machine must be determined by the deviation of

diagnostic parameters from their standard value. Two interrelated diagnostic problems arise from this rule - determination of optimal diagnostic parameters and determination of reference (authoritative) values for each of the parameters, which is a general problem in all branches and types of technical diagnostics.

Determining the reference condition of a machine without malfunction can be done in three ways [4]:

1. By measuring each diagnostic parameter of the same group of machines without malfunction, determining their mean value and setting the limits of their permissible deviations;
2. Observing deviations of the diagnostic parameter in the initial phase of operation of a certain machine, determining the course of that parameter changes and allowed deviations, after which the obtained values can be used as a reference for a given parameter in the future period of machine exploitation;
3. Carrying out certain measurements of the diagnostic parameter in the initial phase of work and their use during the next measurement.

## PROGRAM FOR PREDICTIVE MAINTENANCE OF ROTARY MACHINES

To simplify the procedure of systematic monitoring of the condition of the machine in order to predict its maintenance, an algorithm (Fig. 1.) that defines the sequence of required operations was developed.

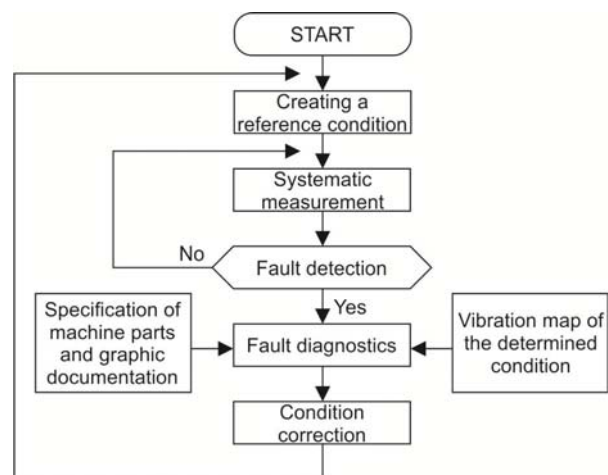


Figure 1. Predictive maintenance algorithm [5]

The initial step is the so-called zero measurements to define the reference condition for each measurement point when the machine is in good condition. Then, at defined time intervals (depending on the condition of the machine), new measurements are performed which are compared with the reference condition (reference total levels and reference spectra), and also deviations are registered. Smaller increases in vibration levels are used for setting a trend that indicates the moment when a malfunction may occur. Increases of the vibration levels in the range of 8-20 dB represent a warning

about serious problems when the machine needs to be stopped and possibly repaired. After troubleshooting (repairing or replacing damaged machine parts), new reference spectra are created.

The program of predictive maintenance of mechanical equipment using vibrations assumes three logical steps: detection, analysis and correction [6].

Detection includes measuring and monitoring the flow (trend) of vibration levels at marked places on each machine covered by the program, based on the prescribed schedule. It is common for machines to be inspected monthly, although critical machines are inspected more frequently, or even continuously, with a permanently installed on-line vibration monitoring system, with the sole aim of detecting significant increases in machine vibration levels that generates a warning and point out the existence of a problem.

Measurement of vibration levels on machines can be done with a simple hand-held analyzer. The instrument contains a transducer that is set to the bearing housing or installed in it, with the task of converting the vibrations of the machine into the appropriate electrical signal that the instrument displays and loads as the vibration level. In order to obtain reliable and accurate information, the procedure and the way of taking data, that is, sampling of the vibration, are very important. Measured vibrations with such instruments can be recorded in the instrument database containing a sketch of the machine to help identify measurement locations and positions. The database also contains the possibility of recording and storing data in graphical form, especially suitable for insight into the entire history of machines, when each recorded increase in vibration levels is a reliable indicator and warning of the existence and development of the problem.

For maintenance programs that include a small number of machines and measurement points, manually operated instruments and systems are quite sufficient. However, programs involving hundreds, or even thousands of machines and measuring points generally require a computerized data collection system, not only to reduce the time taken to collect them, but also to process them. A typical system consists of software for a predictive maintenance program installed in the computer and appropriate instruments for collecting vibration data in the field. The majority of such systems, in addition to the possibility of collecting and monitoring the flow of total levels of machine vibration, provide the possibility of detailed analysis, necessary to identify specific damages and problems in the operation of machines. In this regard, the first step is to set up a maintenance program in the computer software, which includes [7]:

1. Listing of all machines included in the maintenance program;
2. Determining the exact locations on each machine where the vibration reading will be performed;

3. Determining the directions (horizontal, vertical and axial) in which the vibration reading will be performed;
4. Selection of vibration parameters to be measured at each location. In addition to vibration parameters, other parameters can be measured and monitored at the same locations, such as bearing temperature, rotational speed (RPM), pressure, flow, etc.;
5. Determining alarm or warning levels for each measurement;
6. Determining and adjusting details in the spectrum of data required for vibration analysis;
7. Organization of machines into groups suitable for work or organization of routes;
8. Determining the schedule of data collection for each group of machines.

Although the described process may seem rather tiring and time-consuming at first glance, most vibration prevention maintenance software allows for relatively easy use, with numerous advantages that simplify the maintenance program setup process. For example, the program can be set for more than a hundred pump generators in less than an hour. Determining measurement locations, alarm levels and analytical parameters requires special training and extensive staff experience.

Once the maintenance program is set up in the computer software, the next step is to collect the data. According to the previously determined schedule, a certain group of machines is selected and loaded from the computer software into the instrument for collecting vibration data. After taking over the instrument, the operator is directed to the field, accesses a certain area and starts the instrument. The instrument screen directly shows the specific machine, the measurement location and the direction of the measuring transducer. If the transducer is set to the appropriate measurement point, the operator simply presses the button on the instrument to start data collection. When the reading of the data at a given measurement point is completed, the operator presses the button to show the next scheduled measurement. This process is repeated until all measurements within the route have been performed.

After the process of collecting vibration data in the field, the operator returns to the computer and, following a few simple instructions, transfers the data from the instrument to the predictive maintenance software. Once data from the measurement instrument is downloaded, it is possible to determine in many forms of measurement reports which machines have a significant increase in vibration or exceeded the set alarm levels, indicating the development of the problems and malfunctions. The report is prepared in such a way that it contains information about specific machines, measurement points, vibration levels and changes in the condition (in percentage) in relation to the previous measurement in machines with observed problem development. Another form of report is a graphical trend of changing the condition of the machine, where it is possible to visually monitor how

the measured vibration values change progressively over time and thus determine whether the increase in vibration is gradual or sudden. A sudden increase in vibration is generally considered to be potentially more serious than a gradual increase in vibration levels over time (e.g. over weeks or months).

Reports that contain alarms and trends are just some of the many different forms of reports that can be produced on a daily basis by modern computer software for predictive maintenance programs using vibration. Automated data collection and computerized systems for their processing are the basis of simple portable vibration measuring devices and data lists. Automated systems also allow the computer to choose the best solution, that is, to list and classify possible problems in the most successful and fastest way, so that the operator can read vibrations on several machines within the industrial plant with a data collection device in a very short period of time.

Although most general-purpose machines can be protected by periodic vibration checks, some machines are not suitable for the application of "manual monitoring" techniques. With high-performance machines, with essential performance characteristics for maintaining the technological process, such as steam and gas turbines, or centrifugal compressors and pumps with high rotational speeds, problems can arise very quickly, with little or no prior warning. Such machines require continuous monitoring.

When problems in the operation of machines are detected, either by periodic (manual) monitoring, or continuous monitoring, the next step is analysis - identification of certain characteristic problems in order to plan their solution (correction).

The purpose of vibration analysis is to very accurately identify specific problems in machines by detecting and establishing unique vibration characteristics. In most cases, data acquisition instruments and computer software for regular control and monitoring of vibration flow can be used to obtain detailed vibration characteristics, which are necessary for accurate determination of a specific problem. By systematic analysis of vibration, it is possible to identify more general and common problems that occur during the operation of different types of machines, such as: imbalance, misalignment, looseness, damaged bearings, resonance, eccentricity, wear of machine parts and equipment, problems with electricity in motors, problems with drive belts, various forms of material deformation, etc.

The analysis of vibration signals is carried out during the procedure of periodic monitoring of the condition of machine systems when periodic controls reveal a significant increase in the level of total vibrations. The analysis of vibration signals should be done at the beginning of the implementation of the maintenance program according to the condition so that the obtained results on the initial state of the technical system serve

to monitor the trend of the overall level and individual frequency components of vibration.

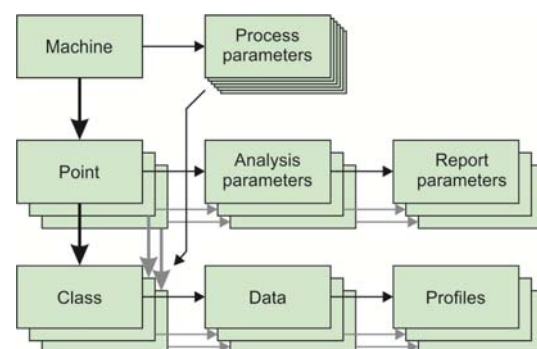
The analysis procedure can be divided into two parts, where the first part is realized through two phases [8]:

1. data collection (preparation for measurement, vibration measurement itself and acquisition of measured data), and
2. identification of measurement results (comparison of registered data with reference data on the condition of system components).

The second phase of the analysis refers to the identification of dominant component sources registered in the time or frequency domain, applying the all previously acquired knowledge about the specific characteristics of the potential vibration picture of moving (usually rotating) machine parts. Frequency is a key parameter in all phases of the identification process, where for many rotating machine parts, (bearings and gears above all) in addition to the fundamental frequency and its higher harmonics, exact mathematical expressions define forced and natural frequencies. Those frequencies in the recorded spectra may correspond to individual machine parts.

If problems are detected and identified, the necessary measures for corrections and repairs can be planned in a suitable period of time, which together makes up the second part of the analysis. In the meantime, any special request or need for personnel (including the engagement of external capacities), spare parts and accessories must be organized in advance in order to reduce the downtime of the machine to an absolute minimum.

The program of predictive maintenance of machines (Fig. 2.) involves the selection and analysis of certain process parameters which, together with data on vibration activity, describe the working condition of the machine. Process parameters are measured during each vibration measurement, and the measured values are used to create machine operating classes.

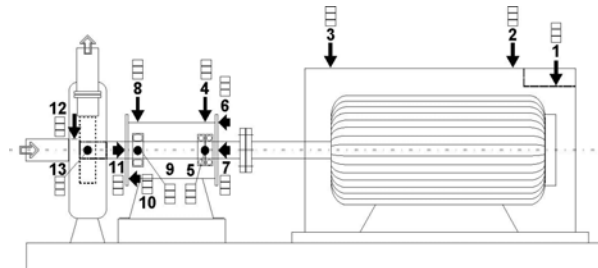


**Figure 2.** Structure of the predictive maintenance program [3]

The definition of measuring points is in line with the requirements and standard ISO 10816 [9]. The measurement is realized on the bearing assemblies, that is, on bearing housings or on other parts of the structure on which dynamic forces are significantly reflected



[10]. Typical measurement positions for the case of a radial centrifugal pump are shown in Figure 3. In order to define the state of vibration at each measuring position, it is necessary to perform the measurement in three mutually normal directions. In practice, it is common to measure in two radial directions and possibly in the axial direction, depending on the type of bearing.



#### LEGEND:

1. Fan-housing;
2. Electric motor housing - non-driving bearing position;
3. Electric motor housing - driving bearing position;
4. Pump ball bearing - vertical radial direction;
5. Pump ball bearing - horizontal radial direction;
6. Pump ball bearing - vertical axial direction;
7. Pump ball bearing - horizontal axial direction;
8. Pump roller bearing - vertical radial direction;
9. Pump roller bearing - horizontal radial direction;
10. Pump roller bearing - vertical axial direction;
11. Pump roller bearing - horizontal axial direction;
12. Pump impeller - vertical radial direction;
13. Pump impeller - horizontal radial direction;

**Figure 3.** Distribution of measurement points for vibration monitoring on a centrifugal pump [11]

One point on the machine can contain several measuring points if different analysis parameters are used for measurements, or vibration measurements are performed in different directions. If the operating condition of the machine affects the value of the vibration amplitudes, then the comparison of the spectra obtained by measurements under different operating conditions is not correct. Therefore, measurements performed under the same operating conditions are grouped into classes. Spectrum differences within one class of measurement reflect the development of the resulting damage, and not the changes caused by the operating mode of the machine. The classification of measurement points into measurement classes defines the reference spectrum of vibrations for the given measuring conditions, that is, the state of the tested element.

The term measurement point means one measuring position of the accelerometer. Hence the need to measure vibrations at several measurement points, since the effect of vibrations is not transmitted equally at all points, as well as the fact that vibrations in different directions are measured with separate accelerometers.

The term measuring class means a set of process parameters of a limited range in which the working condition of the machine does not change significantly.

The assessment of the condition of the machine is performed by comparing the obtained results with the severity zones for the group of machines to which the tested machine belongs, defined by the ISO 10816 standard (Fig. 4):

**Zone 1 - "Good":** Vibrations that are characteristic of new machines. The machine satisfies.

**Zone 2 - "Satisfactory":** Vibration machines in this zone can be operated for an unlimited period. The machine satisfies.

**Zone 3 - "Unsatisfactory":** Machines that have vibrations in this safety zone can work in limited operating loads, that is, in a very short period. The machine does not satisfy.

**Zone 4 - "Unacceptable":** Vibration in this zone can cause damage to the machine. The machine does not satisfy.

Severity zones 1 and 2 define the profile of reliable machine operation. Severity zone 3 defines the warning profile and implies the implementation of measures and activities to reduce vibrations through enhanced monitoring and limited operation. Severity zone 4 defines the alarm or danger profile and provides for the shutdown of the machine from further operation.

The boundaries of the safety zones of a certain class of machines depend on the size of the machine, the characteristics of the foundation of the machine and its purpose.

Machine		Class I Small Machines	Class II Medium Machines	Class III Large Rigid Foundation	Class IV Large Soft Foundation
Vibration Velocity Vrms	in/s	mm/s			
	0.01	0.28			
	0.02	0.45			
	0.03	0.71	GOOD		
	0.04	1.12			
	0.07	1.80			
	0.11	2.80	SATISFACTORY		
	0.18	4.50			
	0.28	7.10	UNSATISFACTORY		
	0.44	11.20			
	0.70	18.00			
	1.10	28.00	UNACCEPTABLE		
	1.77	45.9			

**Figure 4.** Vibration Severity – ISO 10816-1

**Class I:** Individual parts of engines and machines integrally connected to the machine in normal operation. Production electrical motors at a maximum of 15 kW are examples of machines in this category.

**Class II:** Medium-sized machines (typically electrical motors with 15 kW to 75 kW output) without special foundations, rigidly mounted engines or machines (up to 300 kW) on special foundations.

**Class III:** Large prime-movers and other large machines with rotating masses mounted on rigid and heavy foundations that are relatively stiff in the direction of the vibration measurements.

**Class IV:** Large prime-movers and other large machines with rotating masses mounted on foundations that are relatively soft in the direction of the vibration measurements (for example, turbo generator sets and gas turbines with outputs greater than 10 MW).

## CONCLUSION

Conditional maintenance, or predictive maintenance, is the best choice for reducing the life cycle costs of a large number of industrial machines. The success of this maintenance strategy depends primarily on the possibility of sufficiently reliable fault detection. Implementing a predictive maintenance program increases process automation, reduces job losses due to production delays, reduces insurance prices (all insurance companies value the existence of predictive maintenance), raises production quality, reduces energy consumption (5%), reduces warehouse reserves and needs for stocking the equipment. The introduction of predictive maintenance carries with it risks, especially at the beginning of program implementation, and these are lack of management interest, untrained staff, initial errors and excessive equipment on which the test is applied.

The best results of maintenance of technical systems are achieved by a combination of predictive and proactive maintenance methods, which in addition to activities included in preventive maintenance also contains a phase of analysis of causes of failures which reveals the causes of frequent failures at individual machines. Based on this, their solution and removal can be carried out during the design and manufacture of certain elements.

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## BIOGRAPHY

**Darko Mihajlov** was born in 1969, in Nis. He works as an Assistant Professor at the Faculty of Occupational Safety in Nis.

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## MODEL VIBRODIJAGNOSTIČKOG POSTUPKA ZA PREDIKTIVNO ODRŽAVANJE ROTACIONIH MAŠINA

*Darko Mihajlov, Momir Prašćević, Marko Ličanin*

**Rezime:** Rad opisuje model vibrodiagnostičkog postupka za prediktivno održavanje rotacionih mašina, zasnovan na eksperimentalnim ispitivanjima realnih objekata. Sistematsko praćenje stanja rotacionih mašina u dužem vremenskom periodu dozvoljava zaključivanje o potencijalnim nepravilnostima u radu postrojenja, uočavanje izvora nastanka vibracija i stepena oštećenja pojedinih sastavnih delova. Na taj način su ispunjeni uslovi za izradu vibracione karte i preduzimanje preventivnih mera za održavanje postrojenja.

**Ključne reči:** tehničko održavanje, prediktivno održavanje, vibracije, detekcija otkaza, rotacione mašine.