Algorithm for automated defect search by power distribution in the vibration signal spectrum

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Abstract. A useful model of CIP diagnostics of pumping units is presented, which can be used to prevent and develop emergencies by promptly identifying the causes of malfunctioning of the pumping unit. In the beginning, the problem of signal propagation was investigated, which was reduced to the problem of will propagation was solved. Analyzing the experimental results, it was found that it is necessary to consider the damped nature of the signals. For this purpose, a mathematical model has been developed that allows solving the problem of the propagation of damped signals. Comparative analysis allows us to conclude that the constructed model is adequate.

INTRODUCTION

The object of the study was methods and tools for diagnosing pumping units in irrigation pumping stations. Currently, many pumping stations (PS) are replacing large pumps that have exhausted their resource. To clarify the modes of joint operation of new and old pumping units (PU), full-scale tests are carried out. The main type under operating conditions is control tests using diagnostic equipment. They determine the actual parameters of the units under operating conditions. Based on the results of control tests, conclusions are drawn about the compliance of the actual operating parameters of the units with the factory and design, the energy efficiency of the equipment is determined, the impact of existing deviations from nominal conditions is evaluated, as well as the effectiveness of preventive and repair work on the performance of pumping units [1-3].

The subject of research is a method, tool for determining the technical condition of pumping units, its software and a model representing the technical condition of the pumping unit.

According to the research program, three units were subject to control tests at the largest cascade of the Karshi Main Canal (KMC). During the tests, it was constantly in operation on PU No. 3 and alternately on PU No. 2, 6.

Based on the current operating mode of the pumping station (three units of different supply to stabilize the water levels of the downstream and upstream pays), for testing a new unit of the 300VO-37/26Ts type (PU No. 3) and two operating units of the OPV11-260 type (PU No. 2, 6) were selected [9, 10, 12, 19, 20, 22, 23, 24, 25].

Modern technological processes of PU operation are accompanied by, as a rule, significant force and temperature influences with high requirements for process dynamics. For CIP diagnostics of PU, the authors of this article have created a useful model, which can be used to prevent and develop emergencies by promptly identifying the reasons for the failure of the equipment [4].

In full-scale tests, an increase in the diagnostic accuracy and the speed of detecting the reasons for the malfunction of the units was achieved.

This is achieved by the fact that the device for vibroacoustic diagnostics contains series-connected vibration sensors, a tertsoctave analyzer, blocks for matching, analyzing the maximum total vibration levels and reference information. The device operates according to the program for ensuring the reliability of scientific equipment, depending on the determination of its state. The program provides a method for diagnostics of scientific equipment, where the signal about the state of the impeller, impeller chamber and blades is removed from the bearings and based on the data obtained, their residual resources are determined [5, 14].

METHODS

One of the important tasks of vibration diagnostics is to determine the defects arising during the operation of machinery. As noted above, the spectrum of the vibration signal carries the greatest information about the defect. Therefore, most of the existing works in the field of searching for defects are devoted to describing the shape of the spectrum of the vibration signal. One of the complete sources is the "Classifier of vibrodiagnostic signs of defects in rotary machines" [4], further "classifier". This classifier contains a description of a large number (more than 100) of defects of various nodes.

The defect description consists of listing the frequencies at which this defect has the highest power, which is characterized by the maximum values of the amplitudes of the vibration signal spectrum. The classifier describes defects in such units as electric motors, couplings, gearboxes, belt drives, flow paths of compressors and pumps, rolling bearings and plain bearings. All frequencies indicated in the "classifier" depend on the unit's shaft speed and design parameters. If there is sufficient information about the design of the diagnosed machine, using the "classifier", you can calculate the values of the frequencies of various defects. Since the "classifier" contains the most complete and clear list of frequencies for various defects, it was used as an information basis for the diagnostic system in this development [6, 7].

The use of the "classifier" required the creation of a database that stores information about the frequencies of various defects. Hereinafter, this database will be referred to as the "DB of defects". To obtain the numerical values of the defect frequencies, information is needed on the design of the machine units and the shaft rotation frequency. This led to the need to create a database with design parameters of nodes, hereinafter referred to as a "database of nodes", and create a hierarchical model of the diagnosed machine for calculating the turnover frequency.

To carry out diagnostics, the "Algorithm for the automated search for a defect by the distribution of power in the vibration signal spectrum", hereinafter referred to as the "diagnostic algorithm", has been developed. This algorithm is shown in Fig. 1 and consists of two phases:

1) finding a defective node;
2) search for a defect due to which the flock node is defective.

The idea of using these phases is based on the fact that either a defective unit or a defect makes the greatest contribution to the RMS of the vibration signal, namely: the power of the vibration signal is highest at those frequencies that form the defect. This share of power is determined by the formula (1). To calculate it, you need to know the set of frequencies that arise with various defects. We denote this set of frequencies as Ii and propose to call it the defect mask, $i = 1, ..., I$, i is the mask number, I is the number of masks. Depending on the phase (search for a defective node or the defect itself), the masks themselves are formed in different ways. Let's take a closer look at this process.

The hierarchical model of the structure of an enterprise by machinery; Loading routes, unloading vibration measurements; Interface box; Collector given; Shaft rotation frequency at the diagnosed point; Tables of design parameters of diagnosed units; DB of measurements DB of nodes Block for calculating fundamental frequencies are considered [8, 9, 15].

RESULTS

Finding a defective node is described below. The first phase of the automated diagnostics algorithm is to determine the vibration power of a particular machine unit, i.e., the defect's localisation.

Further, the vibration power of the node will be called the "Node power" (NP). For this, masks Ii are formed from the main frequencies of the nodes. To form each mask, information is required on the shaft rotation frequency, design parameters of the unit being diagnosed, and formulas for calculating the basic frequencies of defects.

Formulas for calculating the basic frequencies of defects in various machinery units are taken from [10]. After the formation of masks, the power of the vibration signal is calculated in the selected frequency range:

$$MD^{i} = \frac{\sum_{k \in Ii} A^{2}(k)}{2} \tag{1}$$

where: $i = 1 \ldots I$; A (k) is the values of the amplitudes of the harmonics of the vibration signal spectrum, Ii is the subset of the numbers of the spectrum harmonics for the i is the node, I is the number of nodes.

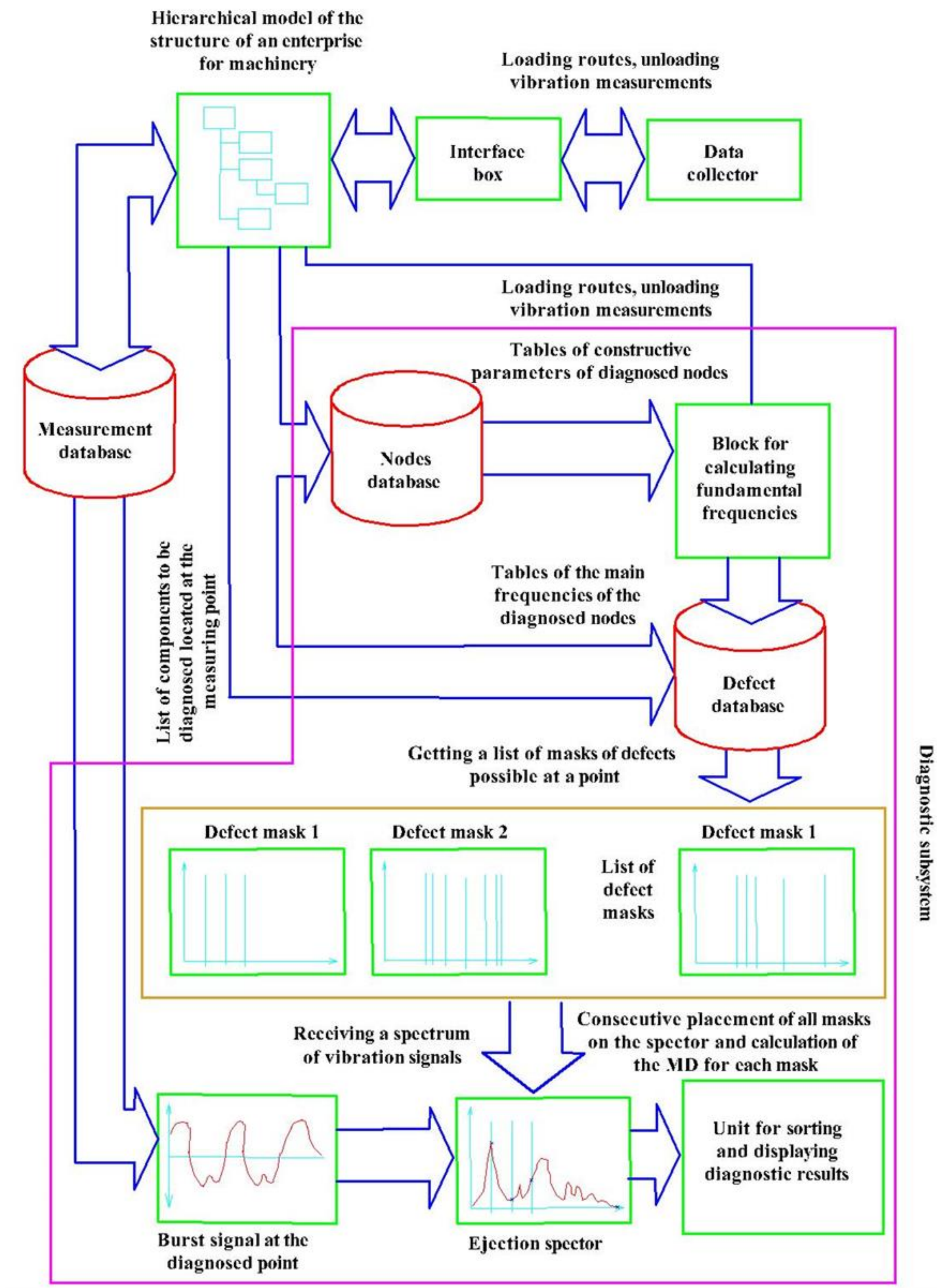

FIGURE 1. Algorithm for automated defect search by power distribution in the spectrum

For a correct interpretation of the notion "group of frequencies of a defective node", we define the term "frequencies of defects of a node". These are the frequencies of the spectrum of the vibration signal received at the points of measurement, at which an increase in the amplitudes of the vibration signal is observed for a particular defect (the defect "makes noise" at certain frequencies and the amplitudes of the harmonics at these frequencies are maximum).

Frequencies of defects of the node are divided into fundamental, harmonics of fundamental frequencies, side harmonics of side frequencies. The main frequencies of unit defects depend on the shaft rotation frequency and the unit design. The number of fundamental frequencies and their names depends on the node type [11, 16].

For example, the list of basic frequencies for a rolling bearing will be as shown in Table 1.

TABLE 1. List of basic rolling bearing frequencies

Frequency	Formula for calculation	Notes (edit)
FTF - separator speed	$FTF = \frac{f_1}{2} \cdot 1 \pm \left(\frac{d_b}{D_b} \cos\gamma \right)$	f_i is shaft speed, D_b is average bearing diameter, d_b is ball diameter, γ is contact angle, «+» is used if the outer race is rotating, «-» is if the inner race is rotating.
BPFI - frequency of passage of balls along the inner ring	$BPFI = f_1 \frac{z_r}{2} \cdot \left(1 + \frac{d_b}{D_b} \cos\gamma \right)$	Zr is number of balls, rollers (rolling elements)
BPFO - frequency of passing balls on the outer ring	$BPFO = f_1 \frac{z_r}{2} \cdot \left(1 - \frac{d_b}{D_b} \cos\gamma \right)$	
BSF - ball speed	$BSF = f_1 \cdot \frac{D_b}{2 \cdot d_b} \cdot \left[1 \pm \left(\frac{d_b}{D_b} \cos\gamma \right)^2 \right]$	
FFB - excitation frequency in case of a defect in the shape of the rolling elements	$FFB = 2 f_1 \left(\frac{D_b^2}{d_b^2} - 1 \right)$	
FFI - excitation frequency when changing the shape of the inner track	$FFI = \frac{f_1 \cdot z_r}{2} \left(1 + \frac{d_b}{D_b} \right)$	
FFO - excitation frequency when changing the shape of the outer track	$FFO = \frac{f_1 \cdot z_T}{2} \left(1 - \frac{d_b}{D_b} \right)$	

Reference data on the design of the nodes and the frequency of rotation of the shaft, it is possible to determine the numerical value of all the main frequencies of the defects of the nodes. So, for example, to calculate one of the basic frequencies of rolling bearing defects "BSF", which is the speed of the ball, the formula is used:

$$BSF = f_1 \cdot \frac{D_b}{2 \cdot d_b} \cdot \left[1 \pm \left(\frac{d_b}{D_o} \cos\gamma \right)^2 \right] \tag{2}$$

where: f_1 is the shaft speed, D_0 is the average bearing diameter, d_{sh} is the ball diameter, γ is the contact angle.

For bearing № 3526 at a shaft speed of 1000 rpm (or 16.67 Hz), the BSF value will be:

$$BSF = 16.67 \cdot \frac{180}{2 \cdot 26} \cdot \left[1 - \left(\frac{26}{180} \cos(11^0) \right)^2 \right] = 42.5 Gs;$$

In addition to fundamental frequencies, a faulty node can generate their harmonics.

Moreover, harmonics can be either whole or multiples of a quarter, third and half of the fundamental frequency.

Side frequencies are frequencies:

$$f_{bok} = f_{osn1} \pm f_{osn2} \tag{3}$$

where: f_{osn1} is one of the fundamental frequencies around which the side frequencies are located, f_{osn2} is any other fundamental frequency, as f_{osn1} and f_{osn2} shaft speed may also be present.

The harmonics of the side frequencies are generally determined by the formula:

$$f_{bok} = f_{osn1} \pm k \cdot n \cdot f_{osn2} \tag{4}$$

where: k is number of harmonics, *n* is can be either an integer or a multiple 0.25, 0.33, 0.5.

The number of harmonic frequencies can divide the defects described in DB defects divided into two types:

- defects for which the number of harmonics is precisely indicated;
- defects for which the exact number of harmonics is unknown.

The values of n in both cases and k in the first case are stored in the "DB of defects". In the second case, the number of harmonics should be determined by vibration diagnostics.

Since most node defects are manifested in an increase in the amplitudes of the spectral components at fundamental frequencies, then to determine a defective node without determining a defect, it is enough to estimate the power of a node using a "mask" of fundamental frequencies using the formula (1).

The second phase of the automated diagnostic algorithm is to identify the defect that has arisen in the node. This phase is performed by imposing masks corresponding to the defects on the spectrum and calculating the "defect power" (DP).

DISCUSSIONS

Finding a defect using a mask is described below. Description of the vibration signal spectrum for various defects is an enumeration of spectrum frequencies on which bursts of vibration signal amplitude are possible. Each defect described has its own set of such frequencies. This allows you to create a mask for each defect.

In the second phase, to create a mask, the numerical values of the main frequencies of the unit being diagnosed, the value of the shaft rotation frequency and information on the frequencies characteristic of each defect are required. Since the second phase of the algorithm is executed only after the first, the values of the turnover frequency and fundamental frequencies are already known. The main task of the second phase of the algorithm is to obtain information about the characteristic frequencies of defects. For this purpose, a "DB of defects" was developed, which contains information on the location of the peaks of the vibration signal spectrum for various defects of various nodes.

The basis of the "DB of defects" was the "Classifier of vibrodiagnostic signs of defects in rotary machines" [12, 132].

After the formation of the masks, the "defect power" is calculated for each mask. For each MD, the calculation is performed according to the formula (1).

For example, such a defect as damage to the rolling elements of bearing No. 412 leads to the appearance of BSF and $BSF \pm FTF$ frequencies in the vibration signal spectrum, which at a shaft rotation speed of 750 rpm (12.5 Hz) will amount to 21.3, 16.7, 25.8 Hz, respectively.

The obtained numerical values of the DP for all possible defects make it possible to judge the degree of development of a particular defect. For example, in the spectrum of a vibration signal taken on a defective rolling bearing (No. 412), and shown in fig. 2, there are clearly visible bursts at frequencies 4.4, 21.9, 43.8, which correspond to the frequencies *FTF*, *BSF* and 2 *BSF* of the rolling bearing.

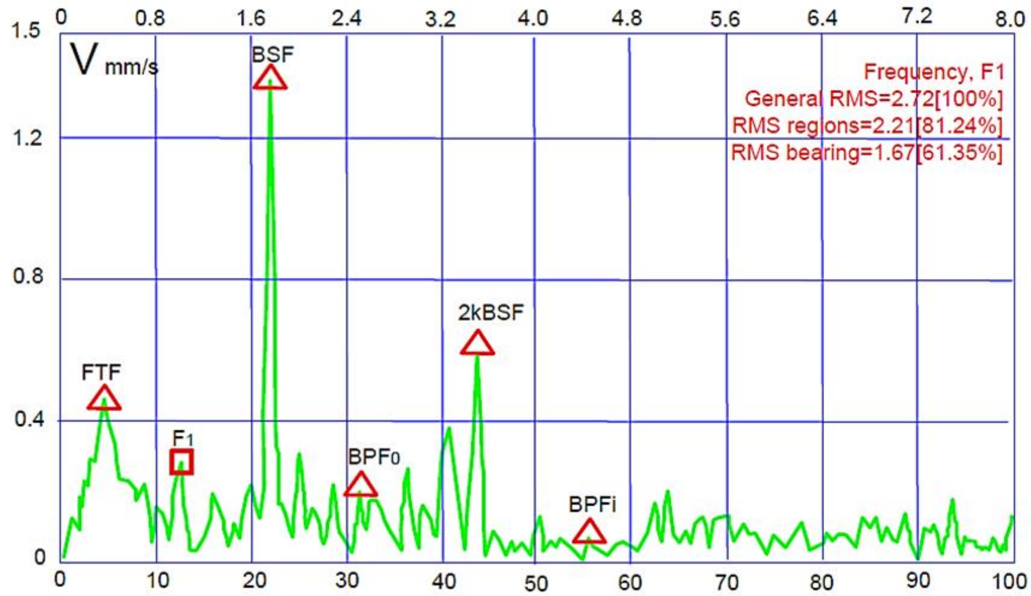

Figure 2. Defective bearing spectrum

After calculating the DP for all rolling bearing defects, we obtain the following values in table 2.

TABLE 2. Defective bearing DP values

Defect	DP
Damage to rolling elements	1.916
Cage imbalance, uneven wear on rolling elements	0.399
Misalignment, uneven wear on the rotating ring	0.393
Bearing race misalignment	0.388

Table 2 shows that the maximum DP has the defect "Damage to rolling elements". Since the diagnosed machine contains a whole set of units, vibrations caused by different units can often be present at one measurement point. For example, when measuring vibration at a point on an electric motor bearing, vibrations may occur due to the electrical circuits of the motor and components connected to the motor shaft, such as a coupling, gearbox, etc. For the correct "binding" of a possible defect to a specific node, a sequential calculation of the DP for each node is applied, which can cause vibration at the investigated measurement point. As a result, a list is formed containing DP for all nodes located at the measurement point.

Thus, an approach is proposed for automated search for defects using a vibration signal spectrum, shaft rotation frequency, information on the design of the diagnosed machine and information on characteristic frequencies for various defects.

CONCLUSIONS

An algorithm for automated defect search based on the power distribution in the vibration signal spectrum has been developed. The algorithm consists of two phases: in the first phase, the defective unit of the machine unit is determined, and in the second, the defect itself, due to which the unit becomes defective. For each of these phases, a method is proposed for determining the combination of vibration signal frequencies, with the definition of a mask of defect frequencies, at which either a defective unit or a defect appears. The concept of a "group of node frequencies", including a set of fundamental, harmonics of the fundamental, side and side harmonics that appear in the event of defects, is introduced and formalized. This formalized concept made it possible to create an algorithm for determining defect masks.

Information support for automated vibration diagnostics of machinery has been developed, consisting of two parts:

a) General information support focused on monitoring, forecasting and diagnostics of the technical condition of machinery. This part contains the "DB of measurements", the structure of the enterprise by machine equipment, a software shell for accessing databases;

b) Information support focused on the task of automated vibration diagnostics of machinery. This part contains "DB of defects" and "DB of units" of machine units and specialized information necessary to work with the vibration signal spectrum and calculate masks. "DB of defects" allows you to identify defects grouped by design features defects that are not related to design parameters, such as imbalance, misalignment, mechanical weakening;

rolling bearing defects; sleeve bearing defects; defects of couplings; defects of gear reducers; belt drive defects; defects of electric motors; defects of pumps (compressors).

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