Current based Normalized Triple Covariance as a bearings diagnostic feature in induction motor

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Abstract. Diagnosis of induction motors, conducted remotely by measuring and analyzing the supply current is attractive with the lack of access to the engine. So far there is no solution, based on analysis of current, the credibility of which allow use in industry. Statistics of IM bearing failures of induction motors indicate, that they constitute more than 40% of IM damage, therefore bearing diagnosis is so important. The article provides an overview of selected methods of diagnosis of induction motor bearings, based on measurement of the supply current. The problem here is the high disturbance components level of the motor current in relation to diagnostic components. The paper presents the new approach to signal analysis solutions, based on statistical methods, which have been adapted to be used by this diagnostic system. First experimental results with use of this method are also presented, they confirm the advantages of this method.

Introduction

The electric induction motor is still the most popular machine in the industry. The majority of the energy produced in the world is consumed by just such engines. Therefore, the diagnosis of these engines is so important for achieving maximum economic effects.
Bearings, the rotor shaft and damage to the components of the electromagnetic coils of the stator, the rotor or the magnetic circuit may are subject to mechanical damage in the induction motor. Bearing failures are by far the most common damage (over 40% of all damage). Therefore, it is the bearing diagnosis which is so important for monitoring the status of the engine.
In the diagnosis of engines, various physical signals, such as: vibration, voltage, magnetic flux, temperature, power supply, acoustic phenomena [1] are used. From those, practically only vibration measurements are used in diagnosis of bearings. Measurements of power supply are still used only in research. There are no commonly used bearing diagnostic systems working on the basis of such measurements. This article gives insight into the topic. Diagnosis by measuring the supply current is appealing on the grounds that it allows for research without the need to install any equipment on the test object. This is particularly important for motors operating in inaccessible conditions (e.g. underground, powered by high voltage, etc.).

So far, the methods used are generally based on the analysis of spectral power. This approach requires the use of devices to measure the current with their own low noise. The commonly used hall effect or clamp transducers do not meet these requirements.
The work widely quoted by authors of the current methods is [2]. In it, the authors gave the theoretical basis of bearing induction motors current diagnosis. In recent years, important achievements in this field were published, among others, in [3, 4, 5, 6]. In all studies, the same problem occurs – how to extract the diagnostic signal from the strongly noisy current waveform. The proposed methods are different (Wiener filter, analysis of Park vector, analysis of the efficiency of the engine and other), but so far have not yielded completely satisfactory effects.
The authors of this paper attempt to solve this problem by developing a method based on statistical methods.

1. Experimental studies

1.1 The measuring system

The majority of diagnostic systems creators focus on data processing systems, without paying much attention to the input elements of the measurement systems. An expression of this approach are numerous publications – in most of them there is no information about the measurement systems, in some the authors inform about applying hall effect current to voltage converters produced by LEM, and sometimes information is given relaying the use of clamp current transformers. The advantage of using LEM transducers may be the fact that they are installed in the sensor less control systems, more and more common. Then one can use the existing sensors for diagnostic purposes.
In the earlier model studies and experiments conducted by the authors team, the requirements for the measuring system have been established:
1) the total system noise should not exceed -110 dB at the measuring frequency range of 20 Hz ÷ 2 kHz, to keep the signal-to-noise ratio of 20 dB,
2) both the mains frequency, and the frequency of rotation of the rotor should be measured with an error of not more than ±0,03 Hz, with the spectrum resolution of at least 1/8 Hz, due to the fact that in the current spectrum there is a number of components closely spaced frequencies,
3) measurement of the angular velocity and frequency of the supply grid must be made and averaged in the same time frame, in which a sample of the signal power has been taken for spectral analysis,
4) uncertainty of current measurement should not be greater than 10%. Amplitudes of current components measured by the appearance of damage rise in orders of magnitude (one or more times) and high accuracy of measurements is not needed.

Hall Effect sensors commonly used for this type of testing do not meet these requirements because:
a) in the case of the deformed current curve the Hall Effect transducers falsify the ratio of harmonic amplitudes,
b) due to the built-in electronics high own noise of the transducers.
Clamp current transformers have similar disadvantages.
Therefore, for test conduct special current transducers have been created based on the linear frequency response over a wide frequency range, and specially designed electronic circuits.
The main part of the system is a transformer wound on a ferrite core with a linear frequency response over a wide frequency range, and an operational amplifier with low noise levels

own elements commercially obtainable. The transformer measures the voltage on the shunt through which current powering the engine flows. This solution allows to easily change the measurement range by switching the shunts. The transformer and the further part of the system work in the same conditions at different measurement ranges.
Three current paths of signal processing are housed in separate, individually shielded spaces. Each track is made up of four separate circuit boards separated by a magnetic screen.
The test results confirmed the expected transducer parameters – low self-noise and linear characteristic over a wide frequency band. Self-noise of the measuring system do not exceed the level of –120 dB which is the value entirely satisfactory for the envisaged application of the measuring system.
The measured processing sensor characteristics indicate the possibility of taking measurements from 20 Hz to above 20 kHz with an acceptable error. For scheduled diagnostic measurement it is a fully adequate range.
Fig. 1 presents a photograph of the test stand.

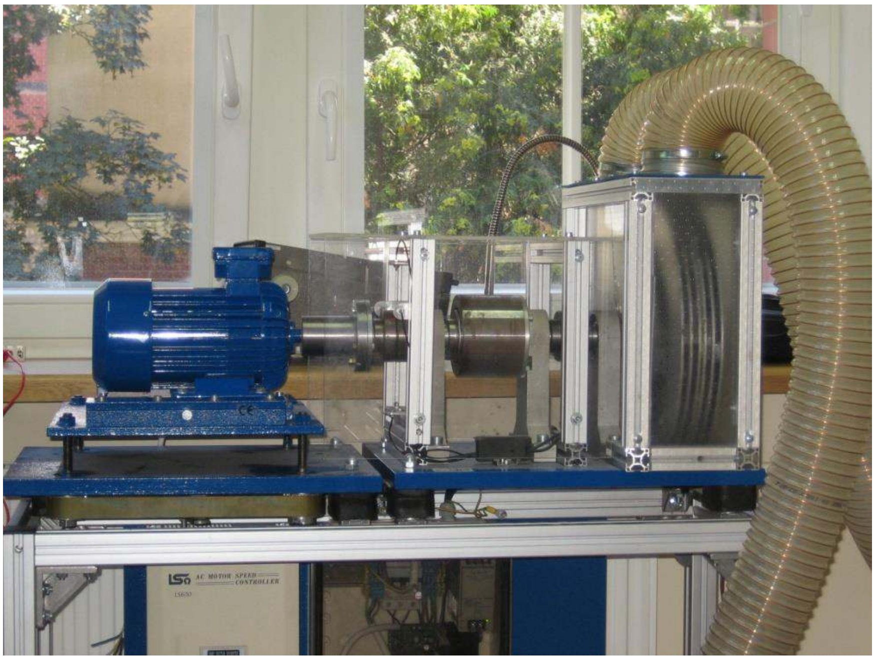

Fig.1. Photograph of the test stand

The built measuring system is connected to a computer, which records the measurements results. The current signal in the computer is further subjected to signal processing in accordance with a predetermined procedure.

1.2 The method of measurement data analysis

The existing methods of current bearings diagnosis were based on the analysis of additional components in the current spectrum, associated with electromechanical phenomena in the induction motor. These methods are developed by analogy with the vibration diagnostics. Amplitude components of current spectrum were analyzed, where frequencies were able to be paired with bearing damage. The development and introduction of statistical methods for the diagnosis allowed the extension of the studied parameters.
Research has shown that the spectrum values of current up to a frequency suitable to assign a specific damage to the bearings are deformed. Therefore, an attempt to support diagnosis of induction motor bearings was based on their shape and not on the amplitude of the

diagnostic components. It is assumed, that the level of diagnostic distortion components in the current spectrum can be a diagnostic symptom for the diagnosis of motor bearings.
For the study of the deformation, a normalized triple covariance (NTC) method has been used. According to formula (1) the average value has been removed from the multiplied signal components resulting in a lack of covariance sensitivity to signals with constant amplitudes and phases. NTC is also insensitive to the signals with linear changes. For such signals NTC values are close to zero. NTC assumes higher values for signals with nonlinear changes.
Existing methods based on measurements of small diagnostic components of the current spectrum have posed problems with the measurements of the amplitude in the presence of the other component. The NTC method avoids this problem.

1.3 NTC

The proposed method of current signal processing is the NTC method described by equation (1).

$$\mathrm{NTC}(x, f_1, f_2, f_3) = \frac{\frac{1}{n}\sum_{i=1}^{n}\left(\left(X_i(f_1) - E\left(X(f_1)\right)\right) \cdot \left(X_i(f_2) - E\left(X(f_2)\right)\right) \cdot \overline{\left(X_i(f_3) - E\left(X(f_3)\right)\right)}\right)}{\sqrt{\sigma^2\left(X(f_1)\right) \cdot \sigma^2\left(X(f_2)\right) \cdot \sigma^2\left(X(f_3)\right)}} \tag{1}$$

where:
x – discreet time domain motor current signal,
n – number of time segments,
$X_i(f_1)$ – Fourier series coefficient from signal x for i-th time segment for frequency f_1,
$E\left(X(f_1)\right)$ – mean value of Fourier series coefficients for frequency f_1 in all time segments,
$\sigma^2\left(X(f_1)\right)$ – variance of Fourier series coefficients for frequency f_1 in all time segments.

The first step to calculate NTC is to cut the discreet time domain signal into segments. In this experiment authors used 10 s segments in order to get 0.1 Hz spectrum resolution. Tests were performed on 64 s three phase induction motor supply current signals with a sampling frequency of 65536 Hz. To get more time segments, cutting was done with a 60% overlap. The next step was to perform FFT with Blackman window for each time segment. Shaft rotation frequency f_r and supply grid frequency f_g was designated from obtained spectrum for each segment. Values of these frequencies are necessary to calculate the characteristic frequencies for bearing damage. The next step is to get complex amplitude values from spectra for three characteristic frequencies in each segment. The following step is to use (1) to calculate NTC. Last operation is to calculate mean value of NTC for three phases of motor current. Authors propose to use value achieved this way as a diagnostic symptom witch can be used for induction motor bearings diagnostic purpose.

1.4 Components Selection

For diagnostic of bearing damage in induction motors through MCSA, authors assumed 32 components. Previous research [7] showed, that these components, with frequencies listed in table 1, can be very useful for induction motors bearing diagnostics.

Table 1 Frequencies of Components

Component no.	Frequency of component
1.	$f_g + f_{def}$
2.	$\lvert f_g - f_{def} \rvert$
3.	$3 \cdot f_g + f_{def}$
4.	$\lvert 3 \cdot f_g - f_{def} \rvert$
5.	$5 \cdot f_g + f_{def}$
6.	$\lvert 5 \cdot f_g - f_{def} \rvert$
7.	$\lvert f_g - f_r + f_{def} \rvert$
8.	$\lvert f_g - f_r - f_{def} \rvert$
9.	$f_g + f_r + f_{def}$
10.	$\lvert f_g + f_r - f_{def} \rvert$
11.	$\lvert f_g - 2 \cdot f_r + f_{def} \rvert$
12.	$\lvert f_g - 2 \cdot f_r - f_{def} \rvert$
13.	$f_g + 2 \cdot f_r + f_{def}$
14.	$\lvert f_g + 2 \cdot f_r - f_{def} \rvert$
15.	$\lvert f_g - 3 \cdot f_r \rvert + f_{def}$
16.	$\lvert \lvert f_g - 3 \cdot f_r \rvert - f_{def} \rvert$
17.	$f_g + 3 \cdot f_r + f_{def}$
18.	$\lvert f_g + 3 \cdot f_r - f_{def} \rvert$
19.	$\lvert 3 \cdot f_g - f_r + f_{def} \rvert$
20.	$\lvert 3 \cdot f_g - f_r - f_{def} \rvert$
21.	$3 \cdot f_g + f_r + f_{def}$
22.	$\lvert 3 \cdot f_g + f_r - f_{def} \rvert$
23.	$\lvert 3 \cdot f_g - 2 \cdot f_r + f_{def} \rvert$
24.	$\lvert 3 \cdot f_g - 2 \cdot f_r - f_{def} \rvert$
25.	$3 \cdot f_g + 2 \cdot f_r + f_{def}$
26.	$\lvert 3 \cdot f_g + 2 \cdot f_r - f_{def} \rvert$
27.	$\lvert 5 \cdot f_g - f_r + f_{def} \rvert$
28.	$\lvert 5 \cdot f_g - f_r - f_{def} \rvert$
29.	$5 \cdot f_g + f_r + f_{def}$
30.	$\lvert 5 \cdot f_g + f_r - f_{def} \rvert$
31.	$\lvert 5 \cdot f_g - 2 \cdot f_r + f_{def} \rvert$
32.	$\lvert 5 \cdot f_g - 2 \cdot f_r - f_{def} \rvert$

where:

f_g – frequency of supply grid,

f_r – frequency of shaft rotation,

f_{def} – frequency of bearing defect.

Previous studies did not permit to determine which of the components are the most susceptible to bearings damage. The solution requires only three components, because their choice is particularly important from the point of view of the separation between the damaged and undamaged cases. Therefore, to select a set of three components to calculate the NTC an appropriate procedure has been prepared based on the Fisher criterion described by the following formula:

$$F = \frac{|m_1 - m_2|^2}{\sigma_1^2 + \sigma_2^2} \tag{2}$$

where:
m_1– mean value of NTC for undamaged cases,
m_2– mean value of NTC for damaged cases,
σ_1^2– NTC variance for undamaged cases,
σ_2^2– NTC variance for damaged cases.

To determine the set of components, which will be the most efficient for use with a triple covariance matrix, the following steps have been undertaken: NTC for all possible combinations of 3 out of 32 of all components participating in the damaged and undamaged bearings experiment have been calculated. Then, out of all the damaged and undamaged bearings a random portion of bearings has been selected, which will be used to choose a diagnostic feature (DF). For this purpose, for a set of bearings the value of Fisher criterion (2) has been calculated for all possible 14880 combinations. In the next step, from 14880 combinations 5 combinations were selected for which the criterion value was the highest. The sum of these five covariance combination serves as a diagnostic feature (DF) to assess the state of bearings, which have not been selected for the component selection.

2. Achieved Results

All presented results, including measurements used for components selection are based on IM current supply measurements in conditions of 60% load (about 0,7kW). IM used for the tests has the following parameters: P_n=1,1 kW, U_n=400 V, n_n=1380 RPM, I_n=2,9 A. The motor was supplied directly from 50 Hz three phase supply grid, with Un= 400 V. The bearings installed in the motor were type 6204.

In the course of this work, a number of research was carried out on damaged and undamaged bearings. At the same time as the IM current was measured, another measurement was performed in each case with the DREAM vibration diagnostic system. Results for bearings outer race (depth of damage) obtained from this system are listed in table 2.

Table 2 List of Bearings Used for Experiment

Bearing number	Introduced damage	DREAM result for outer race
1.	pit damage diameter=1.0 mm and depth=0.5 mm	21%
2.	pit damage diameter=1.5 mm and depth=0.7 mm	17%
3.	pit damage diameter=2.0 mm and depth=1.0 mm	80%
4.	scratch along the rolling direction length=3 mm, depth=0.5 mm, width=1 mm.	31%
5.	scratch along the rolling direction length=3 mm, depth=0.7 mm, width=1 mm.	36%
6.	scratch along the rolling direction length=3 mm, depth=1 mm, width=1 mm.	80%
7.	scratch along the rolling direction length=6 mm, depth=0.7 mm, width=1 mm.	52%
8.	scratch across the rolling direction length=3 mm, depth=0.5 mm, width=1 mm.	68%
9.	scratch across the rolling direction length=3 mm, depth=0.7 mm, width=1 mm.	80%
10.	scratch across the rolling direction length=3 mm, depth=1 mm, width=1 mm.	80%
11. to 42.	bearings with not damaged outer race	0%

All introduced defects are outer race damage. Therefore outer race frequency [8] was used as a f_{def} in all presented cases. Presented experiment was performed on 10 damaged bearings and 32 undamaged bearings. In this paper procedure of components selection (described in paragraph 1.4) was performed three times for three random sets of bearings. Each set contains data for 5 out of 10 damaged bearings and 16 out of 32 undamaged bearings. Results of this operation are presented on graphs Fig 2 – Fig 4. Each graph presents the value of diagnostic feature (DF) for all bearings. Above each graph there are information about set of bearings witch took a part in procedure of components selection for that particular graph. Information which diagnostic indicator was selected in the selection of components for a given set of bearings located in the description of the y-axis, for example, where the NTC (4,24,27) is the NTC calculated for the frequency of the number 4, 24 and 27 according to table 1.

On the presented graphs, ‘X’ stands for bearings with introduced damages and ‘O’ stands for undamaged bearings. The horizontal solid line can be used as a border between healthy and unhealthy cases.

Damaged [2 4 5 6 8]   Not damaged [11 12 13 14 15 16 18 20 21 22 23 28 30 32 34 36]

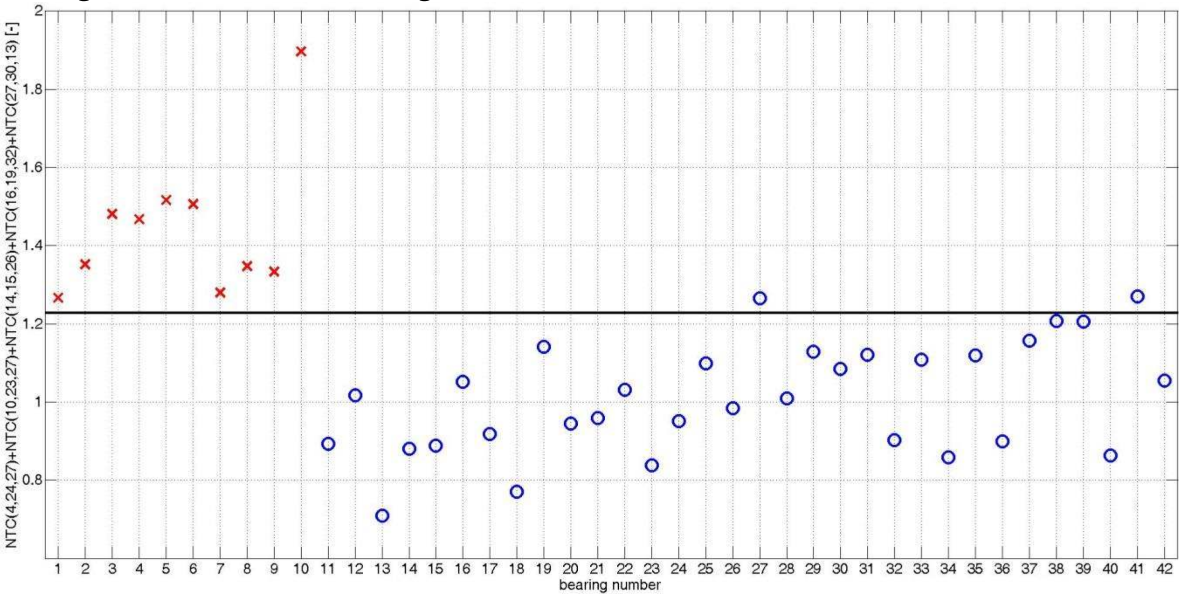

Fig. 2. Diagnostic feature (DF) for set 1.

Damaged [2 5 8 9 10] Not damaged [12 13 15 17 18 21 22 23 25 32 33 35 36 37 38 41]

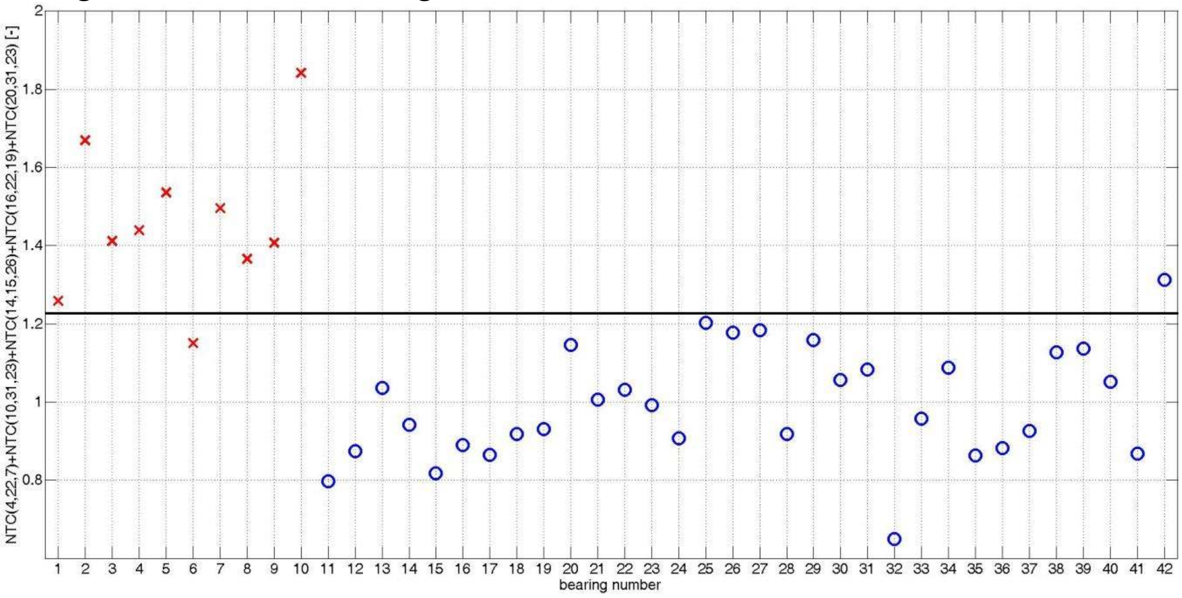

Fig. 3. Diagnostic feature (DF) for set 2.

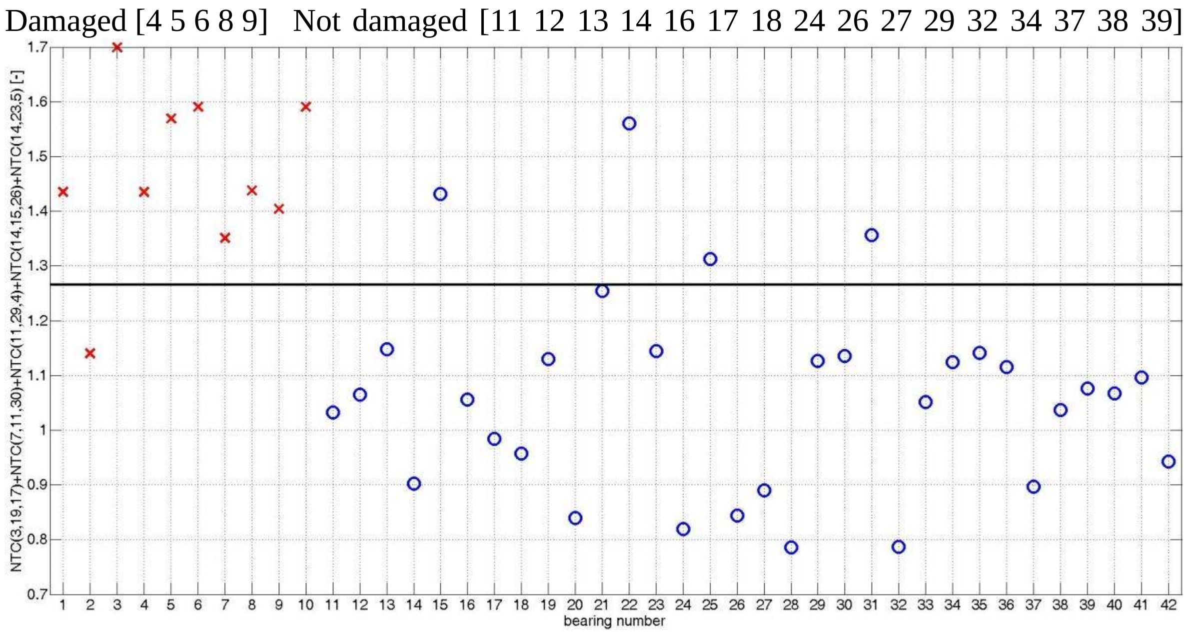

Fig. 4. Diagnostic feature (DF) for set 3

3. Summary

The efficiency of obtained diagnostic feature in shown investigation results was 90% for set 1, 90% for set 2 and 76% for set 3. Diagnostic efficiency was calculated only for data which was not used for components selection. Fisher criterion for all data presented in figure 1 is F1=3,4964. Fisher criterion for all data presented in figure 2 is F2=3,6442. Fisher criterion for all data presented in figure 3 is F3=2,7448.

Preliminary results of diagnosis of bearings obtained by the NTC method show promise. The resulting probability of accurate diagnosis of 90% does not differ from the values achieved with methods of vibration. Further research on the detection of other damage than the outer ring will allow for assessment of the universality of the proposed method.

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