CONTOUR OF VIBROACOUSTIC MAP IN DIAGNOSES OF ENGINE'S FAILURE

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Abstract

Almost all engine failures have an influence on engine's vibration, which is described in the article .Of course not every time diagnostic system can report of that. This is a reason why detection of vibrations must be accomplished with high quality diagnostic systems. Therefore, Doppler laser Vibrometry based on scanner Polytec had been used. To achieve full diagnostic results multidimensional vibration's function has been invented, where the torque moment is used as an extra parameter. Measured vibrations were subjected to digital signal processing like windowing, fast Fourier transform, filtration by finite impulse response windowed filters. The results of measure and processing perform in form of contour 3D plots, which indulge in speed estimate of the usefulness of presented method.

Tested engine performance, vibration measurement parameters, adopted diagnostic circuit, Digital processing of vibration signal, Vibration versus torque and magnitude spectrum (contour vibroacoustic map) of engine in good working order; ω = 2000 rpm, contour vibroacoustic map of engine in good working order; ω = 4000 rpm, contour vibroacoustic map of engine with fail of injection system; ω = 2000 rpm, contour vibroacoustic map of engine with fail of injection system; ω = 4000 rpm, contour vibroacoustic map of engine with fail of turbocharger; ω = 2000 rpm are presented in the paper.

Keywords: *vibroacustic maps, digital processing, automotive diagnosis, vibroacustic analysis*

1. Introduction

Vibroacoustic diagnoses of engine's vibration (especially vibroacustic) is known and used for sixty year. But car services have been used it more than scientist with good results without complicated mathematic operations. For this kind of diagnostic service has been needed professional stethoscope (Fig. 1). Of course this method can be applied only for few valves.

Fig. 1. Diagnostic stethoscope [1]

The reason why science has avoided vibroacoustic is simple: good vibroacoustic diagnosis need interdisciplinary team of mechanics, acoustics, signal processing and more. For the problem termination more than one is needed. However few scientists have fought with these demands on few direction for years with a very good results. They have based on different type of researches:

1. one failure and few ways of digital signal processing like wavelet, Vigner – Wille and fast
2. Fourier transform [2],
3. Few failures and one way of processing based for example on few levels wavelet transform [3].

In this paper authors will present different methodology. The methodology based on engine vibroacoustic vibrations signal measured by Doppler laser Vibrometry based on Polytec scanner. The torque moment has been used as an extra parameter. Measured vibrations were subjected to digital signal processing like windowing, fast Fourier transform and filtration by finite impulse response windowed filters. The results of measurement and processing were presented in contour 3D plots. In this method authors will compare plots of properly working engine and engine with failures. The failure based on fails of injection units and turbocharging system.

2. Measurement methodology

A compression-ignition Volkswagen, 1.9TDi engine was used for the tests. The engine is equiped with direct injection with a system of injection units, a turbocharging system with adjustable charger guide blades a turbocharging air cooling system and an intercooler.

The engine performance specifications are as follow:

1. maximum power – 74 kW (101 KM) at 4000 rpm,
2. maximum torque – 250 Nm at 1900 rpm.

Figure 2 shows he external performance of the tested engine.

Fig. 2. Tested engine performance [14]

The engine test bench was equipped with a Ralpha 240 electrorotary brake made by AVL [4] according to the specification [5]:

1. maximum power – 240 kW,
2. maximum torque – 600 Nm.
3. maximum speed – 10000 rpm.
4. inertia – $0.368 \dfrac{J}{kg * m^2}$.

The vibrations generated by the engine were measured by a scanning vibrometric system PSV made by Politec. The system includes:
1. a controller (OFV-5000),
2. a decoder module,
3. a vibrometric head (PSV400).

The vibration measurement parameters are shown in Tab. 1.

Tab. 1. Vibration measurement parameters

No.	Parameter	Value
1.	Kind of measurement	Speed vector
2.	Averaging	Off
3.	Number of samples	4096
4.	Sampling frequency	2048 Hz
5.	Measurement duration	2 s
6.	Filter	No
7.	Directivity	+Z
8.	Barrier frequency	20 kHz
9.	Vibration range	640 μV/m

Figure 3 shows the adopted diagnostic circuit.

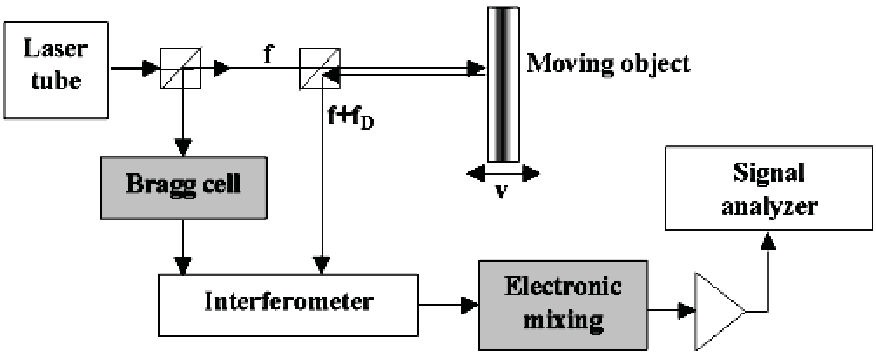

Fig. 3. Adopted diagnostic circuit

An important fact is that it was not necessary to use a reference channel with a trigger arm in the investigations. It means that garage diagnostics without additional specialist equipment could be possible.

3. Digital processing of vibration signal

Without proper signal processing direct measurements do not yield explicit results. In addition, the proposed method requires multidimensional measurements, i.e. a series of vibrations measurement in the torque domain. Process and their description is presented in Fig. 4 and points below.

3.1. Operations on signal in time domain

The aim of all the signal digital processing operations performed during the investigations was to change the shape of the signal spectrum in a replicable way using standard methods. The first operation is signal windowing. In this case, windowing in the time domain since it is limited to the multiplication of the discrete vibration signal and the discrete window spectrum. Naturally, it is also possible to use a window in the frequency domain, but then the convolution of the two discrete signals is required.

A rectangular spectrum would have an ideal windowing sequence for damping uncharacteristic (from the investigation point of view) parts of the spectrum and simultaneously amplifying its characteristic parts. The ideal window would not distort the signal and prevent spectral leakage (an effect where a part of the signal component, not situated by the frequencies for which the analysis is made, appears in all the output discrete signal values after transformation to the frequency domain [6]).

When it is impossible to obtain a rectangular frequency characteristic a compromise is necessary. The compromise consists in the use of the best (from the investigation point of view) windowing sequence.

It has been experimentally found that a flap-top window is a good solution. This window is characterized by a low resolution at high dynamics [7]. Also the amplitude rendering accuracy is quite high. The values of this kind of window are calculated from the following formula (1) [7]:

$$\omega(t) = 1 - 1.93\cos(\frac{2\pi t}{T}) + 1.29\cos(\frac{4\pi t}{T}) - 0.388\cos(\frac{6\pi t}{T}) + 0.0322\cos(\frac{8\pi t}{T}), \quad (2)$$

where: $0 \le t \le T$ and ω(t)=0 for values from outside the domain.

3.2. Transformation to frequency domain

After windowing the signal is transformed to the frequency domain, using the fast Fourier transform with a base of 2. The way in which the FFT algorithm is introduced has been known since 1965 and is widely described in the literature [6, 7]. The fast Fourier transform used for discrete signals is expressed as follows:

$$X(k) = \sum_{j=1}^{N} x(j)\omega_N^{(j-1)(k-1)} \quad , \quad (3)$$

where: $\omega_N = \exp(\frac{-2\pi i}{N})$; N – the number of samples, k– the current sample of the frequency domain, j – the current sample of the time domain.

Thanks to the algorithm the calculations can be significantly speeded up and a modern PC does the job in a few seconds.

3.3. Filtering in frequency domain, Remez algorithm

One of the features of the discrete signal after the Fourier transformation, i.e. the time domain shift theorem, was used in the investigations. It follows from the definition of the Fourier transformation that a shift of the signal in the time domain by the value x is equivalent to multiplying the signal spectrum by the complex number $e^{-j\omega x}$ [8]. The multiplication result has no effect on the shift of the spectrum in the frequency domain. Generally, the dependence can be written as:

$$x(t - t_0) \xleftrightarrow{FFT} X(\omega)e^{-j\omega t_0}, \quad (4)$$

hence:

$$x(t - t_{01}) \xleftrightarrow{FFT} |X(\omega)| \quad (5)$$

and

$$x(t - t_{02}) \xleftrightarrow{FFT} |X(\omega)|. \quad (6)$$

The above feature, thanks to which after the Fourier transformation (FFT) the spectral module is insensitive to time sample shift (5), (6), forms the basis of the proposed diagnostic method. There is no need to search for the same measuring point in each sample, i.e. for the top dead centre (TDC).

Since the spectral module is insensitive to the shift a decision was made to use the finite pulse response (FPR) filter design method. It is a very popular method of designing filters (except phase filters) [7].

In order to obtain the current output signal sample, FPR filters use only the previous samples and the current sample, which shortens and simplifies the analysis. As a result the method is suitable for real diagnostic systems.

The low-pass filter generated by the Remez method (also called the Parks-McClellan method) was amplified.

Since the spectrum of the filter was characterized by considerable damping and low stability, the obtained filter samples were multiplied in the time domain by the Blackman window (7):

$$\omega(k+1) = 0.42 - \cos(2\pi \frac{k}{N-1}) + 0.08\cos(4\pi \frac{k}{N-1}), \tag{7}$$

where:
N - the number of samples,
k - the current sample.

The filter samples prepared in this way are multiplied in the time domain by the samples of the frequency spectrum of the vibrations generated by the engine. One should note that windowing and filtering are possible in both the time domain and the frequency domain. However, windowing in the frequency domain would require the convolution of the window frequency spectrum and the signal spectrum and the filtering in the time domain would also require the convolution of the filter time spectrum and the vibration signal spectrum. As a result of the additional transformations and the convolution, the method would become complicated. Therefore the particular operations were performed in their natural domains, i.e. windowing by multiplying the window and the signal in the time domain and filtering by multiplying the filter samples and the signal samples in the frequency domain. Regardless of the path taken, the two operations are equivalent.
Diagram of described process is presented in Fig. 4.

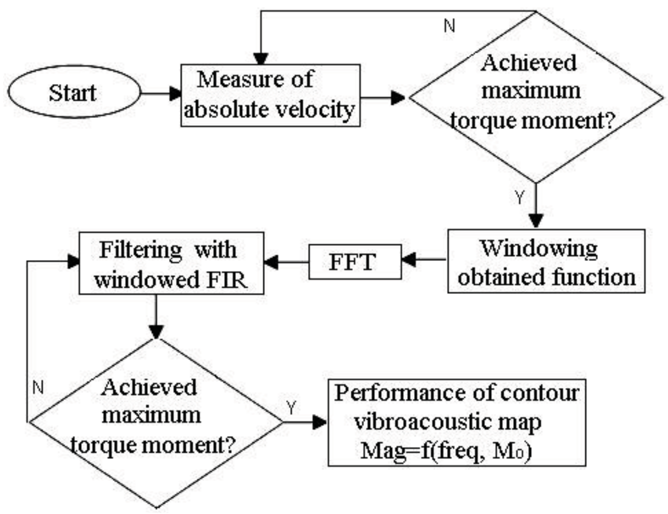

Fig. 4. Digital processing of vibration signal

4. Analysis of results

The digital signal processing operations were performed multidimensionally. This means that the digital signal processing operations described were performed for all the signals measured at different torques at a constant rotational speed.

In the first step, measurements were performed for the engine in proper working order as the reference. The obtained characteristic is shown on Fig. 5 (2000 rpm) and 6 (4000 rpm)

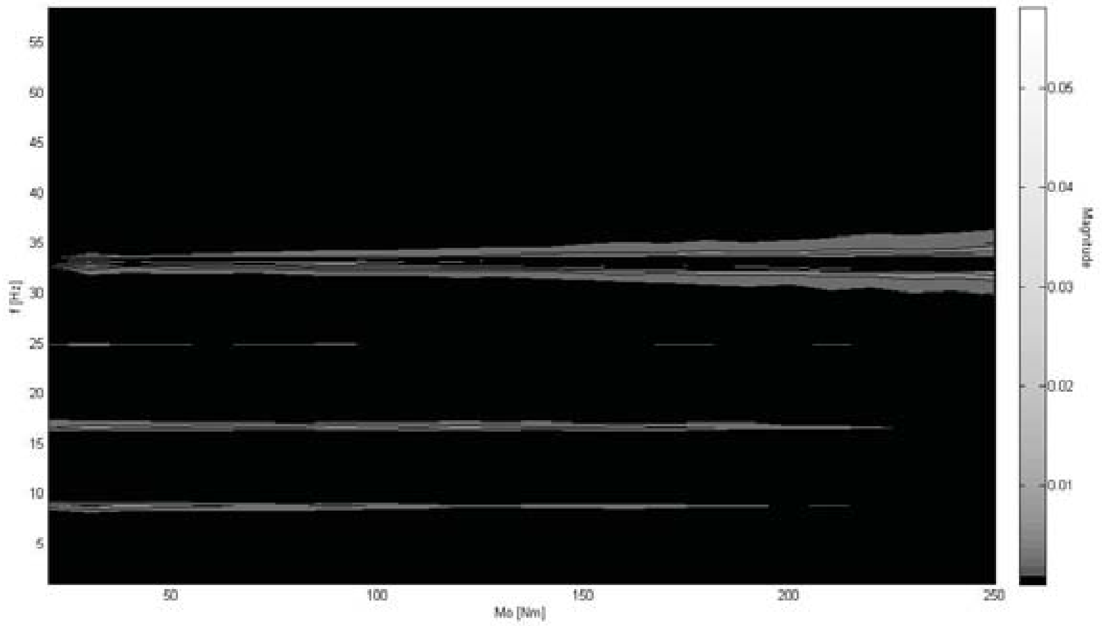

Fig. 5. Vibration versus torque and magnitude spectrum (contour vibroacoustic map) of engine in good working order; ω = 2000 rpm

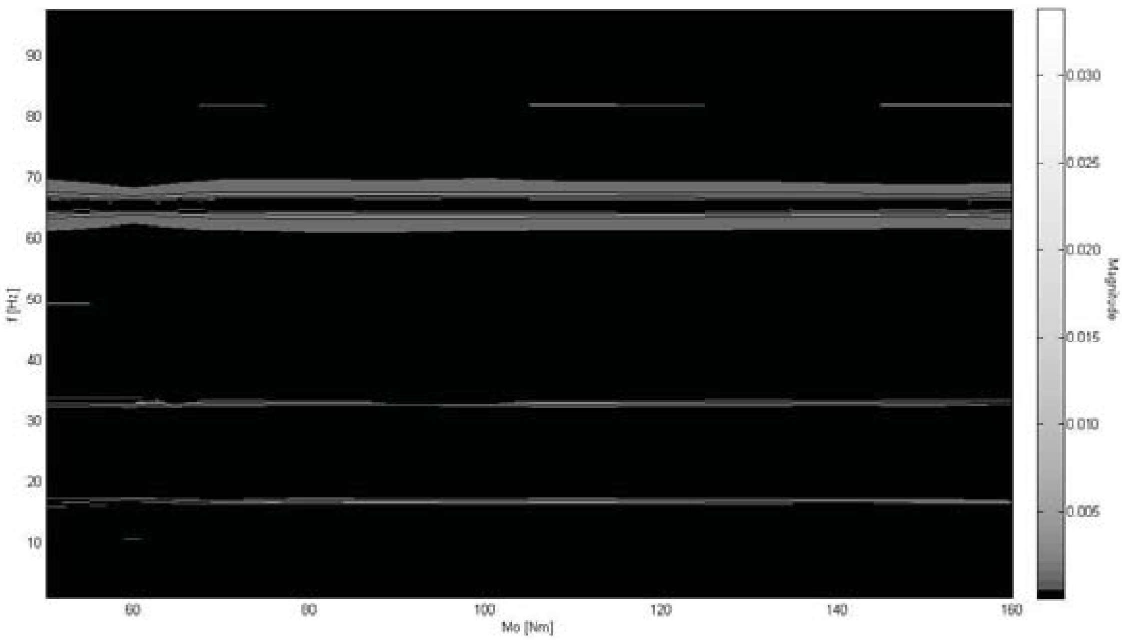

Fig. 6. Contour vibroacoustic map of engine in good working order; ω = 4000 rpm

Next the one of injection units was switched off, vibrations generated by the engine were measured again. The obtained signal was processed in the same way as previously. The result is shown on Fig. 7 (2000 rpm) and Fig. 8 (4000 rpm). The area in which considerable signal amplitude deviations are observed is obvious.

One can notice that the function for the all torque moment has a different character. Moreover, the measurement is not fully replicable but characteristic for a given engine when the measurement according to the described methodology is used.

The difference between not and properly working engine is laid in new magnitude's area which is indicated on failure. It is quite good visible for 42, 49 and 57 Hz (for 2000 rpm – Fig. 5 versus 7) and 49, 81 Hz (for 4000 rpm – Fig. 6 versus 8). Moreover engine with failure didn't achieve maximum torque moment which is obvious for this kind of failures.

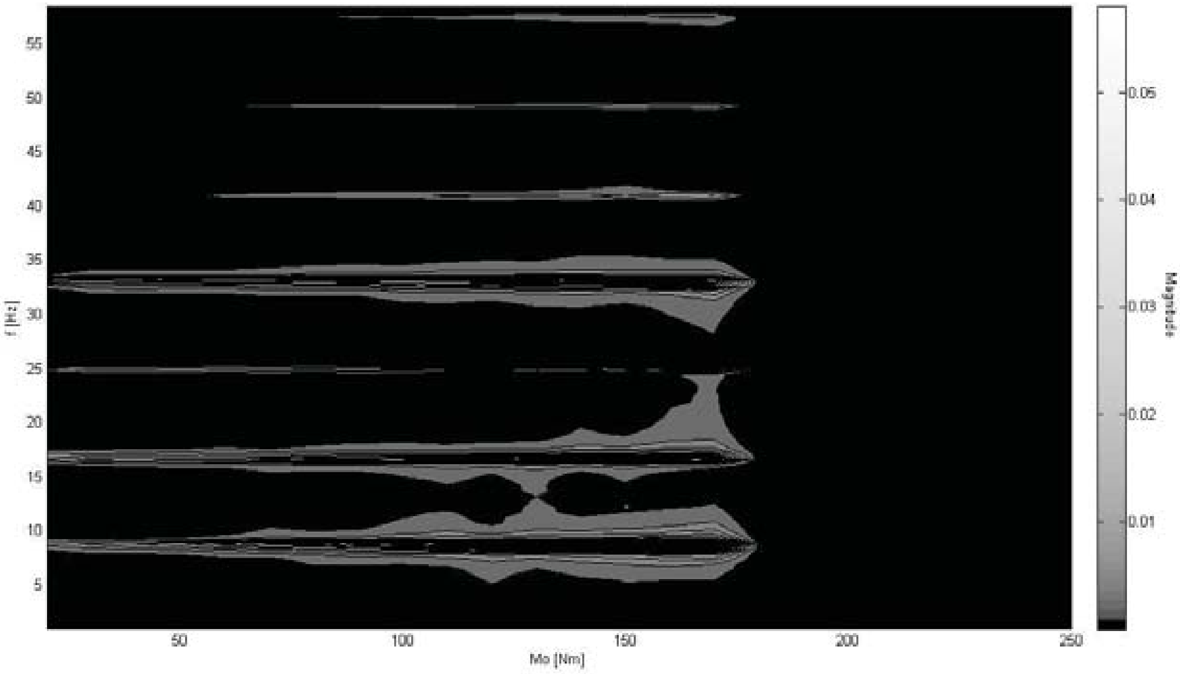

Fig. 7. Contour vibroacoustic map of engine with fail of injection system; ω = 2000 rpm

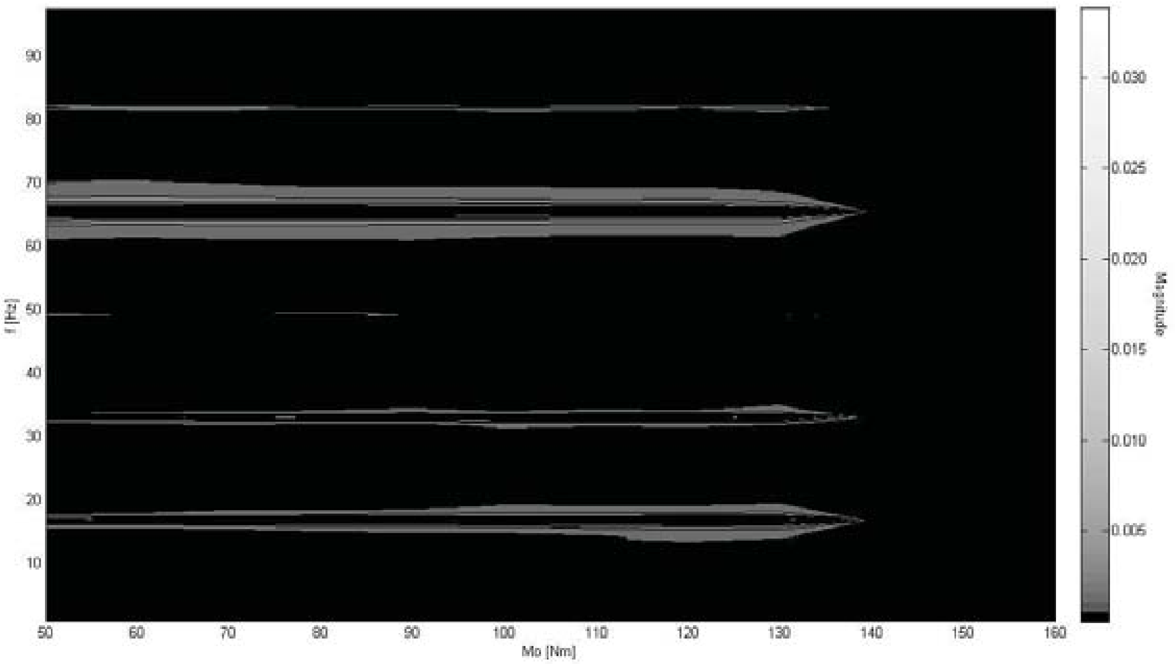

Fig. 8. Contour vibroacoustic map of engine with fail of injection system; ω = 4000 rpm

Next step based on failure of turbocharging system with adjustable charger guide blades (turbocharger was switched off). Fig. 9 presents contour vibroacustic map of this failure for 2000 rpm. Power of engine was not enough to measure it for 4000 rpm.

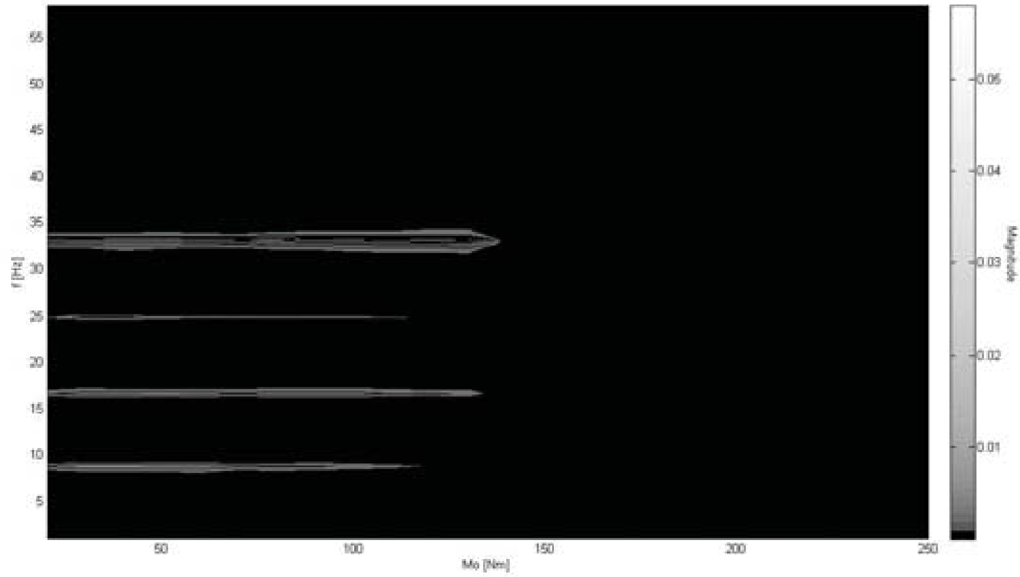

Fig. 9. Contour vibroacoustic map of engine with fail of turbocharger; ω = 2000 rpm

In this case some areas are invisible especially for more than 140 Nm (in comparison with Fig. 5). Moreover with this failure magnitude for frequency equals 25 Hz is underlined.

5. Conclusions

1. In vivo diagnostics of combustion engines, based on the analysis of vibration, is a tool which can be successfully used.
2. Although the method is quite complex, particularly in its digital signal processing aspect, it can be implemented in the widely available diagnostic systems thanks to the increasing popularity of signal processors.
3. Several faults and failures which have been already considered to have a negligible effect (or no effect) on the engine operation can be immediately detected by engine vibrations.
4. The multidimensional analysis of engine vibrations, especially based on contour of vibroacoustic map can be applied even in real services.
5. The proposed method requires dates of the vibroacustic measurements for each model of properly working engine as a base for further failures measurement. Measurements performed in accordance with the principles of digital processing of signals are replicable.
6. Engine vibrations are not an individual characteristic of each engine, but of the model.

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