DOPPLER’S EFFECT AS DIAGNOSTIC INFORMATION IN THE ACOUSTIC SIGNAL

Jacek DYBAŁA, Szymon GONTARZ, Stanisław RADKOWSKI
Instytut Podstaw Budowy Maszyn
Politechnika Warszawska
02-524 Warszawa, ul. Narbutta 84, tel. +48 22 660 82 76
e-mail: jdybala@simr.pw.edu.pl; sgontarz@simr.pw.edu.pl; ras@simr.pw.edu.pl

Summary

The paper presents a new concept of a diagnostic system supported by a model as well as relevant, for this concept, possibility of analyzing the acoustic signals coming from a moving vehicle and registered by a byside diagnostic station.

Keywords: modelling, result of Doppler Effect, resampling, beat effect, histeresis.

EFEKT DOPPLERA JAKO ŹRÓDŁO INFORMACJI DIAGNOSTYCZNEJ W SYGNALE AKUSTYCZNYM

Streszczenie

W pracy przedstawiono nową koncepcję systemu diagnostycznemu wspartego modelowo oraz odpowiednią dla tej koncepcji możliwość analizy sygnału akustycznego pochodzącej od poruszającego się pojazdu a rejestrowanego przez przytorową stację diagnostyczną.

Słowa kluczowe: modelowanie, efekt zjawiska Dopplera, przepróbkowania, zjawisko dudnienia, histereza.

1. INTRODUCTION

Operation of technical objects is associated with occurrence of numerous physical phenomena caused by the operation of the object itself as well as by the environment in which a given object operates. The result of these interactions is the degradation of individual parts of devices, which leads to subsequent states of wear and tear until destruction. While being guided by these simple relations one applies, in a planned manner, Preventive Maintenance which consists of regular inspections and replacement of the parts which are subject to wear. As has been proven by research, such an approach leads to a situation where e.g. 34% of rolling bearings are dismantled too early. This simple analysis fails to account for failures or accelerated wear and tear caused by overload during the machines operation, its improper use or occurrence of extreme environmental impact, leading to accelerated wear or even sudden failure. The reasons of all these undesirable effects is the lack of assessment of the actual technical condition, which is indispensable especially in those cases when the technical object may have influence on human health or life. The constant awareness increases the importance of technical diagnosis while driving the development of Condition Based Maintenance. Numerous activities and analyses, both of the object and the signal received from it, must be performed in order to enable such an analysis. In order to carry out the analysis of operation of a system capable of such an evaluation, one first needs to collect the information on the object with the use of sensors (receptors). We obtain a certain signal which is a function in time of some physical quantity. Such information must then be processed into a set of features (parameters, symptoms) whose values serve as the basis for describing the condition of diagnosed objects. Then one still needs to define the relationships between the condition of the objects and the diagnostic parameters, that is the classification rules. From mathematical point of view it is mapping of the space of parameters to the space of states. Based on the supplied diagnostic parameters the classifier determines the class to which the examined object belongs. Due to certain arbitrary nature of the response of the classification system, this response is called the decision [1]. However for such a diagnostic system to operate one needs to solve a serious problem, that is extraction and selection of relevant diagnostic parameters which would be useful enough so as to enable performance of the diagnosis of an object’s condition on their basis. The awareness of the problem of the need for constructing comprehensive diagnostic systems leads to the emergence of more and more advanced concepts. Despite this, unforeseen, tragic catastrophes continue to happen:

Catastrophes of machines:

- 1988, Aloha, B-737, multi-site damage, one casualty;
- 3.06.1998, derailing of a train in Eschede, 101 dead, 300 injured.

Catastrophes related to construction structures:

- 14.02.2004, Transvaal swimming pool with glass, concrete and metal dome, 28 dead, 110 injued;
- 17.03.2005, collapse of the roof in Leroy-Merlin hypermarket in Gdańsk;
- 28.01.2006, collapse of the roof of Katowice International Trade Fair building, 65 dead, 170 injured.

As we can see catastrophes happened both in the past and nowadays when technical diagnosis is much more advanced. Thus there is need for continuous development of this field, mainly to ensure safety of use of technical objects/facilities by people. The goals also include achievement of the following economic benefits:

- Increasing the reliability, security and readiness of machines;
- Reducing the cost of maintaining the fleet of machines, improvement of material management by tapping on the material reserves, reducing failures, downtimes and loss;
- Improvement of electrical power management, reducing the strain on the natural environment by reducing the emission of harmful materials as well reducing the generation of vibration and noise.

Below please find one of the concepts of the structure and functioning of a diagnostic system which could serve our purpose while monitoring any technical object throughout its operating life.

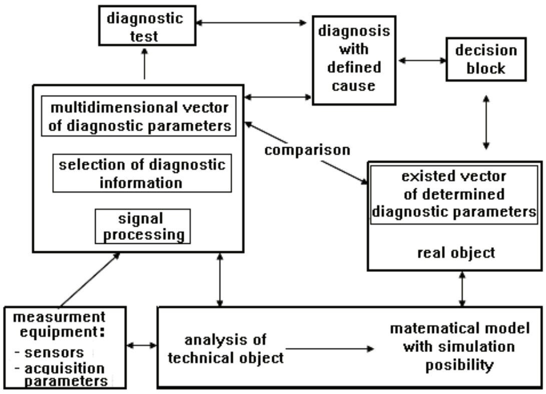


Fig. 1. State-of-the-art concept of the diagnostic system for any technical object.

The main difference when comparing to the structure and principles of operation of a classical diagnostic system involves introduction and use of a mathematical-and-physical model of the examined object during the entire diagnosis. Based on the analysis of the technical object and the physical phenomena associated with it, we create the preliminary structure of the diagnostic system. The functions of designated physical values are subjected to processing. The diagnostic information is subject to selection and comparison to the simulations in mathematical-and-physical model. During the entire period of object monitoring, the multi-dimensional vector of diagnostic parameters is compared against the actual parameters of the device, the vector of specific parameters, and it is also tested when new, earlier unknown conditions and behavior appear. The diagnosis, along with justification, is proposed and then a decision is made as regards the use of the object. All the information on the operation of the system is stored and thanks to this, as new events occur, the knowledge about diagnosis of an object or a certain groups of objects, which is fully contained in the mathematical model, is enriched and strives towards full learning of the occurring phenomena and the associated threats.

2. ANALYSIS AND PROCESSING

Even in the case of the most sophisticated diagnostic system, the evaluation of the technical condition on the basis of the signal reflecting the change of certain physical quantities generated by the object is generally not an easy task. This is so mainly due to the fact that the diagnostic information contained in the signal can have varied form (vibroacoustic signal contains not only the information on the dynamic forces associated with the object but also the information on the condition of structure which intermediates in carrying the signal from the source to the measuring point) while the richness of the information carried is an obstacle to its direct use and to making the comparison with the calculated multi-dimensional vector of diagnostic parameters which result from the mathematical-and-physical model of the object. For such an assumed comparison to make sense, one needs to account for the differences between the actual and the model processes which never fully reflect the reality. Transfer between the "two worlds" is realized through advanced methods of signal analysis and processing.

There are numerous techniques which process the signal to the form in which the diagnostic information is visible and close to the information assumed by the model in the extent which enables construction of the proper vector of diagnostic parameters. The present progress and advancement of technical objects as well as stringent requirements for diagnostic systems have enforced development and use of signal processing techniques which will be able to deal with complex systems of mixing and interaction of signals which make up the global run of physical quantities received by the receiver. As Fig. 2 presents, each subsequent source signal si(k), which represents a signal coming from various interworking parts of the machine, has its own propagation path and is disturbed by additive noise.

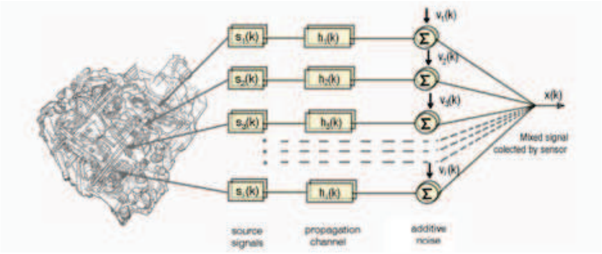


Fig. 2. Model of registration of a signal generated by a complex technical object [2].

Due to this a signal registered by a single sensor will be a composition of various sources and noises with various delays [2]. Let us consider a practical example when we want to separate a signal belonging to an operating bearing. In this case it is nearly always required that the real signal of the bearing is identified among the noise and vibration generated by other components which can be either in a good or bad technical condition. As long as all other components of the signal are so small that the bearing signal is dominant, the diagnostic parameters can be implemented without any fear. Otherwise this will lead to false values of calculated diagnostic parameters, which as a result will lead to false analysis. The presented issue is the main dilemma which has to be considered before we decide to apply a defined method of signal processing for a specific technical object.

To recapitulate, the task of detection of defects in technical objects, while relying on the analysis of the signal generated by the diagnosed object, entails the need for solving numerous problems. This in particular concerns the following issues [3, 4]:

- separation of the useful vibroacoustic signal from the noise;
- selection of relevant diagnostic parameters;
- formulation of diagnostic relations.

Analysis of the above issues calls for adopting a relevant mathematical-and-physical model of emergence of certain characteristic phenomena observed in the analyzed signal. Quick detection of model counterparts will enable avoidance of the situation when the advanced stage of a defect, which is detected late, offers not much time for taking corrective actions. Immediate repairs are necessary often and as a result the object has to be shut down regardless of the economic impact (the probability of the failure becomes too big). Early detection of the defect (in the initial stage of defect formation) allows for performing the repairs of the device in the most favorable moment from the point of view of minimization of losses and prevention of failure. If relevant methods are applied to analyze the registered processing of signals, then the detection of early stages of defect development by a diagnostic system becomes possible.

The form of the registered signal depends to a great extent on the transmittance of the propagation path of individual signals from their sources to the measuring point as well as on various types of interference, and it can be very complicated in the general case. Additional difficulty results from changes in the signal caused by varied level of load on the technical object [4] or varied environmental conditions. State-of-the-art techniques of signal analysis and processing should account for all of the above listed aspects in order to extract the informational features of the signal so as to be able to create, on their basis, the non-distorted, multidimensional vector of diagnostic parameters.

3. BYSIDE DIAGNOSTIC STATION

Along with the development of science and new cognitive tools, contemporary diagnostics sets increasingly difficult challenges for itself. One of the more interesting challenges is the diagnosis of moving vehicles, e.g. trains [5]. Diagnosis would be performed from a stationary wayside station and its purpose would be to analyze each vehicle traveling on the tracks. The main task would be to detect the information on the technical condition of the rolling systems of passing trains, and in particular to detect the early stages of defect formation. Additional stimulus for building such wayside systems includes the extensive consequences and the associated, enormous loss that a catastrophe of such a mean of transport could bring as well as the requirements of the users regarding operational availability, reliability and safety.

Assuming that diagnostically useful information is available from an acoustic signal emitted by a passing rail vehicle, one could propose a method of diagnosing defect development by means of stationary diagnostic equipment. The task that has to be solved first is to develop a mathematical model of physical phenomena, while accounting for the Doppler's effect in particular, as this phenomenon will occur for sure as the train will be a moving source of sounds vs. the receiver. As the basis for the analyses needed to construct the model, one should assume that the low-energy components of the signal are transmitted by the machine's structure from the measurement source located on its body as a result of modulation of a relevant carrier function. Particular attention should be paid to the phenomena of amplitude-and-phase modulation of a signal and occurrence of non-linear effects. Since the measured actual signal will contain both, the part generated by the diagnosed kinematic pair as well as additional components transmitted by the structure of the diagnosed object to the measurement point, hence the problem which needs to be solved is the issue of separation of diagnostically useful information contained in the non-linear part of the signal. The solution of this task will in fact depend on the results of search for diagnostically useful information contained in the non-linear part of the signal. The solution of this task will in fact depend on the results of the search for a set of diagnostic parameters which in a sufficient degree will be able to define the changes of the properties of the diagnosed object and which will be characterized by relevant resistance to noise. Finding such a vector of diagnostic parameters can be possible following an in-depth physical analysis of all the phenomena accompanying the assumed situation of an object's diagnosis, as well as by confronting the relevantly processed actual signals and signals simulated with the use of the developed model.

Based on the to-date theoretical considerations, we can create the certain necessary assumptions and create a model of the method of conducting the measurement by so-designed wayside monitoring station:

a) The source of signal will be moving with a permanent speed along a straight line,
b) The signal will be registered by a microphone, located at some distance from the path of the moving object,
c) Signal measurement will be conducted continuously, for various consstant speeds of the vehicle.

The diagram of such a diagnostic station could look like in Fig. 3:

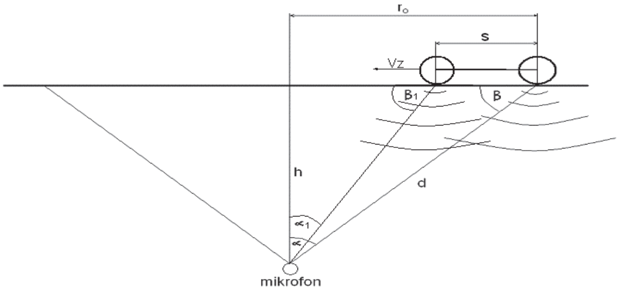


Fig. 3. Diagram of a measuring system.

It is of course most important that the created model reflects the reality and the main physical phenomena connected with it as precisely as possible. The result of the work on such a model is a mathematical expression which accounts for the main phenomena leading to distortion of the signal generated by a moving source:

$$y=\frac{ModA}{\sqrt{h^2+(h\cdot tg\alpha-V_z\cdot t)^2}}\cdot\cos(2\cdot\pi\cdot f_0\cdot\frac{1}{1-\frac{V_z}{V\cdot\sqrt{1+\frac{temp_{pow}}{273}}}\cdot\frac{h\cdot tg\alpha-V_z\cdot t}{\sqrt{h^2+(h\cdot tg\alpha-V_z\cdot t)^2}}}\cdot t+ModF)$$

$$\text{gdzie: } ModF=\frac{m\cdot\sin(2\cdot\pi\cdot f_2\cdot t)}{1-\frac{V_z}{V}\cdot\frac{h\cdot tg\alpha-V_z\cdot t}{\sqrt{h^2+(h\cdot tg\alpha-V_z\cdot t)^2}}}$$

$$ModA=A_0\cdot(1+M\cdot\cos(2\cdot\pi\cdot f_1\cdot t))$$

which accounts for the following physical phenomena:

- amplitude and frequency modulation;
- Doppler effect;
- acoustical pressure which is inversely proportional to the distance from the source of sound;
- change of the velocity of the acoustic wave propagation depending on temperature.

Analyses of model situations have demonstrated that the element of key importance is the occurrence of signal distortion by Doppler's effect which in line with its essence, and depending on the speed of signal source, will change the actual carrier frequency of the signal, like in the below example in Fig. 4.

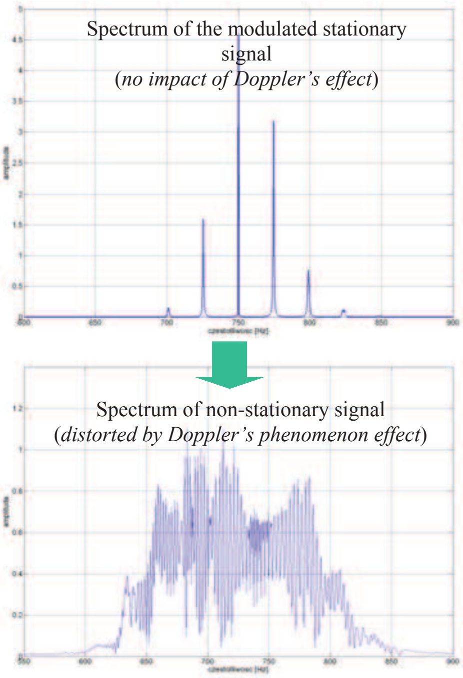


Fig. 4. Impact of the Doppler's phenomenon effect.

Further processing in terms of search for diagnostic information in a signal coming from the model led to distinction of three cases for which specific analysis should be assumed.:

I – Optimization of parameters to omit the Doppler's phenomenon effect
II- Separation and numerical elimination of Doppler's phenomenon effect
III – Analysis and use of Doppler's phenomenon

In the first case we will use the already proven claim that in a stationary diagnostic station the main disturbance for a moving object will be the effect of "non-stationarity" associated with the occurrence of the Doppler's phenomenon. The analysis of the created model has enabled us to note that in the case of certain assumptions as well as relevant parameters of the measurement, there exists the chance of minimizing the distortion caused by the Doppler's effect. Fig. 5, 6.

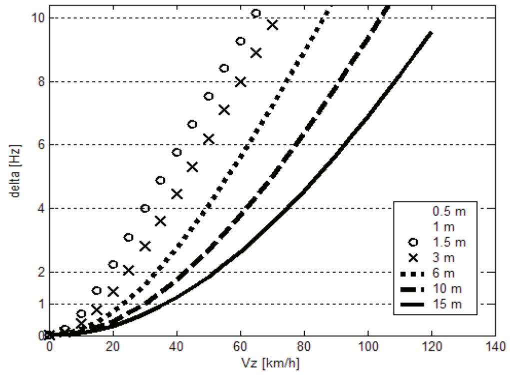


Fig. 5. Influence of Doppler's phenomenon effect in the function of speed of the drive for various distances between the microphone and the track.

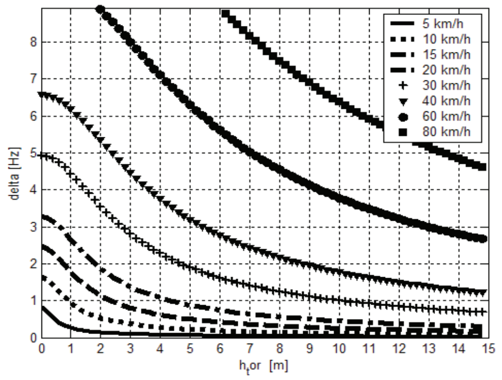


Fig. 6. Impact of the Doppler's phenomenon effect depending on the distance of the microphone from the track for various speeds of the vehicle.

The above graphs show that the relevant manipulation with such parameters as the object's speed and the distance between the microphone and the track we are able to control the delta value [Hz], representing the size of the disturbance caused by Doppler's phenomenon effect. Adoption of a relevantly small distortion will enable further analysis and signal processing to a form on the basis of which it will become possible to build the relevant diagnostic measures.

Another case assumes that due certain reasons, e.g. due to the required high speeds, it is impossible to disregard the impact of the Doppler's effect. In addition, there appears the problem of separation of signals coming from relevant driving systems, which may occur for some types of rail vehicles. Although the first problem calls for use of signal processing method in order to reduce the Doppler's effect, in the second case we can formulate relevant conditions for which separation and further analysis can be appropriate.

While taking a complex signal that has been obtained and that has been generated during the run of the railway car's truck, we are unable, based on the amplitude-and-time run, to separate the parts of the signal belonging to one or the other wheel. Let us remember however that the wheels moving in respect of the receiver, introduce the disturbance of carrier frequency to the signal. At any moment in time, as the car passes, a different value of the basic frequency is recorded. Such a change can be observed in Fig. 7:

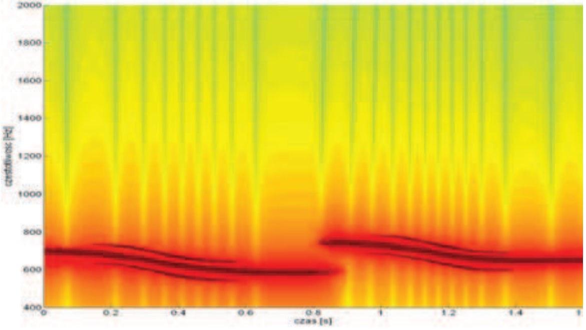


Fig. 7. Signal coming from two moving sources.

We have obtained the run of frequency change in time and at the same time the change of the value of amplitude, which is shown by the spectrum of colors in the spectrogram. For a relevant velocity of the source, when there is big scope of the change of the signal's frequency value caused by the Doppler's phenomenon, we are able to isolate the values of the frequencies belonging to individual signal sources. Apart from the signal's carrier frequency, we also note less distinct changes of modulating frequencies. Summing up, the main conditions which have to be fulfilled, in order to perform the separation properly, look as follows:

$$f_0 \cdot \min f_{dop} \neq f_1 \cdot \max f_{dop}$$

where: f_{dop} - the coefficient resulting from Doppler's phenomenon.

When the condition is fulfilled (like in the figure), then by using the time axis we can use the time ranges corresponding to respective signal sources.

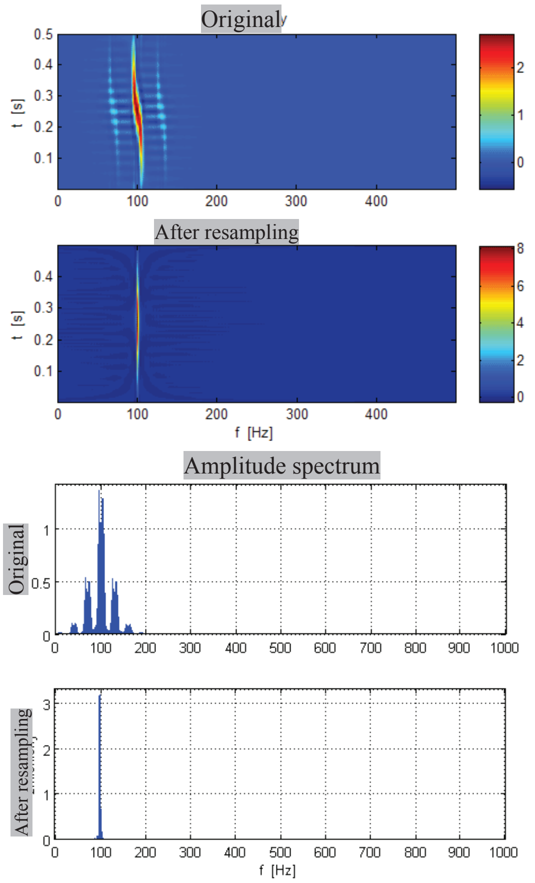
Let us go further in our considerations and let us look at the practical sense of such a procedure. From the spectrogram let us choose the range/interval of $\Delta t = 0.2$ seconds (from $t = 0.3[s]$ to $t = 0.5[s]$), which corresponds to the signal generated by the first source. The velocity of the signal's source was $V_z = 11\left[\frac{m}{s}\right]$ in the analyzed case. Thus the distance that the source traveled during Δt equals:

$$s = V_z \cdot \Delta t = 2.2[m]$$

If the examined object was a wheel of a train with diameter of 0.92 m (a 424 W EVANS freight car), then diagnosing its diameter and the bearing would only be possible once it makes one full turn. The path traveled when one full turn is made by the wheel is equal to the wheel's perimeter, that is $s_{kola} = 2.89[m]$.

The calculated parameter defines the minimum wheel track of the truck which enables conducting the analysis of its technical condition. Assuming that the condition has been fulfilled, let us conduct further analysis . Let us note that S_{kola} is too big for the wheel to make the full turn during the selected time interval Δt. The conclusion from this is that the source must move at bigger speed in order to achieve this. This in turn leads to a situation where the frequency change, caused by Doppler's effect, will occur in a shorter time interval. Ultimately the time interval may turn out too small to be able to isolate a signal's sample with $\Delta t = 0.2$ [s]. The situation calls for finding the so-called "golden mean", that is to obtain the compatibility of selected parameters whose values can be obtained through subsequent trials.

If we are able to reach a single source of signal in which we look for diagnostic information, then we can start dealing with reduction of the Doppler's phenomenon effect which effectively hinders the diagnostic interpretation of the signal. It seems appropriate at this point to use the dynamic re-sampling of the signal [6], which should theoretically deal with the frequency disturbance.


Original

After resampling

Amplitude spectrum

Fig. 8. Illustration of operation of dynamic signal resampling.

The simulation was performed for source velocity of 80 kph, distance of the microphone from the track of 2 m while the signal's carrier frequency was 100 Hz. As we can see in Fig. 8, the disturbed carrier frequency of the signal along with modulating frequencies has been reduced to the original carrier frequency. The procedure of dynamic resampling worked, however the module of automatic search for frequency changes, which was contained in it, caused destruction of the diagnostic information which modulating frequencies could carry. While using the model that we have developed, we can simulate the conditions of the experiment and obtain a realistic picture in the extent in which the model describes the phenomenon and the course of changes caused by the Doppler's effect phenomenon. This way we obtain the below curve, Fig. 9:

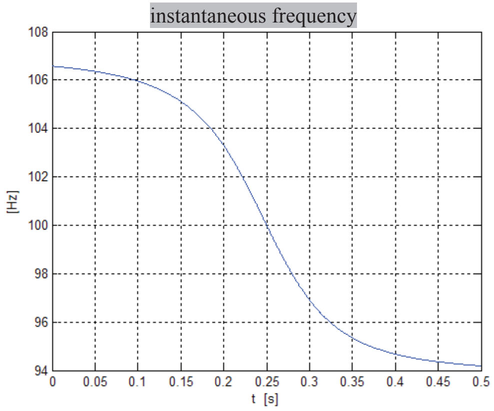

instantaneous frequency

Fig. 9. Model course of change frequency caused by the Doppler's effect phenomenon.

By introducing the apriori knowledge to the dynamic resampling method, which was used earlier, we can expect that the processed signal will not only contain the distortions caused by the Doppler's phenomenon effect but that also the information contained in the modulating frequencies will be visible.

The obtained, modified signal (Fig. 10) does not demonstate the features of a non-stationary signal associated with motion of the signal's source versus the receiver and can be successfully subjected to further analysis while diagnostic measures can be constructed on its basis. In the described analysis we saw how the model of a signal, which is to be subjected to analysis, protected us from unaware removal of diagnostic information from the signal, as well as how it enabled us to introduce corrections to the method of dynamic resampling so that it worked correctly in our specific case of signal disturbance by the Doppler's phenomenon effect.

Another concept, which emerged during analysis of the model of the considered physical phenomena associated with the wayside diagnostic station, was not an attempt to escape from the Doppler's phenomenon effect, but search for valuable, from diagnostic point of view, information in this effect.

Let us note that by controlling the measuring parameters we are able to influence, at our discretion, and to change the course of change of frequency caused by the Doppler's phenomenon, Fig. 11.

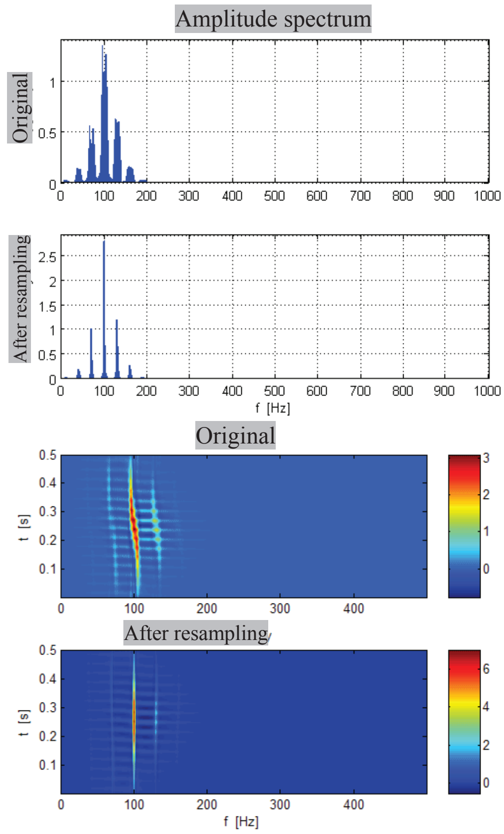


Fig. 10. Illustration of the operation of dynamic signal resampling method after introducing the apriori knowledge on the Doppler's phenomenon.

While analyzing the above graphs, one can see that the distortions of signal frequency by the Doppler's effect can be very rapid (a steeper curve) and assume higher values but they can also last longer, be milder and achieve smaller values.

Let us remember that while referring to the reality we need to take into account the fact that the registered signal will contain the data coming from two or more consecutive sources. Such a situation will occur e.g. for the passing trucks of a railway car. We know that separation of the registered signal into components, coming from individual sources, is not always possible. That is why let us add complexity to our model so that it simulates a moving pair of signal sources, separated from each other by a defined distance, and in addition let us use two, separated from each other by a relevant distant, microphones for registering the signals. Such a situation will roughly correspond to the moving railway car truck. While assuming the following parameters for performing the measurement:
Source velocity – 50 km/h
Distance from the microphone to the track – 2 m
Carrier frequency – f1=f2= 100 Hz
Distance between signal sources – 1.8 m
Distance between the microphones – 6 m
we will accordingly obtain the signals and frequency runs accounting for the Doppler's phenomenon effect from subsequent microphones, Fig. 12.

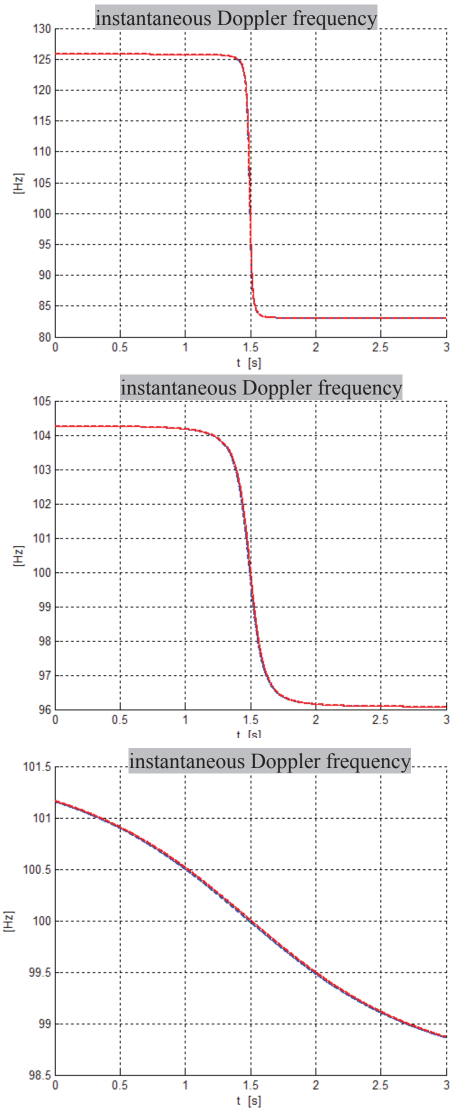


Fig. 11. Model change of the course of the frequency caused by the Doppler's phenomenon effect, depending on the measuring parameters selected.

Having at our disposal the situation modeled in such a way, we can observe the emerging shape of hysteresis created by the curves of carrier frequency changes for two sources. Hysteresis plays a major role in physics, taking into account the possibility of describing quite specific physical phenomena as well as the practical use of physical relationships associated with it. In our case we can influence the shape of the hysteresis by selecting the measurement parmeters and conditions. Model simulations demonstrated the physical phenomenon called dumping when the relative distance between signal sources increases, which is synonymous with increasing the area of the artificially generated hysteresis. Below we performed the simulation of signals (Fig. 13) for the following data:
Source velocity – 50 km/h
Distance from the microphone to the track – 2 m
Carrier frequency – f1=f2= 100 Hz
Distance between signal sources – 10.8 m
Distance between the microphones – 6 m

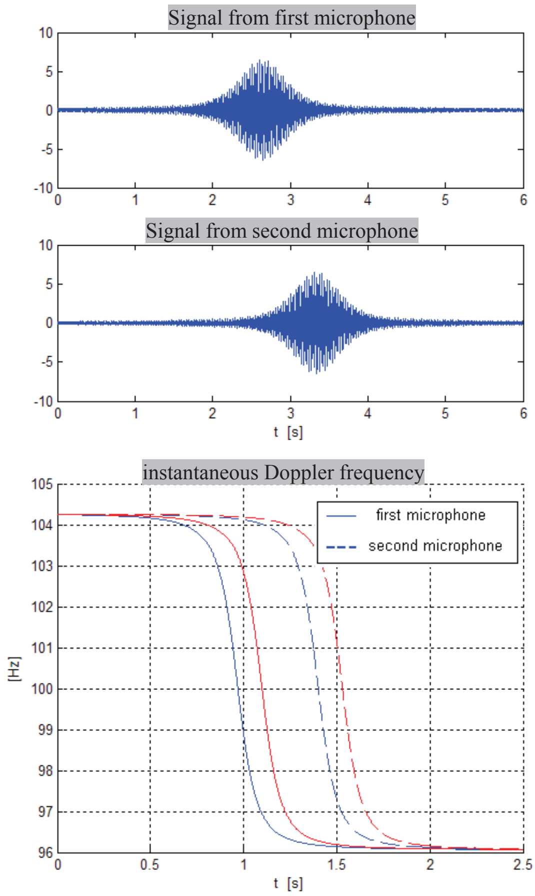


Fig. 12. Simulation of frequency changes for two moving sources.

This specific phenomenon, which has been generated, is characterized by the relationship concerning the frequency of interfering signals:

$$f_{dudnienia} = \left| f_1 - f_2 \right|$$

In order to confirm the phenomenon that emerged, we examined the envelopes of interfering waves.

The frequency of around 8Hz is clearly visible which in accordance with signal disturbance model (Fig. 14) can be linked to the occurrence of the Doppler's effect phenomenon for two signal sources. The additional low-frequency component, which occurred in the spectrum of the amplitude-modulating signal, is associated with the change of acoustic pressure depending on the distance between the source of sound and the microphone.

The phenomenon of beat effect was generated by us by extending the shape of the hysteresis coming from two moving sources of signal, which is synonymous with the time of delay between signals. The impact of this delay is significant from the point of view of the ability to identify the phenomenon, which is presented in Fig. 3.15.

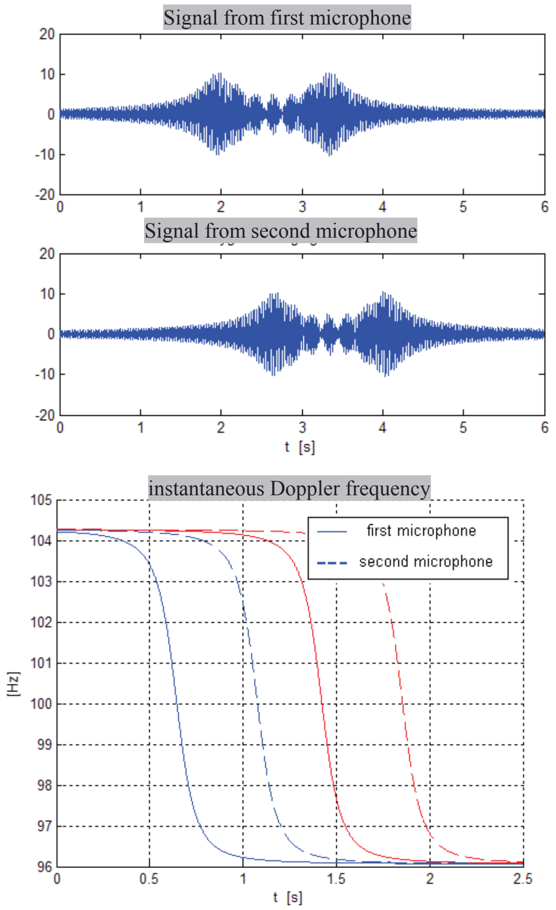


Fig. 13. Simulation of frequency changes for two moving sources for increased distance between them.

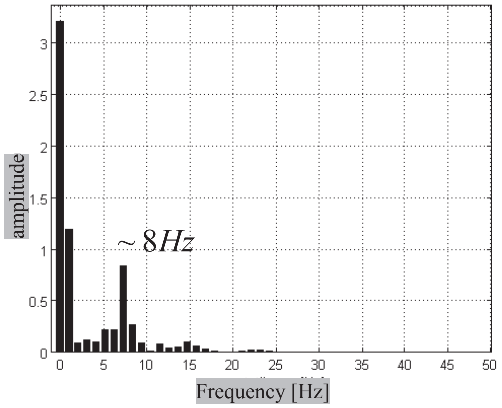


Fig. 14. Spectrum of the amplitude-modulating signal.

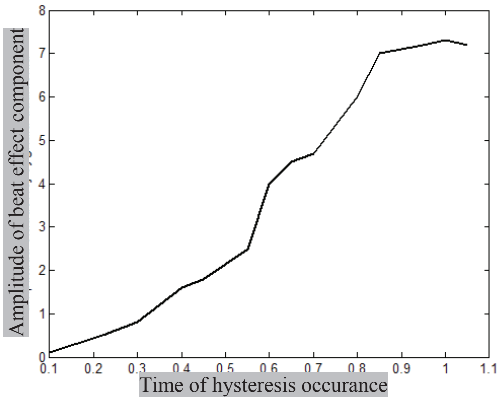


Fig. 15. Influence of duration of hysteresis on the possibility of identifying the frequency of the beat effect.

Longer duration of occurrence of "hysteresis" will enable better distinction of the frequency of beat effect among the components of the analyzed signal.

By correctly identifying the beat effect frequency, we can reach the information on the scope of change of the frequency, introduced by the Doppler's effect, which can be used, among others, foyr estimating the speeds of moving objects. What is also essential is the fact that damping effect occurred only in in the area where hysteresis occurs. This demonstrates that sources frequencies are identical, which we will see below.

So far the modeled signals described an idealized situation where the carrier frequencies of two sources were identical. In reality they will differ and the essential difference will be indicative of the relative difference in the nature of operation of the two systems. In the case of the truck of a railway car, this can be caused by different diameters of the truck's wheels. Let us look at the results of simulation (Fig.16) for the following parameters:

Source speed – 50 km/h
Distance from the microphone to the track – 2 m
Carrier frequency – $f_1 = 105Hz, f_2 = 100Hz$
Distance between microphones – 6 m

We observe the beat effect for two, different values of relative distance between the sources. In addition the scope of its impact covers the whole range of the registered signal. In this case the dumping frequency points to the existence of differences between carrier frequencies of the sources, which is the evidence of a different nature, kinematic and dynamic nature of the individual driving systems. Further detailed analysis can decide whether this could be the information about emerging or developing defects of the object.

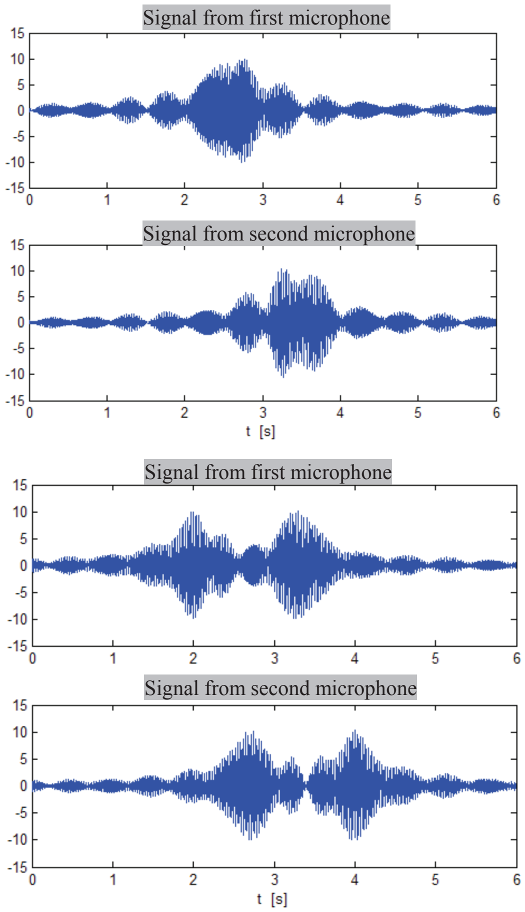


Fig. 16. Simulation of signals for two moving sources with a similar carrier frequency.

Such situation (Fig. 16) is more complex compared to the model with two moving sources with identical carrier frequency, since it has a bigger number of interfering signals. As a result, we will for sure obtain a signal which will be responsible for the occurrence of the beat effect due to the difference between the carrier frequencies of source signals:

$$y_1 = A_D \cdot \cos\frac{1}{2}(\omega_1 + \omega_2)t$$

where: $A_D = 2A \cdot \cos\frac{1}{2}(\omega_1 - \omega_2)t$

The frequency of occurrence of maximum value of amplitude $\pm 2A$ is the dumping frequency. This frequency is two times higher than $\frac{1}{2}(\omega_1 - \omega_2)$ since the maximum value of dumping occurs both for $\cos\frac{1}{2}(\omega_1 - \omega_2)t = 1$, and for $\cos\frac{1}{2}(\omega_1 - \omega_2)t = -1$. Thus, dumping frequency is: $\omega_D = (\omega_1 - \omega_2)$.

When analyzing a signal for small distance between the sources (1.8m), it is the calculated damping frequency that should be distinctly visible in the spectrum of amplitude-modulating signal. Let us subject the model signal to demodulation in order to reach the frequency (Fig. 17).

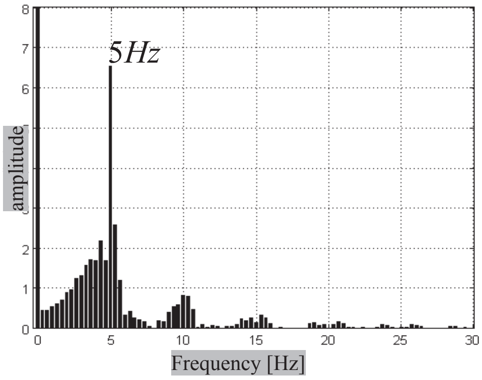


Fig. 17. Spectrum of amplitude-modulating signal.

The obtained spectrum confirmed our theoretical considerations. Let us now analyze the case when the relative distance between the sources increases in such an extent so that a beat effect phenomenon becomes possible, which is caused by the Doppler's effect phenomenon (relatively broad hysteresis of frequency disturbance caused by the Doppler's effect). The formula for the interfering signals within the area of artificially caused hysteresis will look as follows:

$$y_2 = A_{DD} \cdot \cos\frac{1}{2}(\omega_3 + \omega_4)t$$

where: $A_{DD} = 2A \cdot \cos\frac{1}{2}(\omega_3 - \omega_4)t$

Apart from another dumping frequency which has emerged $\omega_{DD} = (\omega_3 - \omega_4)$, one should remember that in the case of dumping phenomenon it is the carrier frequency of individual signals (components) that changes and equals to the arithmetical average of the source frequencies. Taking this phenomenon into account we discover another interference whose result will be dumping with frequency of:

$$\omega = \frac{(\omega_1 + \omega_2)}{2} - \frac{(\omega_3 + \omega_4)}{2}.$$

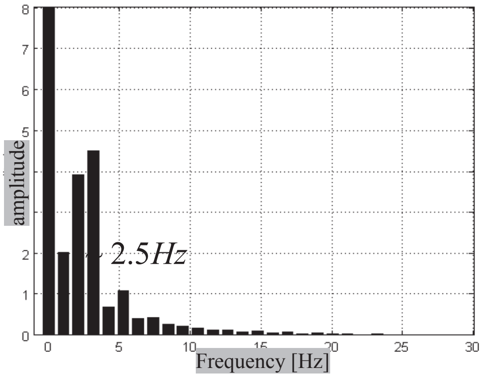


Fig. 18. Spectrum of amplitude-modulating signal.

While analyzing the amplitude spectrum for a time signal, which includes the phenomenon of occurrence of a hysteresis which disturbs the frequency, we can isolate the beat effect which was calculated earlier and which equals to the difference of average frequencies of dumping signals (Fig. 18). When the whole time run is subjected to the analysis, then we will see, in the amplitude modulating spectrum, the trace of this frequency as well as the dumping frequency which results from various frequencies of source signals.

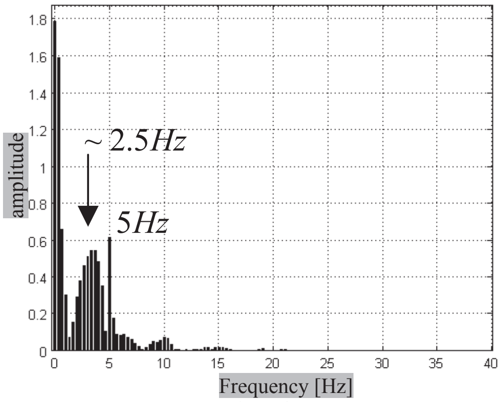


Fig. 19. Spectrum of the amplitude-modulating signal.

While continuing the analsysis of the model used, we can note the possibility of exploiting the fact that registration is done with the use of two microphones. Even when the hysteresis area is not big enough to observe the beat effect caused by the effect of Doppler's phenomenon for two moving sources, we can still bring it about while exploiting the fact of the difference of signal frequency while approaching and moving away from the signal. We can cause it, while making use of the difference in terms of a signal when coming closer or moving away from the source of signal, Fig. 20:

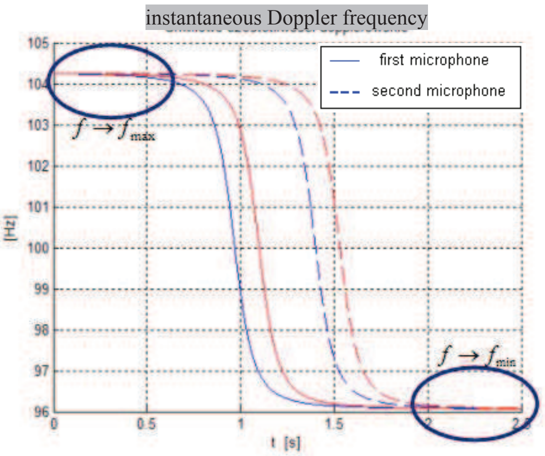


Fig. 20. Illustration of the possibility of capturing the maximum difference between the frequencies, as caused by the Doppler's phenomenon.

This way, while manipulating with the set of microphones, it becomes possible to combine with each other the signals while approaching and while moving away, which should trigger sufficient condition for causing the dumping phenomena (Fig. 21), providing us with the information on the frequencies distorted by the Doppler's effect phenomenon.

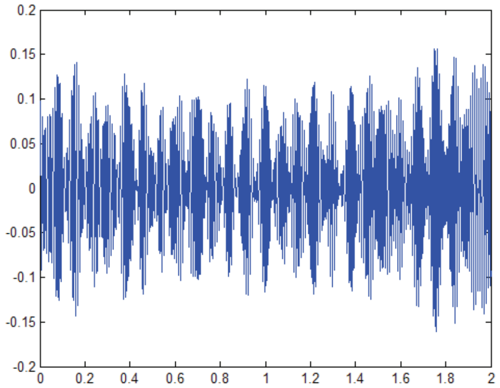


Fig. 21. Simulation of the damping phenomenon while using a model with two moving signal sources registered by two relevantly removed microphones.

All the up-to-date analyses of the beat effect concerned changes of the carrier frequencies of signals and can be also extended to include the analysis of the modulating frequencies (dumping caused by signals with similar modulating frequencies). The frequencies of modulating signals differ usually from the carrier frequencies of signals and that is why one should not expect the occurrence of the damping effect between them but a doubt emerges whether the observed dumping phenomenon, for the signals' carrier frequencies, could disturb the identification of the modulating frequency. Let us perform the simulation of two moving sources, of which one is amplitude-modulated (depth of modulation = 0.2; modulating signal frequency = 5Hz) while at the same time relevant conditions occurred for stimulating the damping phenomenon through Doppler's phenomenon. The envelope of such a signal was subjected to spectral analysis (Fig. 22)

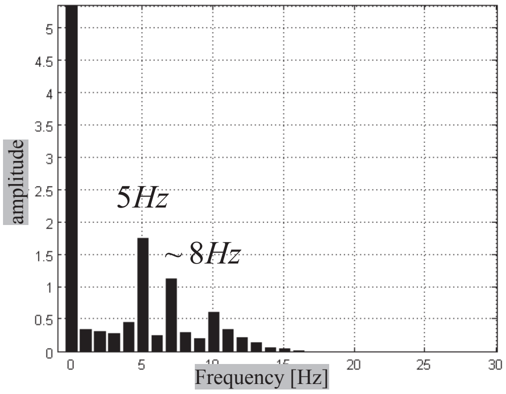


Fig. 22. Identification of amplitude modulation frequency.

Apart from the identified dumping frequency of $\sim 8Hz$, it is also the modulating frequency of 5Hz that is visible. Thus dumping will not interfere with the interpretation of the frequency of modulating signals which could appear in real-life signals in moving objects.

4. CONCLUSIONS

As we have demonstrated, the model can be used for proper selection of the conditions and methods of measurement as well as diagnostic parameters already at the stage of designing the entire diagnostic system. It is also later, at the moment of functioning of such a system that the model should continue to be updated in order to be able to meet the new measurement states and conditions as they appear during the operation. We have also demonstrated that there are several possibilities in the approach to diagnosis of objects in motion while using a stationary monitoring station, even in spite of the disturbance caused by the Doppler's effect.

BIBLIOGRAPHY

[1] Sobczak W., Malina W.: *Metody selekcji informacj*i (*Methods of information selection*). Wydawnictwa Naukowo-Techniczne, Warszawa, 1978

[2] Jacek Dybała, Jędrzej Mączak, Stanisław Radkowski: „*Wykorzystanie sygnału wibroakustycznego w analizie ryzyka technicznego*"; monograficzna seria wydawnicza ("*Use of vibroacoustic signals in technical risk analysis*;" a monographic publishing series: Biblioteka Problemów Eksploatacji, Warszawa-Radom 2006

[3] Jacek Dybała, Szymon Gontarz, Stanisław Radkowski, "*The pattern recognition in analysis of vibroacoustic signal*", Materiały konferencyjne ICSV13, Wiedeń 2006.

[4] Szymon Gontarz, Peter Tse and Xiaojuan Wang, "*Enhanced eigenvector algorithm for recovering multiple sources of vibration signals in machine fault diagnosis*", Mechanical Systems and Signal Processing 21 (2007) 2794–2813.

[5] Jacek Dybała, Szymon Gontarz, Stanisław Radkowski, "*Use of information embedded in vibroacoustic signal to crack evolution tracking of gear failure*", Materiały konferencyjne WCEMA 2007, Harogate 2007.

[6] Gałęzia A., Gontarz Sz.: referat pt.: „*Redukcja efektu zjawiska Dopplera dla potrzeb stacjonarnego stanowiska diagnostycznego*". VIII Seminarium Naukowe Studentów i Młodych Inżynierów Mechaników 2005 (*Reduction of the Doppler's phenomenon effect for the needs of a stationary diagnostic station.* 7th Scientific Seminar of Students and Young Mechanical Engineers, 2005)

[7] Jacek Dybała, *Use of task–oriented dynamic resampling in reduction of signal non–stationarity*. Diagnostyka 4(48)/2008. str.25-30.