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Evaluation of the vehicle state with vibration-based diagnostics methods

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Abstract. Timely detection of a trouble in the mechanisms work is a guarantee of the stable operation of the entire machine complex. It allows minimizing unexpected losses, and avoiding any injuries inflicted on working people. The solution of the problem is the most important for vehicles and machines, working in remote areas of the infrastructure. All-terrain vehicles can be referred to such type of transport. The potential object of application of the described methodology is the multipurpose rotary-screw amphibious vehicle for rescue; reconnaissance; transport and technological operations. At the present time, there is no information on the use of these kinds of systems in ground-based vehicles. The present paper is devoted to the state estimation of a mechanism based on the analysis of vibration signals produced by the mechanism, in particular, the vibration signals of rolling bearings. The theory of active perception was used for the solution of the problem of the state estimation.

1. Introduction

Continuous monitoring of the equipment condition is essential for the failure risk reduction of equipment [1]. There are several approaches for the solution of this problem. One of the solutions is the usage of methods of vibration-based diagnostics. It allows evaluating the technical condition of the research object. The diagnosis is performed in operational conditions without mechanism dismantling. The diagnosis is based on the analysis of the characteristics of vibro-acoustic processes accompanying the work of the mechanism. The vibro-acoustic diagnostic techniques, in a short time, allow identifying the problem and detecting the emerging defects at the early stages.

The solution method for the task of vibration-based diagnostics can be decomposed into three stages: a preliminary signal processing, calculation of signs, and decision-making. In the most general case, we can assume that the analysis of vibroacoustic nonstationary signals is performed.

Let us consider the disadvantages of known approaches to the solution the problem of vibration diagnostics, considering the decomposition of the problem into three stages [2, 3].

The preprocessing step. This step usually consists in filtering the vibration signal. Considering the fact that the recognition is achieved under conditions of a priori uncertainty, which means that there are no information about a hindrance, the selection of the appropriate filter is difficult. The well-known works pointed that the dividing of the signal into segments does not solve the problem of the choice of the signal segment length. However, this division is necessary in the analysis of non-stationary signals.



The step of a system signs forming. The problem of formation of the system of the signs is associated with the selection of the final set of features to ensure the uniqueness of the solution of the classification problem at the recognition stage and meets the requirements of necessity and sufficiency. The step of choice of the system of the signs is necessary for reduction of the dimensionality of the input description.

The decision step. The decision step consists in the comparison of the sign descriptions of the analyzed vibration with the existing benchmark. It is assumed that a compact set of points in the signs system complies with the benchmark. However, hindrances, structural changes of the same class representative, lead to overlapping classes. Therefore, the problem of the decision-making closes on the problem of the signs system forming, which allows generating the benchmark having a compact representation.

The purpose of the work is the development of new approach for further solution of the task of vibration-based diagnostics of vehicles. The diagnostics is based on the theory of active perception, which allows solving issues, connected with implementation phases of preliminary signal processing and the signs system formation.

2. The proposed approach to the implementation of the vibration-based diagnostics system

The proposed approach to the solution of the vibration diagnostics problem of a rolling bearing is based on the using of machine learning techniques and active perception theory [3]. Considering the vibration-based diagnostics system as a pattern recognition system, it is possible to distinguish three stages of information processing: pre-treatment; calculation of signs and decision-making.

Pretreatment means the performance of the Q -transformation, which consists in the application of the addition operation of the original signal segments:

$$g(t) = \sum_{k=(t-1)L+1}^{tL} f(k), t = \overline{1, N},$$

where L – the number of readings, within the segment, N – the number of signal segments, g – the result of application of the Q -transformation to signal f , $f(k)$ – k – reading of signal f , $g(t)$ – t – reading of signal g .

Formation of the feature description of the original signal is the application of the set of Walsh filters of the Hartmut system to signal g :

$$\mu(k, c(t)) = \sum_{i=0}^{M-1} F_k(i) \cdot g(((t-1) \cdot M + 1) : (t \cdot M)),$$

where $\mu(k, c(t))$ is the result of application of the sets of Walsh filters of the Hartmut system to signal g , $k = \overline{0, M-1}$, $t = \overline{0, |c|-1}$, $c = \{1, P, 2 \cdot P, 3 \cdot P, \dots, N - T \cdot P\}$ is a set of the offset values for signal g , $|c|$ – is a cardinal number of set c , P – is an offset value for signal g ($1 \leq P \leq M$), M – is the number of the used filters. Thus, the feature description of the signal represents the size of matrix $M \times |c|$ and each line of the feature description is a result of the U -transformation the signal segment.

The consequent application of the Q -transformation and filter systems to the signal implements the U -transformation, which is basic in the theory of active perception.

The U -transformation has the lowest possible computational complexity, since for its realization only simple operations are used – addition and subtraction. Standard transformations require the implementation of convolution, and the level of weighting coefficients – the operation of arithmetic multiplication.

Let each filter $F_i \in \{F_i\} \equiv \mathbf{F}$ correspond to coordinate-defined binary operator $V_i \in \{V_i\} \equiv \mathbf{V}$; Then, components $\mu_i \neq 0$ of vector μ is permissible to put in line with operator V_i or \bar{V}_i depending on the component sign. As a result, vector μ is associated with a subset of operators $\{V_i\}$, with a design similar to the filter, but having a different meaning of the vector elements ($+1 \leftrightarrow 1$; $-1 \leftrightarrow 0$). By specifying set-theoretic operations of multiplication and addition on set $\{V_i\}$, we have the algebra of

the signal description of one-dimensional Boolean functions. Taking into account the reversals, all in all, there are 15 operators that can be used in the formation of feature descriptions, as the V_0 operator receives only the direct value.

On the set of operators, the algebra group is formed (the stage of synthesis) of the analyzed signal:

1) The family of algebraic structures (called the complete groups) $\{P_{ni}\}$, where $P_{ni} = \{V_i, V_j, V_k\}$ with the power of 35;

2) The family of algebraic structures (called the closed groups) $\{P_{si}\}$, where $P_{si} = \{V_i, V_j, V_k, V_r\}$ with the power of 105, where each group is formed of a pair of complete groups connected in a certain way.

Among the complete groups, we can allocate the complete groups for the operations of addition and the operation of multiplication, among the closed groups - closed groups and closed sets.

The set of operators describing the signal is formed with using of the spectral representation of signal μ . Then, the set of complete and closed groups is formed as well:

$$V = GV[\mu], P_{na} = GP_{na}[\mu, V], P_{nm} = GP_{nm}[\mu, V], P_s = GP_s[\mu, V, P_{na}, P_{nm}], P_c = GP_c[\mu, V, P_{na}, P_{nm}],$$

where GV – is an operator for calculation of feature descriptions V using spectral representation of the signal on the basis of operators: GP_{na} (GP_{nm}) – on the basis of complete groups for the operations of addition P_{na} (multiplication, P_{nm}), GP_c (GP_s) – on the basis of closed groups P_s (closed sets P_c).

A model of signs descriptions, which takes into account the connection between adjacent segments of the signal, is proposed. In this case, the calculation method of the signs descriptions consists in the forming of the matrix of transition probabilities between neighboring segments descriptions.

The signs systems based on the matrices of transition probabilities are proposed. The following variants of the systems are considered:

1) The signs system describing the probabilities of transitions between the values of the operators (the operator can take three possible values: direct, inverse and zero). The values are calculated from the adjacent signal segments, without considering the connections between the various operators, the dimension of the feature space – $3 \times 3 \times 15$;

2) The signs system describing the probabilities of transitions between the values of the operators. The values are calculated on neighbour segments of the signal, taking into account the connection between operators, the dimension of the feature space – 45×45 .

3) The signs system of describing the probabilities of transitions between segments of the descriptions is provided in the form of complete groups, the dimension of the feature space – 140×140 ; in case of using the full group, it is allowed using only a few groups of maximum weight;

4) The signs system describing the probabilities of transitions between the descriptions of the segments provided in the form of closed groups, the dimension of the feature space – 840×840 ; with using closed groups, it is allowed using only a few groups of maximum weight.

The formation algorithm of signs system based on the complete groups (closed groups, $Desc_i$ – description of the i -th segment signal in the form of complete or closed groups):

$$\forall i = 1, \overline{N}$$

$$\forall k = 1, \overline{|Desc_i|}$$

$$\forall l = 1, \overline{|Desc_{i+1}|}$$

$$MPG_{Desc_i}(Desc_i(k), Desc_{i+1}(l)) = MPG_{Desc_i}(Desc_i(k), Desc_{i+1}(l)) + 1.$$

The following notations will be used: PP_{na} (PP_{nm}) – the matrix of transition probabilities between the full groups (multiplication), PP_c – the matrix of transition probabilities between the closed groups.

The formation algorithm of the PVI signs system based on operators without considering connections (V_i – a description of the i -th signal segment as operators): The formation algorithm of the PVD signs system by operators, considering the connections between operators:

$$\begin{array}{ll}
\forall i = \overline{1, N} & \forall i = \overline{1, N} \\
\forall k = \overline{1, 15} & \forall k = \overline{1, 15} \\
\text{if } V_i(k) == -1 & \text{if } V_i(k) == -1 \\
\quad p = 1 & \quad p = 1 \\
\text{if } V_i(k) == 0 & \text{if } V_i(k) == 0 \\
\quad p = 2 & \quad p = 2 \\
\text{if } V_i(k) == +1 & \text{if } V_i(k) == +1 \\
\quad p = 3 & \quad p = 3 \\
\quad p = p + (k - 1) \cdot 3 & \quad p = p + (k - 1) \cdot 3 \\
\text{if } V_{i+1}(k) == -1 & \forall l = \overline{1, 15} \\
\quad q = 1 & \text{if } V_{i+1}(k) == -1 \\
\text{if } V_{i+1}(k) == 0 & \quad q = 1 \\
\quad q = 2 & \text{if } V_{i+1}(k) == 0 \\
\text{if } V_{i+1}(k) == +1 & \quad q = 2 \\
\quad q = 3 & \text{if } V_{i+1}(k) == +1 \\
\quad q = q + (k - 1) \cdot 3 & \quad q = 3 \\
PVI_{Desc, k}(p, q) = PVI_{Desc, k}(p, q). & \quad q = q + (k - 1) \cdot 3 \\
& PVD_{Desc}(p, q) = PVD_{Desc}(p, q).
\end{array}$$

The matrices of transition probabilities between descriptions of the segments can be used as the signs systems. At the same time, it is possible to take into account the transition probabilities between many segments and not only between neighbor segments (i and $(i+1)$). For the i -th segment, we can consider not only $(i+1)$, $(i+2)$ and further segments, but also $(i-1)$, $(i-2)$ segments, i.e. not only the ‘next’ segments can be considered, but ‘previous’ segments can be considered as well.

3. The computational experiment

3.1. The experiment description

The computational experiment was carried out based on the database of vibration signals, described in [7]. The database contains records of vibration signals recorded by defects of rolling bearings (on the outer and inner track roller body) and without defects. The defects dimensions constitute 0.007, 0.014, 0.021 and 0.028 inches in diameter. In the twenty-one, the bearing condition can be classified in the database: 1) normal; 2-5) rolling element defect (defect sizes: 0.007, 0.014, 0.021, 0.028); 6-9) defect in the inner tracks (defect sizes: 0.007, 0.014, 0.021, 0.028); 10-21) outer race defect (defect positions: centr, orth, opp; defect sizes: 0.007, 0.014, 0.021, 0.028).

The computational experiment was directed to study of the accuracy of determining the condition of the bearing depending on the features of the system. Solution of the problem of classification is performed based on the method of the support vector machine (SVM) and the k-nearest neighbor (KNN).

3.2. Results

The tests results of existing vibration-based diagnostics methods of a rolling bearing are shown in Table 1.

Table 1. The tests results of existing vibration-based diagnostics methods

Source	Signs	Signs amount	Classification method	The amount of the classification conditions	Accuracy of recognition (R_B %)
[5]	Mel frequency cepstral coefficients	16	Gaussian mixture model	4	94
[6]	Statistical signs	26	The method of support vector machine	21	92.88
[6]	Spectrum of the complex envelope	72	The method of support vector machine	21	85.47
[7]	Properties coefficients of wavelet decomposition	5	Radial basis function network	4	72.1
[7]	Properties coefficients of wavelet decomposition	5	Multilayer perceptron	4	100

3.3. The study of the proposed approach

Table 2 shows the results of the accuracy of the rolling bearing condition evaluation. Various systems and signs of classifiers were used during the evaluation.

Table 2. The results of the computational experiment

Classifier / Signs system	PVI	PVD	PP_{na}	PP_{nm}	PP_s
KNN	85	95	95	97	-
SVM	81	91	91	97	-

Conclusions of the experiment results:

- 1) using the system of signs PP_{nm} and classifier KNN provides the best results;
- 2) the testing of the system of signs PP_s was not performed successfully because of lack of RAM;
- 3) the accuracy of the achieved results is comparable with the known ones, and in some cases exceeds them.

4. Conclusion

The vibration-based diagnostics methods of a rolling bearing were considered in this paper. The solution was performed from the standpoint of the theory of active perception. The investigations of the proposed method showed the ability to increase, as compared to known approaches, the accuracy of the estimate of the rolling bearing condition. The results are a significant advance in the field of forecasting and monitoring the state of the diagnosed object. Timely assessment of critical components and mechanisms is an appropriate stage of development and improvement of various all-terrain vehicles.

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