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A concept of context-based inference in technical diagnostics

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At present, inference about technical state of machinery or industrial processes on the basis of analysis of residual signals is one of the most developed fields of technical diagnostics. Results of analysis are usually huge sets of signal features, whose changes carry information about technical state of an object. Correct interpretation of such results is the most important problem of technical diagnostics. It is particularly important in the case of complex machinery and processes, whose operation parameters vary in time and additionally the environment of investigated objects, can not be assumed to be unchangeable. The approach described in the paper was based on the assumption that signal features can be presented in the form of a dynamic scene. Changes in the scene are determined by means of simple methods of image processing. The background of diagnostic inference is context-based reasoning (CxBR).

1. INTRODUCTION

The analysis of signals and interpretation of results of the analysis is the basis of numerous applications, also these ones that are not related to technical problems. Examples of signals are sounds, speech, music but also noise and vibrations, which are usually considered to be residual signals. At present, inference about technical state of machinery or industrial processes, on the basis of the analysis of residual signals, is one of the most developed fields of technical diagnostics [1, 2]. An advantage of such an approach is that research can be performed during ordinary operation of machinery or a process.

Diagnostic procedures consist in observation of residual signals and their analysis. Results of analysis are usually huge sets of signal features. Changes of these features carry information about a technical state of an object. Correct detection of these changes is considered to be the most important problem of technical diagnostics. It is particularly important in the case of complex machinery and processes, whose operation parameters vary in time and additionally the environment cannot be assumed to be unchangeable. Residual signals observed in such conditions are always non-stationary. Because of that, special methods of analysis are required to be applied and obtained results are usually very difficult to interpret.

Nowadays, the analysis of described signals is mostly based on time-frequency methods. The estimation of changes of signal features is performed mainly visually, what is very often complicated. A reason is that changes of signal features carry information not only about a technical state of an object, but also about its environment and other factors.

The research conducted until now has shown that within determined periods of object observation only a part of signal features provides useful information, whereas others can be omitted [10–14]. Basing on that, within the huge sets of signal features one can distinguish leading, supporting and irrelevant features, and also these features that can be treated as a noise. It suggests the analogy of the way of analyzing diagnostic signals to interpretation of a scene [3, 10–13].

It was assumed that results of described research, in the form of results of signal analysis, are presented in the form of a dynamic scene that is a sequence of ordered single scenes corresponding to consecutive periods of machinery or process observation. Objects of the scene are features of diagnostic signals. In the case of the part of research described in the paper, the objects are mainly signal features extracted from time-frequency characteristics. In order to find signal changes in scenes, whose objects are these signal features, the scenes can be compared between themselves. Another approach is to consider a scene with taking into account different viewpoints. It is important that in the case of described research a scene is always more than three-dimensional. Considering this, it should be stressed that in this case not only simple viewpoints are required to be taken into account but also scene intersections. Backgrounds of the proposed solution to discussed research problems are inference methods based on contexts. An example of such the approach is context-based reasoning (CxBR) [4–6].

The main aim of the research is to develop a method of automatic or semi-automatic diagnosing machinery and industrial processes. The method is based on the application of context-based reasoning and dynamic scene analysis. It is expected that this approach can improve realization of diagnostic procedures aimed at complex objects, particularly these ones that operate in varying conditions.

Procedures of data processing were based on methods of image processing, analysis and recognition [7–9, 11–14]. The application of simple image processing based on convolution methods and description of images by means of an alphabet based on semantic descroptions seems to be particularly important and interesting. The applications of these methods makes it possible to automatize interpretation of plots of signal features. Further stages of the method being developed can also lead to automatic image understanding. An example of such the approach is described in [9]. The authors undertook a task of automatic inference on the base of medical images.

2. DYNAMIC SCENE AND A CONCEPT OF ITS ANALYSIS

Diagnostic observation of a machine is usually performed by means of different signals. They are usually non-stationary and can be analysed with the use of different methods that give as a result a huge set of signal features. They differ in types and formats. Exemplary, one can distinguish between two- and three-dimensional features as well as between features estimated in time or frequency domains. Their direct comparison is impossible. Concerning the approach briefly presented in the introduction, the analysis and interpretation of signal features can be based on the analogy to objects observed and recognized in a scene. In the considered case, scene objects are courses of features of diagnostic signals. Since usually conditions of operation of an object and also values of non-stationary signals vary in time one can state that considered scene is dynamic.

In the wide sense, a dynamic scene is understood to be a set of objects, whose features and properties, such as placement, colour and size are time functions [3]. One can assume that the dynamic scene is a result of observation of a machine or industrial process and signal analysis. Examples of such the scene can be sets of following objects: courses of mean or mean root square values, spectra and features estimated with the use of time-frequency characteristics. As it was mentioned above, enumerated features can be not only results of operation of a machine but also different other factors that influence on the observed object. It must be stressed that such the scenes have to be considered as multi-dimensional ones. An idea of the application of a dynamic scene in a process of interpretation of results of analysis of diagnostic signals was presented in [10–13].

A method of the analysis and interpretation of the scene was based on the analogy to a scene in the wide sense [3]. In that case, scene objects are observed, recognized and considered with the use of different criteria. An example of such interpretation is distinguishing between leading and supporting objects. Similarly, one can consider objects with taking into account motion criterion or divide objects into groups related to background or interference. Summing up, it is possible to state that this interpretation is a kind of object classification. Criteria of this classification are determined by a way of interpretation of scene objects. Such an approach lets us identify a change of technical state of a machine. The set of criteria constitutes a given context. The application of contextual interpretation of dynamic scenes makes it possible to analyse the scene with the use of a given, small part of knowledge, which is related to a given context.

A context is understood to be the words around a word, phrase, statement, etc. often used to help explain (fix) the meaning, or the general conditions (circumstances) in which an event, action, etc. takes place. In the case of observed research it is a set of a part of data and information, which are included within a dynamic scene and are related to a given sequence of events. According to some assumptions made during realization of the research, contexts correspond to scene intersections and viewpoints. Considered parts of information will be related either to machinery subassemblies, determined operation conditions or determined states of a process.

A simple example of context-based observation and interpretation of a scene was presented in Fig. 1. Scene observers are indicated by O1 and O2. The observers look at the same scene but they are able to recognize objects from different viewpoints. The viewpoints determine contexts of scene interpretation. The example presented in Fig. 1 shows that descriptions of a scene given by two independent observers differ between them. The difference is caused since observers use different numbers of parameters, and generally different grammars in order to describe the same scene. Sets of parameters required to describe a single viewpoint is an alphabet, which is determined for a single observer. Exemplary description determined by two alphabets used by O1 and O2 can be defined as follows: $P1 = r, l$, $P2 = r, c, l$. It means that O1 is able to see balls in two cells (right and left), whereas O2 is able to recognize three placements of a ball (right, left and central).

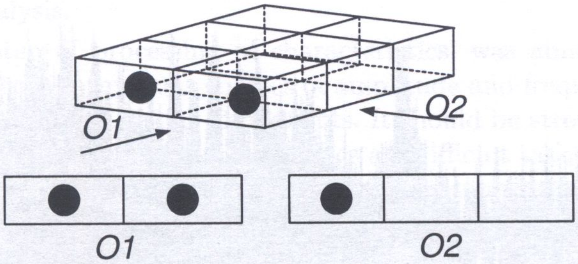

Fig. 1. An example of a context-based scene observation [4]

Sets of parameters that constitute the alphabet are required to be defined for each observer separately, thus for each context. The grammar determines a way of description of observations made by consecutive observers. According to the assumptions a context is exemplary considered to be a sequence of events characterized by changes occurring in object neighbourhood, changes of operation conditions or given process parameters. The main idea of such a solution is that in reasoning process only a small part of information is necessary to be processed. The presented example of a context definition seems to be very easy. However, in the case of real and complex scenes its determination becomes more problematic.

Review of bibliography [4, 5] lets us state that defining a context is a difficult task. There are no guidelines indicating a common solution. In the case of presented problems, the definition of a context should make it possible to select these parts of data, which are essential according to specific diagnostic tasks. Moreover, the possibility of automatic activation of proper contexts and procedures of signal analysis and interpretation of analysis results is also very important. A change of the context can influence the contents of a dynamic scene, and additionally it can control kinds and numbers of observed diagnostic signals.

Determination of viewpoints and intersections of a scene depends on undertaken problems and scene complexity. Contexts related to a multi-dimensional scene, discussed in the paper, are problematic tasks. This kind of observation and inference is based on an assumption described in [5]. Apart from that one can also enumerate variety of papers devoted to this problem [4–6].

Procedures of data processing and transformation, used during realization of described research, were based on image processing, analysis and recognition, especially the methods based on syntactic image descriptions [11–14]. Consecutive stages of analysis and interpretation of a dynamic scene, whose objects are results of analysis of diagnostic signals, are presented and explained in the next paragraphs of the paper.

3. AN EXAMPLE OF SIGNAL ANALYSIS AND EXTRACTION OF SIGNAL FEATURES

The research described in the paper was based on multi-dimensional observations of a machine and a set of laboratory signals. Signals observed and recorded within the framework of discussed investigations are always non-stationary vibrations or signals generated on the basis of mathematical models of signals recorded during operation of rotating machinery. They can be analyzed by means of numerous methods. However, in the case of non-stationary data the best solution is to apply time-frequency representation. Examples of such methods are Short Time Fourier Transform (STFT) and Wavelet Transform (WT). The most important is that they results, in the form of time-frequency characteristics, provide us with large sets of information. They make it possible to identify changes both in time and frequency domains. As it was discussed in the introduction, the interpretation of such characteristics is difficult. An example presented in further parts of the paper is based on the analysis of signals recorded during operation of turbogenerator (Fig. 2).

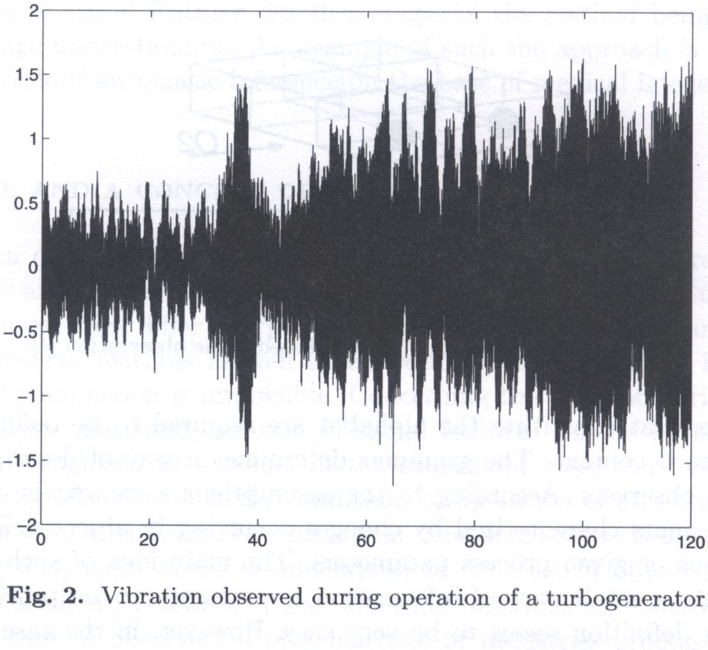

Fig. 2. Vibration observed during operation of a turbogenerator

Interpretation of results of signal analysis, and first of all identification of changes, as well as correct identification of reasons of these changes are main problems of technical diagnostics. It should be emphasized that signal changes can be caused not only by phenomena taking place in the neighbourhood of the observed object, but also they can be effects of the object operation. At the same time, these changes can result from varying conditions of the object operation, influence of other objects and also in the case of a complex machine by malfunctions or faults characteristic for its subassemblies (e.g. gearboxes, couplings or bearings) or parts of other processes. Identification of these malfunctions and their reasons is often difficult. Signal analysis applied during realization of the research was based on STFT. Its results coulor time-frequency characteristics. A dynamic scene described in the paper contains the objects, which represent features extracted from these characteristics.

Transformation of characteristics into the form of scene objects was performed by means of simple methods of image processing. The first step was related to conversion of colour characteristics into the form of black and white images. An example of such the image corresponding to time-frequency characteristics, estimated for the signal presented in Fig. 2, was presented in Fig. 3. There are several identified components in the characteristics.

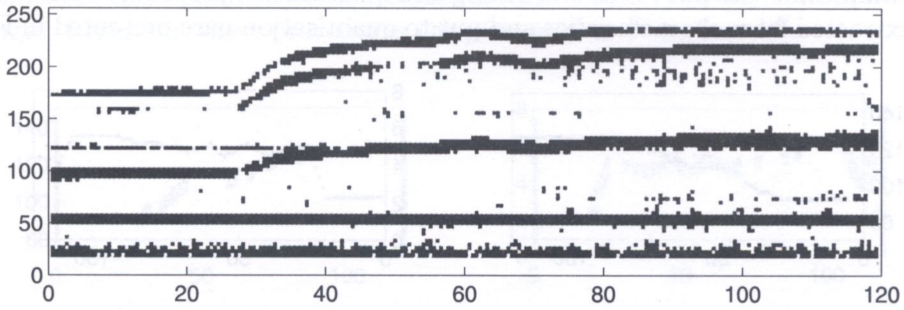

Fig. 3. Black and white image corresponding to colour time-frequency characteristic

Transformation of colour characteristics into the image (Fig. 3) was based on thresholding. Values below a determined threshold were not taken into account and were replaced by the white colour. Values above the threshold were shown in the image as black pixels. Taking into account the general aim of the elaborated method this approach seems to be acceptable and does not influence further interpretation of signal analysis.

A goal of the second step of processing of characteristics, was aimed at extraction of signal features. As results of this transformations courses of amplitude and frequency were obtained. They correspond to consecutive identified signal components. It should be stressed that determination of discussed intersections of time-frequency characteristics are difficult tasks. It is particularly difficult when characteristics is a set of a large number of signal components visible in time-frequency characteristics as crossing lines. It must be stressed that algorithms applied at this stage of signal analysis are main reason of mistakes made during formulating a diagnose.

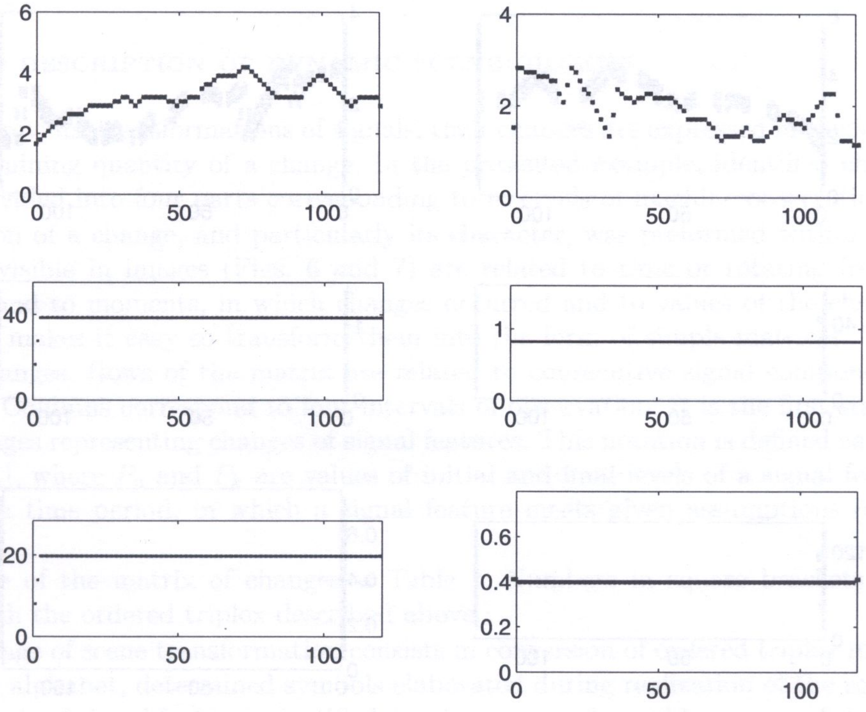

Fig. 4. Components (1–3) identified on the basis of the scalogram from Fig. 4

As it was mentioned above, the basis of determination of the technical state of an object is identification of changes of features of diagnostic signals. Taking into account that temporary fluctuations of these values are not important in the case of discussed diagnostic procedures, courses of frequency and amplitude, are put to the smoothing and quantisation procedures. Six identified signal components, extracted from characteristics and put to quantisation pare presented in Figs. 4 and 5.

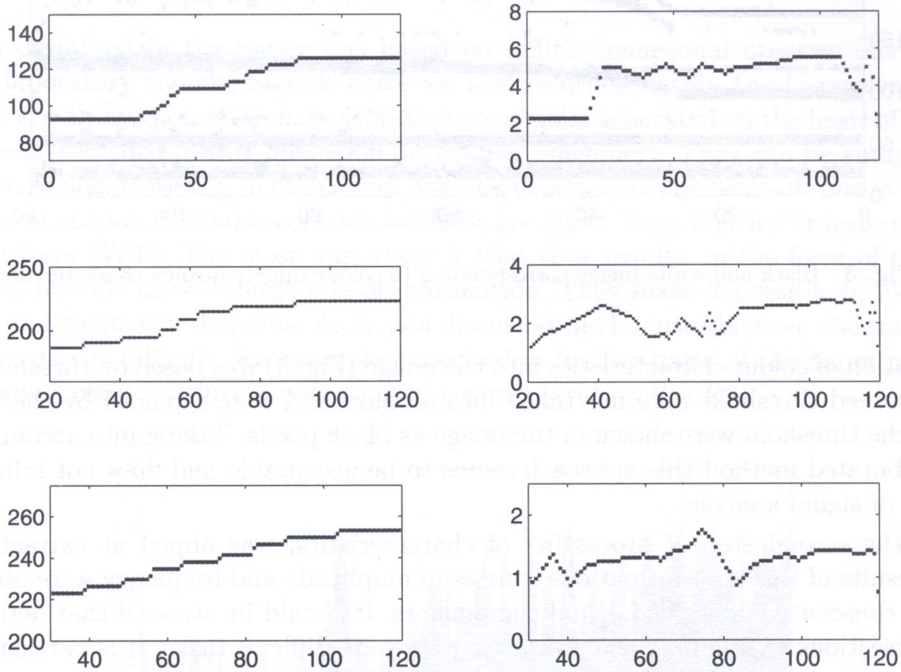

Fig. 5. Components (4–6) identified on the basis of the scalogram from Fig. 4

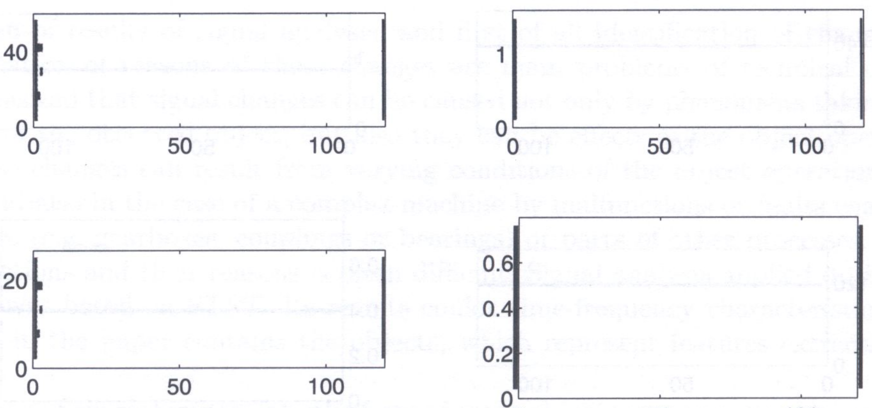

Fig. 6. Identified changes of components 1–3

At the next stage of the research, these courses, can be analysed by means of simple methods of image processing [7, 1, 13]. They are based on convolution of an image with small matrix represent changes. As an effect of the application of these methods, changes are represented as single points in images. Placement of these points determines time moments and frequency values, which correspond to these changes. Results of these procedures are presented in Figs. 6 and 7.

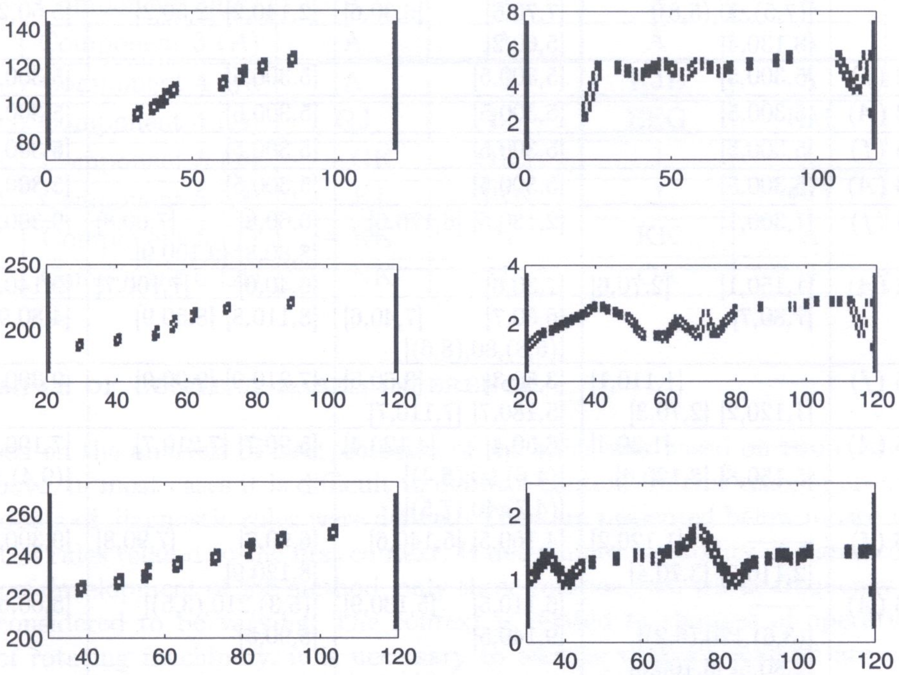

Fig. 7. Identified changes of components 4–6

4. SYMBOLIC DESCRIPTION OF DYNAMIC SCENE OBJECTS

According to previous transformations of signals, their changes are expressed in the form of numbers of levels determining quantity of a change. In the presented example, identified changes of signal features are divided into four parts corresponding to intervals of machine observation.

Identification of a change, and particularly its character, was preformed within these intervals. Single points visible in images (Figs. 6 and 7) are related to time or rotating frequency values, which correspond to moments, in which changes occurred and to values of the change. Described representation makes it easy to transform them into the form of simple matrices. They are called matrices of changes. Rows of the matrix are related to consecutive signal components, which are scene objects. Columns correspond to four intervals of observation. It is the first stage of syntactic analysis of images representing changes of signal features. This notation is defined as ordered triplex $z_n = [P_p, T, P_k]$, where P_p and P_k are values of initial and final levels of a signal feature, and T is the length of a time period, in which a signal feature meets given assumptions (e.g. increase or decrease).

An example of the matrix of changes is Table 1. Numbers in square brackets are written in accordance with the ordered triplex described above.

The next stage of scene transformation consists in conversion of ordered triplex into sequences of symbols of the alphabet, determined symbols elaborated during realization of the research (Fig. 8). Changes of values of signal features identified previously transformed by means of the alphabet were presented in Table 2. This transformation makes it possible to identify a character of the change.

Table 1. Matrix of changes

	Interval 1	Interval 2	Interval 3	Interval 4
Component 1 (f)	[1,120,4] [5,80,5] [6,100,7]	[7,130,7] [(7,5),110,(5,7)] [7,60,8]	[8,100,9] [9,50,9] [9,90,5] [5,60,5]	[5,60,8] [8,60,8] [8,80,5] [5,100,5]
Component 1 (A)	[8,110,7] [(7,5),60,(5,8)] [8,130,4]	[(4,2),40,(2,7)] [7,70,6] [6,30,6] [5,60,2]	[3,40,3] [4,70,2] [2,140,2] [2,50,2]	[4,120,3] [4,90,6] [5,50,2] [2,40,1]
Component 2 (f)	[5,300,5]	[5,300,5]	[5,300,5]	[5,300,5]
Component 2 (A)	[5,300,5]	[5,300,5]	[5,300,5]	[5,300,5]
Component 3 (f)	[5,300,5]	[5,300,5]	[5,300,5]	[5,300,5]
Component 3 (A)	[5,300,5]	[5,300,5]	[5,300,5]	[5,300,5]
Component 4 (f)	[1,300,1]	[2,130,5] [6,170,6]	[6,60,8] [7,60,8] [8,80,8] [9,100,9]	[9,300,9]
Component 4 (A)	[1,150,1] [2,70,6] [7,80,7]	[7,30,6] [6,50,7] [7,40,6] [(5,8),80,(8,6)]	[6,40,6] [7,100,7] [8,110,8] [8,50,9]	[9,140,9] [9,80,4] [4,80,9]
Component 5 (f)	—— [1,110,1] [1,120,2] [2,70,3]	[3,50,3] [3,60,5] [5,180,7] [7,110,7]	[7,210,9] [9,90,9]	[9,300,9]
Component 5 (A)	—— [1,30,4] [5,150,8] [8,120,6]	[6,50,4] [4,120,4] [(4,6),90,(6,4)] [(4,7),40,(7,5)]	[5,90,7] [7,210,7]	[7,190,9] [(9,4),110,(4,9)]
Component 6 (f)	—— [1,120,2] [2,110,3] [3,70,4]	[4,160,5] [5,140,6]	[6,90,7] [7,90,8] [8,120,9]	[9,300,9]
Component 6 (A)	—— [(3,6),120,(6,2)] [2,80,5] [5,100,6]	[6,110,5] [5,130,9] [9,140,5]	[(5,3),210,(3,5)] [5,90,5]	[5,60,6] [6,240,6]

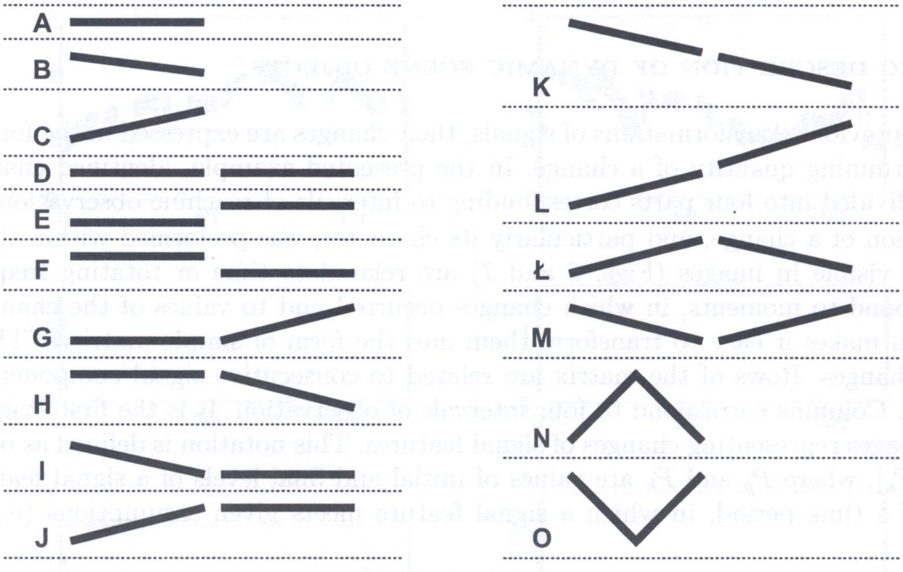

Fig. 8. The alphabet

Sequences of symbols (Table 2) are basis of inference on a technical state of the object with the use of contexts.

Table 2. Description of signal changes by means of the alphabet

	Interval 1	Interval 2	Interval 3	Interval 4
Component 1 (f)	JG	AOB	JMI	JMI
Component 1 (A)	BOC	NJM	HJD	MML
Component 2 (f)	A	A	A	A
Component 2 (A)	A	A	A	A
Component 3 (A)	A	A	A	A
Component 4 (f)	A	J	KJE	A
Component 4 (A)	GJ	ŁŁ	EEG	HM
Component 5 (f)	— GK	GKJ	J	A
Component 5 (A)	— KŁ	JNN	J	BO
Component 6 (f)	— KK	K	KK	A
Component 6 (A)	— NK	MŁ	OA	J

5. AN EXAMPLE OF CONTEXT-BASED INFERENCE

Inference based on the analysis of interpretation of the scene was based on two contexts. As it was mentioned above, in most cases it is difficult to define a context. In this case, in order to describe a context, some sets of diagnostic rules were defined. They are presented below in two tables. Table 3 contains a set of rules related to the first context. It determines variability of signal components. At present stage of development of the method, only these components, whose frequency values change in time are considered to be varying. The context is related to changes of operation conditions. In the case of rotating machinery, it is necessary to assume that all changes are compared with rotating frequency.

Table 3. Context I – a set of rules – variability determination

	$kX(f)$	$kX(A)$
Feature value varying time	increase	increase
	decrease	decrease
	increase	constant
	decrease	constant
Feature value constant in time	constant	constant
	constant	constant
	increase	decrease

Table 4 contains a set of rules corresponding to identification of symptoms, which constitutes the second context. On the basis of this table one can identify four typical malfunctions and phenomena taking place during machinery operation. Taking into account further development of the method, the second context is required to be divided into more detailed cases of malfunctions. It should be stressed that at present stage of the research these two contexts are comparatively simple to define.

Results of application of context-based scene analysis are shown in Table 5. Diagnoses are established within consecutive intervals.

Symbols used in Table 5 are not a part of the alphabet (Fig. 8). They are abbreviations used only for the needs of the paper. "C" means that a given component within an interval is recognized to be constant, whereas "V" is related to components that vary in time. An indicator "U" entails that an identified component in determined intervals is recognized as a symptom of unbalance. "Bk" indicates that an identified component is not related to rotating frequency. At present, these components are

Table 4. Context II – a set of rules – symptom identification

	$1X(f)$	$1X(A)$	$kX(f)$	$kX(A)$
Object operation	const	increase	increase	increase
	const	increase	const	fluctuation
	const	increase	increase	increase
	const	increase	const	fluctuation
Backgrounds	other examples			

considered to be unrecognizable phenomena or faults, which are treated as background. They can be effects of phenomena occurring in neghbourhood of a machine. "O" entails that frequency of a component is proportional to frequency of the component connected with unbalance. Previous research and comparison of their results with results of the application of other methods let us state that there are some mistakes in Table 5. It should be stressed that they are mainly caused by imperfections of algorithms of extraction of signal components on the basis of time-frequency characteristics.

Table 5. Results of diagnostic inference with the use of two contexts

	Interval 1	Interval 2	Interval 3	Interval 4
Component 1	V	V	V	V
	Bk	Bk	Bk	Bk
Component 2	C	C	C	C
	Bk	Bk	Bk	Bk
Component 3	C	C	C	C
	Bk	Bk	Bk	Bk
Component 4	C	V	V	C
	U	U	U	U
Component 5	V	V	V	C
	Bk	O	O	O
Component 6	V	V	V	C
	Bk	O	Bk	O

6. CONCLUSIONS AND FURTHER REMARKS

The approach to diagnostic tasks dealing with the application of a dynamic scene and its context-based analysis makes it possible to aid their realization. The possibility of the application of very simple methods of image processing, analysis and recognition, seems to be one of the main advantages of this concept. However, experience gained during previous and presented research makes it also possible to formulate some critical conclusions. Since the size of interpreted data sets is very large, during realization of the research it became obvious that some assumptions have to be done about that which parts of provided information should be related to given contexts. Moreover, detailed analysis of this problem lets us also state that even better solution would be to influence on scene contents and on that which signals should be observed and which signal analysis should be employed. It would require to return to stages of signal observation and analysis. The object state, which is determined as unusable, does not demand the application of any advanced methods during object diagnosing. This part of the research is strictly related to a definition of new contexts. It is also planned that methods of signal analysis with the use of time-frequency methods (STFT and WT) to be broaden by joint signal analysis and higher order analysis. During the research, a number of algorithms of estimation of features on the basis of time-frequency characteristics were elaborated and applied. Their description was omitted in the paper. Obtained results proved that applied procedures required to be improved since correct identification of signal components influences further scene analysis and interpretation.

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