

A Vibroacoustic Diagnostic System as an Element Improving Road Transport Safety

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Mechanical defects of a vehicle driving system can be dangerous on the road. Diagnostic systems, which monitor operations of electric and electronic elements and devices of vehicles, are continuously developed and improved, while defects of mechanical systems are still not managed properly. This article proposes supplementing existing on-board diagnostics with a system of diagnosing selected defects to minimize their impact. It presents a method of diagnosing mechanical defects of the engine, gearbox and other elements of the driving system on the basis of a model of the vibration signal obtained adaptively. This method is suitable for engine valves, engine head gasket, main gearbox, joints, etc.

vehicle driving system vibroacoustic signal diagnostic model

1. INTRODUCTION

An undiagnosed defect or worn-out mechanical elements of the driving system can cause an engine to stall, which is always a problem. Modern systems of on-board diagnostics, standard in passenger vehicles, make it possible to find defects in electric and electronic systems. Unfortunately, they cannot prevent a sudden break-down of the engine or gearbox. Mechanical defects affect the emission of exhaust fumes; however, if limit values are not exceeded, a defect is not signalled. This is so when, e.g., failure results from worn-out gearbox teeth. Other examples include increasing wearing out of valve seats and faces, shifting of the gear phase, wearing out of the cylinder bearing surface. Adaptive engine control is the most common reason why a diagnostic system does not react. Adaptive control systems compensate for mechanical defects and the wearing out of elements, especially in their initial stages. Faults are hidden or adapted [1, 2, 3]. Thus, diagnostic systems in vehicles should be supplemented with a system for detecting mechanical defects. This would significantly improve road transport safety.

The simplest way is to record the vibration signal; this signal is sensitive to the wearing out and defects of elements, and the measuring method is not invasive.

Antoni, El Badaoui, Guillet, et al. [4], Antory [5] and Lee, Park, Park, et al. [6] discussed the connection between the defects of a vehicle driving system and vibroacoustic characteristics. However, diagnostics based on experimentally found symptoms is costly (labour- and time-consuming): it requires gathering broad databases and is true for only one investigated object. If fast, diagnosing on the basis of a model is much better [7, 8, 9].

When modelling a driving system, selecting the right degree of abstraction (complexity) is difficult. It is possible to design one global model of a vehicle driving system [10] and to expand it; however, its complexity will not make using it for on-line (on-board) diagnostics possible.

Instead of a structural model, which is too complicated, this article discusses a model of vibroacoustic signal propagation on a very high level of abstraction. Accurate formal identification is a necessary condition for the model to operate properly [11]. This model is created in adaptively: (a)

the accelerated model is identified, (b) the model is adjusted to a driving system and its working time [12].

Designing such a model requires a series of measurements in selected points of the driving system and additional synchronizing of signals during routine vehicle maintenance, i.e., when driving at steady velocity, without abrupt changes in load. The base model considers the response of all elements of the driving system. This conceptual approach considers the driving system of a vehicle, with its n elements, as a whole (Figure 1).

Equation 1 describes the spectrum of the vibroacoustic signal observed at the engine:

$$Y_e(j\omega) = X_{ee} + H_{ec}(X_{cc} + H_{cg}(X_{gg} + H_{gm}(X_{mm} + H_{md}(X_{dd} + H_{dj}(X_{jj} + H_{jw}X_{ww})))))) + \Psi, \quad (1)$$

where $X_{ec}(j\omega)$ = excitation spectrum of engine, $H_{ec}(j\omega)$ = engine–clutch transfer function, $X_{cc}(j\omega)$ = excitation spectrum of clutch, $H_{cg}(j\omega)$ = clutch–gearbox transfer function, $X_{gg}(j\omega)$ = excitation spectrum of main gear, $H_{gm}(j\omega)$ = gearbox–main gear transfer function, $X_{mm}(j\omega)$ = excitation spectrum of differential gear, $H_{md}(j\omega)$ = main gear–differential transfer function, $X_{dd}(j\omega)$ = excitation spectrum of joint, $H_{dj}(j\omega)$ = differential–joint transfer function, $X_{jj}(j\omega)$ = excitation spectrum of wheel, $H_{dj}(j\omega)$ = joint–wheel transfer function, $X_{ww}(j\omega)$ = excitation spectrum of bearings, $\Psi(j\omega)$ = noise transform.

As the amplitudes of the components of individual subassemblies overlap, it is often difficult to separate them from the whole signal. However, Equation 1 makes it possible to consider the driving system as a whole and to diagnose its defects on the basis of the signal observed in an arbitrary point.

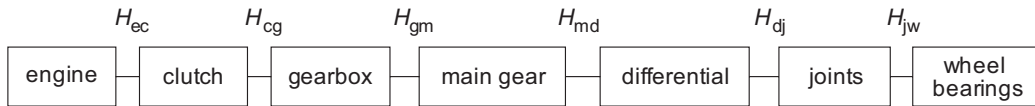


Figure 1. Block diagram of a vehicle driving system.

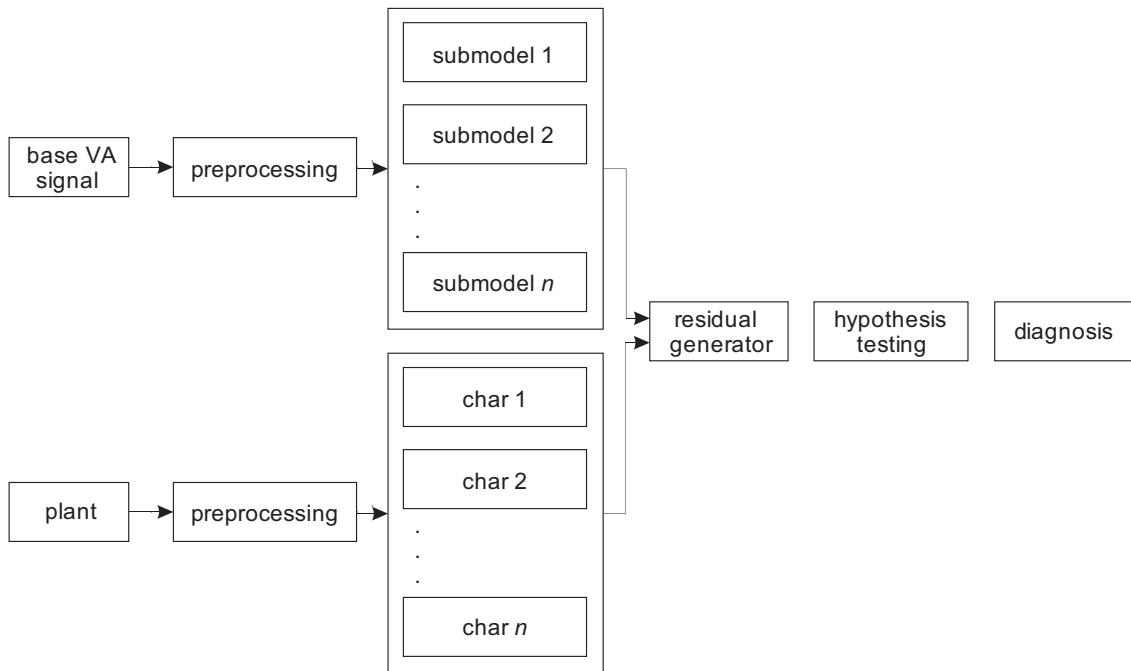


Figure 2. Idea of diagnosing a vehicle driving system with a vibroacoustic (VA) diagnostic model. Notes. Submodel 1 ... submodel n = model in a selected domain (e.g., time, frequency, harmonic number) and in a selected range (time, frequency). Char 1 ... char n = characteristics of the vibroacoustic signal compared with submodels in respective domains and ranges.

Figure 2 presents the idea of diagnosing a driving system by selecting residual signals on the basis of simplified models of the vibration signal.

Vibroacoustic signals generated by individual kinematic pairs and engine fittings, gears, couplings, bearings, joints, shafts, due to nonlinear effects caused by clearances and nonlinear characteristics of elastic elements, etc., are usually unsteady. Measuring vibrations is complex because signals from various sources overlap. Therefore, a diagnostic method based on a vibroacoustic signal requires advanced pre-processing operations.

2. VIBRATION SIGNAL IN VEHICLE DRIVING SYSTEM

The process of generating vibrations and noise in internal combustion engines is complex. Vibrations are combinations of periodic waves related to rotating elements and responses to impulse forces corresponding to plane-rotary motions of pistons and to excitations caused by the pressure of gas on the walls of cylinders. Strong transient states in a vibroacoustic signal originate from the operation of inlet and exhaust valves, injectors, the combustion process, pistons stroking cylinder bushing, etc.

For diagnostics purposes, it is necessary to separate response signals from various forces and to analyse them individually. To identify excitation sources, it is necessary to move from the time domain into the domain of the angle of rotation of the crankshaft. Then, most components of the acoustic signal can be investigated as periodic. It is especially difficult to analyse this signal on-line because the operation parameters of the vehicle driving system vary on the road. So, it is necessary to consider various load, engine rotational velocity, vehicle velocity and additional excitations caused by road conditions acting as external forces.

Some excitations are periodic, e.g., piston strokes on cylinder bushing, opening and closing of valves (in engines with constant valve timing), while others are characterized by angle variability (injection, ignition). Therefore, when measuring vibrations, it is necessary to record additional informative and synchronizing signals, e.g., the position of the crankshaft.

Transient processes, which respond to the closing of valves, dominate in the vibration signal recorded during a work cycle. To use vibrations to draw conclusions on-line on the state of the engine, it is necessary to study the influence of the parameters of engine work on the vibration

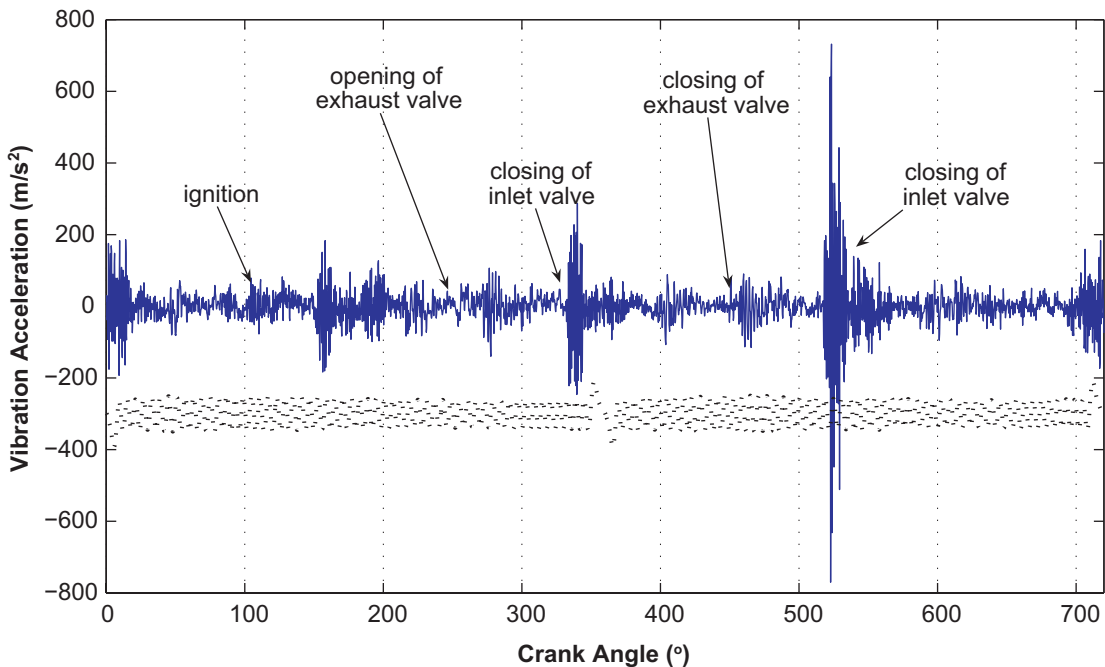


Figure 3. Signal of vibration acceleration of a 4-cylinder engine in one work cycle, with synchronization signals. Notes. — = vibration acceleration, ---- = synchronization signal.

signal. Crankshaft rotational velocity is most important. Its increase is accompanied by an increase in the amplitude of the vibration signal, especially in the components responsible for the closing of valves (Figure 3).

Signals of vibration acceleration of the remaining elements of the vehicle driving system are quite different. Those are periodic signals; for constant rotational velocity, they are also stationary and ergodic with elements of random noise. Figure 4 presents spectra of vibration acceleration of gearbox housing, main gearbox and triple joint for an efficient driving system.

It is not necessary to use three sensors and to process so much information: the gearbox generates most vibrations in this part of the driving system. Its casing also transfers vibrations from other elements.

Figure 5 presents the spectrum of the vibration signal the gearbox generates. Trains of harmonics of crankshaft rotational velocity are its main components. This is a broadband spectrum; the generation of so many harmonics is related to unbalanced and misaligned shafts changed during driving, and to transferred vibrations caused by cyclic operations of engine valves. The successive har-

monics corresponding to the operation of cylinders are visible in the band of low frequencies (for a four-cylinder engine, this is half of crankshaft frequency). The tooth-passing of the gearbox, the main gearbox and their harmonics are the next excitation source. The component of the half-shaft and the components related to the operation of individual cylinders can be seen in the range of low frequencies (up to the crankshaft rotational frequency f_0).

This analysis of the vibration signal shows that the block diagram in Figure 1 can be reduced to two blocks joined by the clutch, whose vibrations are recorded for diagnostics (Figure 6).

Equation 2 describes the spectrum of the vibroacoustic signal of the system observed on the engine:

$$Y_e(j\omega) = X_{ce} + H_{ec}(X_{cc} + H_{cg}X_{g..w}) + \Psi, \quad (2)$$

where $X_{ce}(j\omega)$ = excitation spectrum of engine, $H_{ec}(j\omega)$ = engine-clutch transfer function, $X_{cc}(j\omega)$ = excitation spectrum of clutch, $H_{cg}(j\omega)$ = clutch-gearbox transfer function, $X_{g..w}(j\omega)$ = excitation spectrum of remaining part of system (from gearbox to wheel), $\Psi(j\omega)$ = noise spectrum.

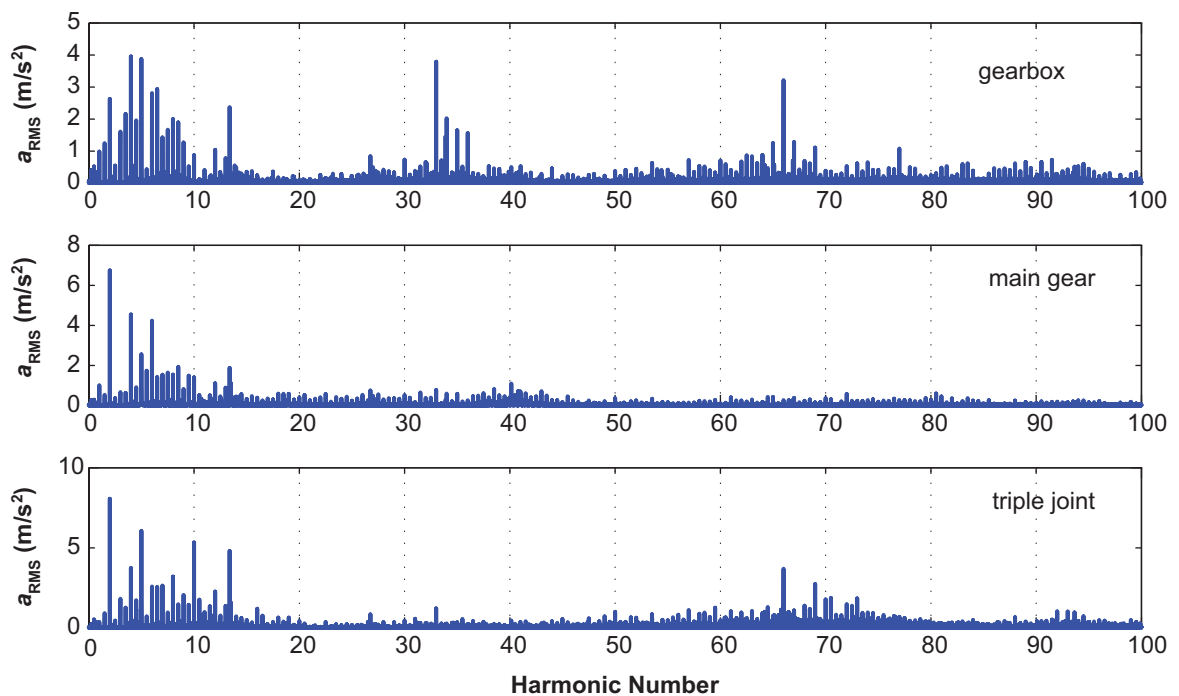


Figure 4. Spectra of vibration acceleration of gearbox housing, main gearbox and triple joint for an efficient driving system.

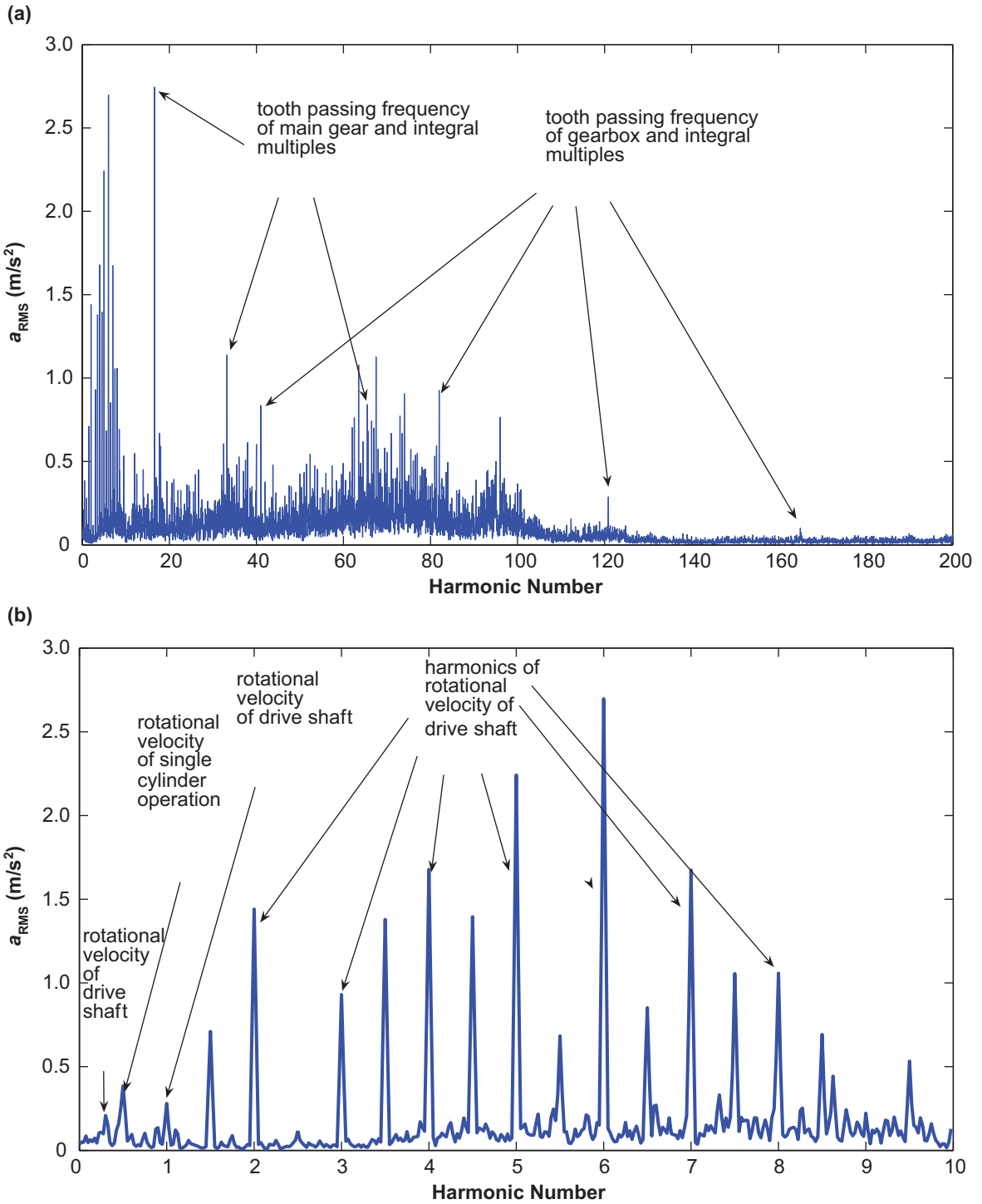


Figure 5. Average spectrum of gearbox vibration acceleration: (a) entire measurement range, (b) low frequency range.

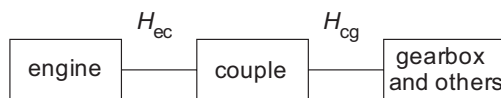


Figure 6. Simplified block diagram of a vehicle driving system.

This is a description of a linearized model, where all components formed due to nonlinear influences are contained in the noise Ψ . The acceleration spectra of the engine and gearbox vibrations are divided into components generated by individual elements of the driving system (Figure 6). A four-cylinder internal combustion engine generates several harmonics related to the cyclic operations of the frequency $k \frac{f_w}{2}$, which is a multiple of half of crankshaft frequency f_w . The vibration spectrum is then very broad, whereas components related to the operation of toothed gears, shafts, half axles, etc., can be observed on the gearbox. Some components are apparently divided due to their mutual superpositioning harmonic components of crankshaft rotational velocity and components of the gearbox toothed wheels (and their multiples), etc. Komorska described a vibration analysis of the vehicle drive system in detail [13].

3. MODELLING VIBRATION SIGNALS

During the lifetime of the driving system, its vibration characteristics change, the spectrum is smeared, new components are added, etc. To be universal, the model has to adapt itself to various driving systems in various states of wear. There must be a base model for the new system. Such a model should automatically update itself after each repair or change of parts. Finally, it must be determined for selected engine rotational velocities since the vibration characteristics strongly depend on this parameter.

The basic measures of the vibration signal, which is the reference in the diagnostic process, are then determined on the basis of the adaptive base model for a system in a good physical condition

3.1. Modelling Harmonic Signals

The vibration signal can be considered polyharmonic and analysed with the Fourier transform, after filtering off the high-frequency com-

ponents. In such a situation, the signal is reconstructed as the sum of the components of the largest amplitudes. Thus, signals of the vibrations of shafts, gears, wheels, etc., can be used for diagnostic purposes.

Let us consider a simple model of a vibration signal of the gearbox. The main dominants of the signal are crankshaft rotational velocity and its harmonics. The model can be expressed in the time domain:

$$x(t) = \sum_{i=1}^n A_i \sin(2\pi i f_w t - \phi_i), \quad (3)$$

where i = number of harmonics of crankshaft, n = number of considered harmonics (in this case, $n = 70$), f_w = crankshaft rotational frequency, A_i = amplitude of i th component, ϕ_i = phase shift of i th component.

The model can also be expressed in the frequency domain:

$$X(f) = \sum_{i=1}^n A_i (i f_w), \quad (4)$$

where i = number of harmonics of crankshaft, n = number of considered harmonics (in this case, $n = 70$), f_w = crankshaft rotational frequency, A_i = amplitude of i th component.

To diagnose the gearbox, a broader frequency range should be compared. Figure 7 compares the envelopes of vibration spectra of the gearbox in a good physical condition and one with worn-out teeth of the fifth gear. Figure 8 presents the residual spectrum at an increase of the amplitudes of components by over 100%. Table 1 lists the amplitudes of frequency components that should be investigated first.

The deviations in the high-frequency range (over 3 kHz) are related to engine defects, which include valves, the head gasket and knock combustion. Frequency bands are more important for diagnostics than individual components. They can overlap the natural frequencies of the vibrations of systems or sensors, which cause an increase in amplitude. Their frequency response is broadband, since it originates from pseudoimpulse forces. It is more justified then to analyse the signal in the time domain or in the domain of the angle of rotation of the crankshaft.

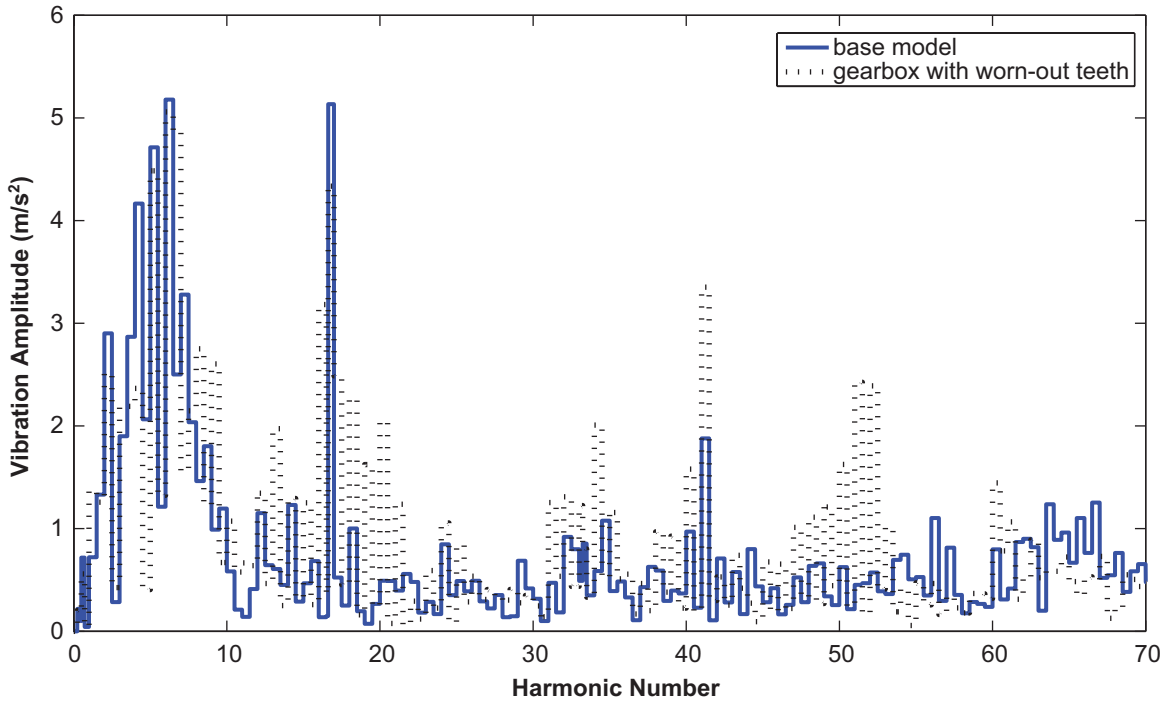


Figure 7. Comparison of envelopes of spectra of base model and spectra determined for gearbox with worn-out teeth (velocity 3000 rpm, 5th gear).

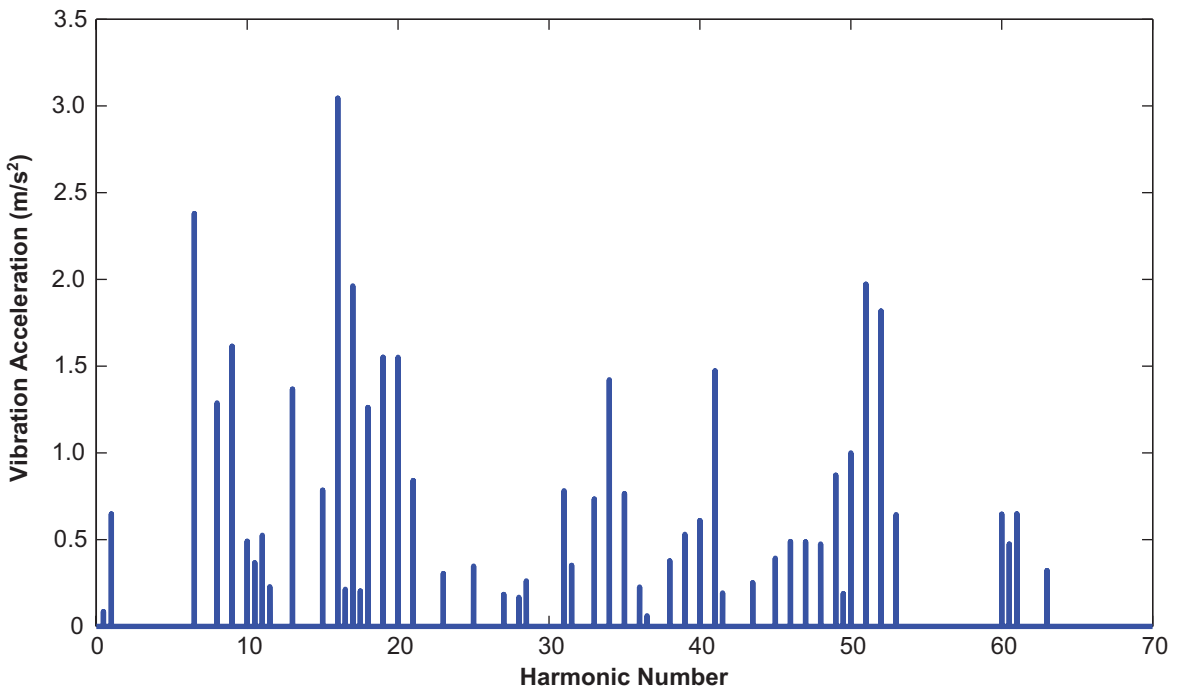


Figure 8. Residual spectrum of recorded signal and base model (at worn-out teeth of 5th gear).

TABLE 1. Vibroacoustic Spectral Model of the Drive System in a Fiat Punto (5th Gear)

Component	Symbol	Harmonic Number ($\times w_1$)
Rotational velocity of drive shaft	ω_1	1
Integral multiples of rotational velocity of drive shaft	$i\omega_1$	2, 3, 4, 5, 6, 7, 8 ...
Tooth passing frequency of gearbox	Ω	41
Integral multiples of tooth passing frequency	$j\Omega$	$j = 2, 3, 4 \dots$
Rotational velocity of drive shaft	ω_2	$k \cdot 1.108$
Rotational velocity of half-shaft	ω_3	$k \cdot 0.297$
Tooth passing frequency of main gear and its integral multiples	ω_m	$k \cdot 16.63$ $k = 1, 2, 3 \dots$
Single cylinder work frequency of 4-cylinder engine	ω_e	$k \cdot 2$ $k = 1, 2, 3 \dots$
Cycle frequency of 4-cylinder engine	ω_c	$k \cdot 0.5$ $k = 1, 2, 3 \dots$

3.2. Parametric Identification of the Model

Generating the base spectrum and comparing it with the signal spectrum is the easiest method; however, this method is less suitable for diagnosing defects in valves or the head gasket. If, in addition, the recorded waveforms are not long enough to obtain a sufficient resolution of the spectrum, time waveforms seem more suitable. They require, of course, synchronizing or synchronous averaging.

The model can be determined with parametric identification consisting in finding the vector $P = [p_1, p_2, \dots, p_n]$ of unknown representation parameters [14]:

$$Y = O(Y, X, P, t), \tag{5}$$

where Y = vector of recorded values (output vector), X = input vector, t = time.

However, that model has its limitations, since it is local, i.e., it simulates the signal only within certain surroundings of the state in which it was recorded. On the one hand, the local compatibility of the model with the signal is a defect, since it is not possible to extend the reasoning to other states on its basis. On the other hand, it has the advantage of being more accurate in estimating outputs than a global model, in which several simplifications are necessary.

In relation to the vehicle driving system, the model is true only for the determined rotational velocities of the engine, which has a strong influence on vibration characteristics.

When impulse forces and the character of signal responses are known, and the signal has the features of random noise, it is better to choose the Auto Regressive Moving Average model structure (ARMA), which contains both the influence of the exciting signal x and components with past output values. Differential Equation 6 describes it [14]:

$$y(k) = b_0x(k) + \dots + b_ny(k-n) - a_1y(k-1) - \dots - a_ny(k-n) + \varepsilon(k) = \sum_{i=1}^n b_i x(k-i) - \sum_{i=1}^n a_i y(k-i) + \varepsilon(k) = v(k)\theta, \tag{6}$$

where

$$v(k) = [x(k), x(k-1), \dots, x(k-n), -y(k-1) - y(k-2) - \dots, -j(k-n)], \tag{7}$$

$$\theta = [b_0, \dots, b_n, a_1, \dots, a_n]^T. \tag{8}$$

The number n of time instants is the order of the model.

Equation 6 can be expressed in another form [14]:

$$y(k) = B(z)x(k) + A(z)y(k) + \varepsilon(k), \tag{9}$$

where

$$A(z) = -a_1z^{-1} - a_2z^{-2} - \dots - a_nz^{-n}, \tag{10}$$

$$B(z) = b_0 + b_1z^{-1} + b_2z^{-2} + \dots + b_nz^{-n}. \tag{11}$$

The ARMA structure corresponds to the block diagram of the digital mixed filter, where $y(k)$ denotes the past values of the output signal versus the current moment k , i.e., $y(k-1)$, $y(k-2)$, etc. (Figure 9)

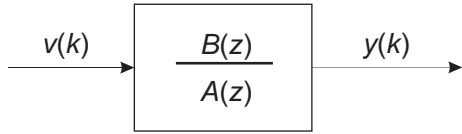


Figure 9. Model of Auto Regressive Moving Average (ARMA). Notes. $v(k)$, $y(k)$ = input and output, respectively; $A(z)$, $B(z)$ = parameters of ARMA; k = iterations.

Before the identification, the signal must be properly prepared. It is necessary to remove constant components and trends, filter to select a characteristic frequency range, determine the autocorrelation function or synchronous averaging and decimate. To perform parametric identification for the time-waveform of the gearbox vibration signal in the low-frequency range of a driving system in a good physical condition, the signal had to be prepared by filtering out high frequencies (higher than threefold the crankshaft frequency) and by synchronous averaging. Ten-fold decimation was also applied since the signal was oversampled and the model identification would have required too many useless coefficients. The model was identified with the Matlab/Identification Toolbox version 7.1.0.246 (R14)

Service Pack 3. Figure 10 compares the recorded vibration signal with the ARMA model output of 16 coefficients a and 18 coefficients b .

Figure 11 compares the residual signals of a base model of low-frequency vibration signal of the gearbox with signals recorded for a defective differential gear and a triple joint.

3.3. Modelling Nonstationary Signals

The wavelet transform allows a linear decomposition of the signal with the arbitrary base function, characterized by a short finite interval, in which it assumes other than zero values. If $\psi(t)$ is the mother wavelet, the wavelet daughter has the form [15]

$$\psi_{a,b}(t) = \frac{\psi(t-b)}{a} \tag{12}$$

where a = scale coefficient, b = shifting.

By changing parameters a and b , it is possible to create a wavelet family. Equation 13 determines the continuous wavelet transform of $x(t)$ function:

$$C(a,b) = \frac{1}{\sqrt{a}} \int x(t)\psi_{a,b}^*(t)dt, \tag{13}$$

where * = complex coupling.

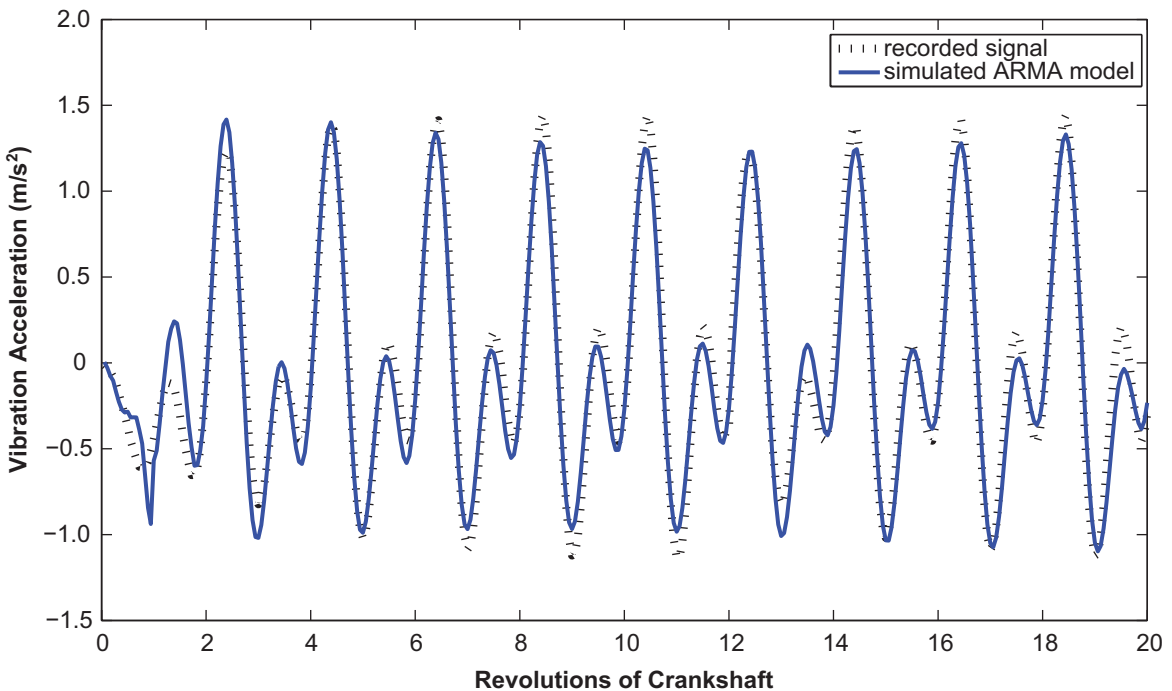


Figure 10. Comparison of recorded signal for low frequencies and for Auto Regressive Moving Average (ARMA) model.

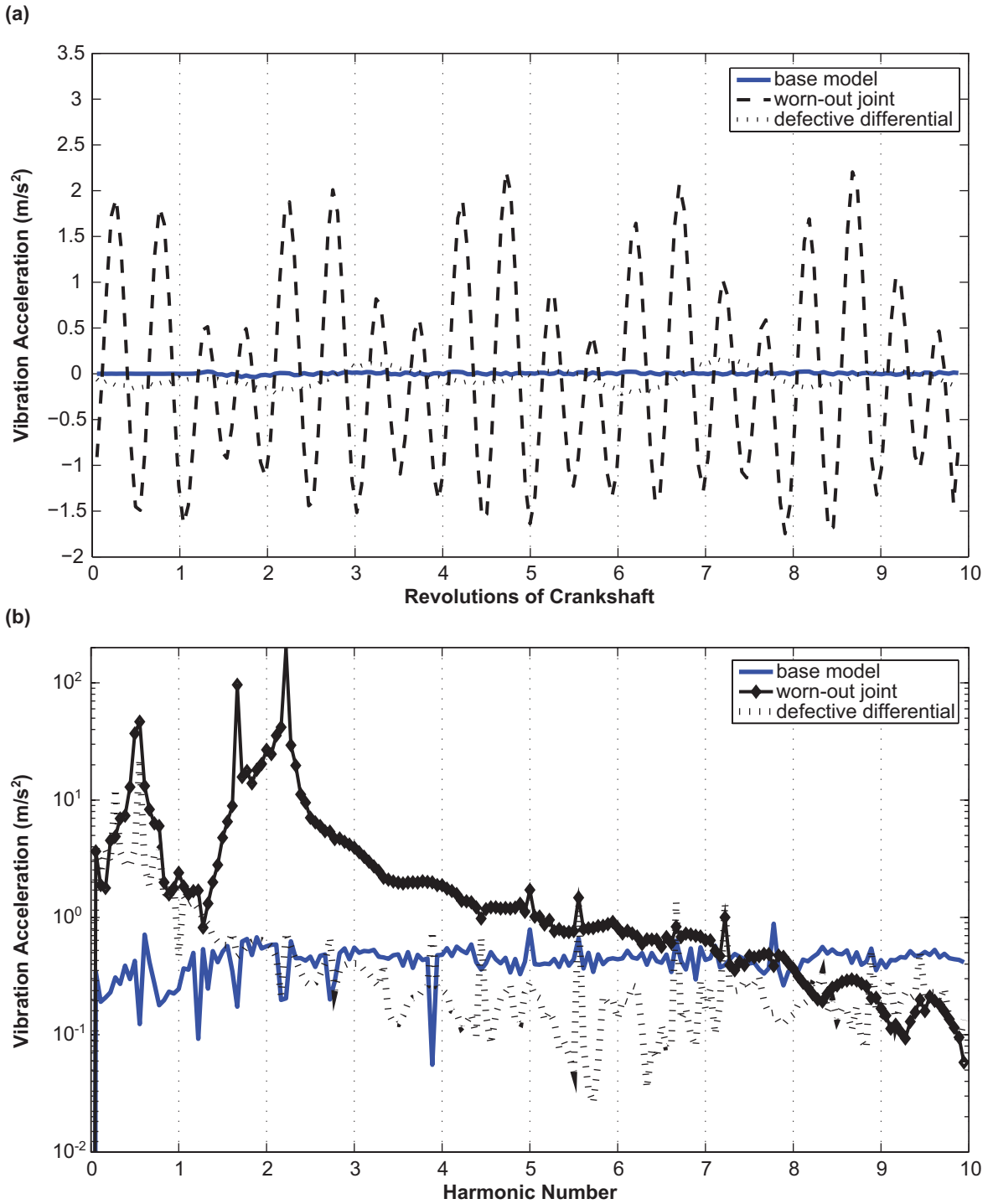


Figure 11. Residual signals determined for base model of low-frequency vibration signal of gearbox and signals recorded for defective differential gear and triple joint: (a) time waveform, (b) spectrum.

Since wavelets daughters are medium-pass filters, the wavelet transform is a filtering operation. The wavelet transform is a proper tool for describing nonstationary signals [15, 16, 17, 18, 19]. Figure 12 presents the results of wavelet

decomposition with the Daubechies 4 wavelet (db4) [20].

Figure 12a presents the result of a wavelet analysis for the original head gasket. The only meaningful vibrations constitute the response of the

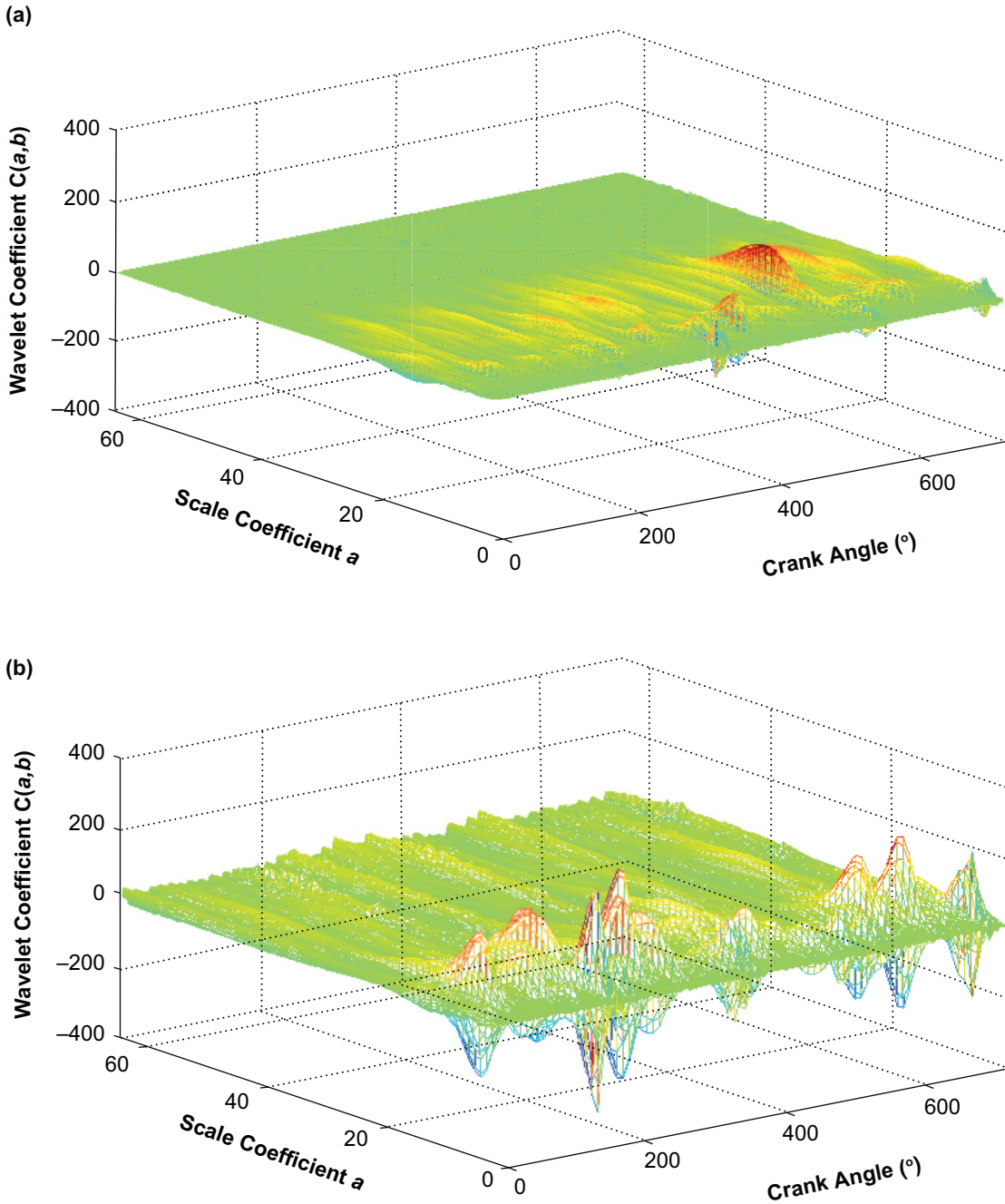


Figure 12. Continuous wavelet decomposition of vibration signal: (a) base model, (b) defective head gasket [21].

system to closing the inlet valve. Figure 12b is a similar analysis for a defective gasket. There are several transient components in the high-frequency range (lower scales). There are quite a few components for scale 9, which corresponds to pseudofrequency of 8125 Hz.

The inverse discrete wavelet transform makes reconstructing the signal possible; Equation 14 describes it [20]:

$$f(t) = \sum_{m,n} (f, \Psi_{m,n}) \Psi_{m,n} = \sum_m \sum_n d_m[n] \Psi_{m,n}, \quad (14)$$

where $d_m[n] = (f, \Psi_{m,n})$ = wavelet coefficients (in this case, $n = 9$), $\Psi_{m,n}$ = wavelets of scale (frequency) coefficients m and shifting in time n .

Figure 13 presents time waveform of the engine head vibrations filtered by the Daubechies 4 wavelet for scale coefficient 9.

Reconstructing the wavelet makes it possible to separate vibration responses corresponding to gasket leakage. To compare, envelopes of a signal

filtered with the db4 wavelet were determined (Figure 14).

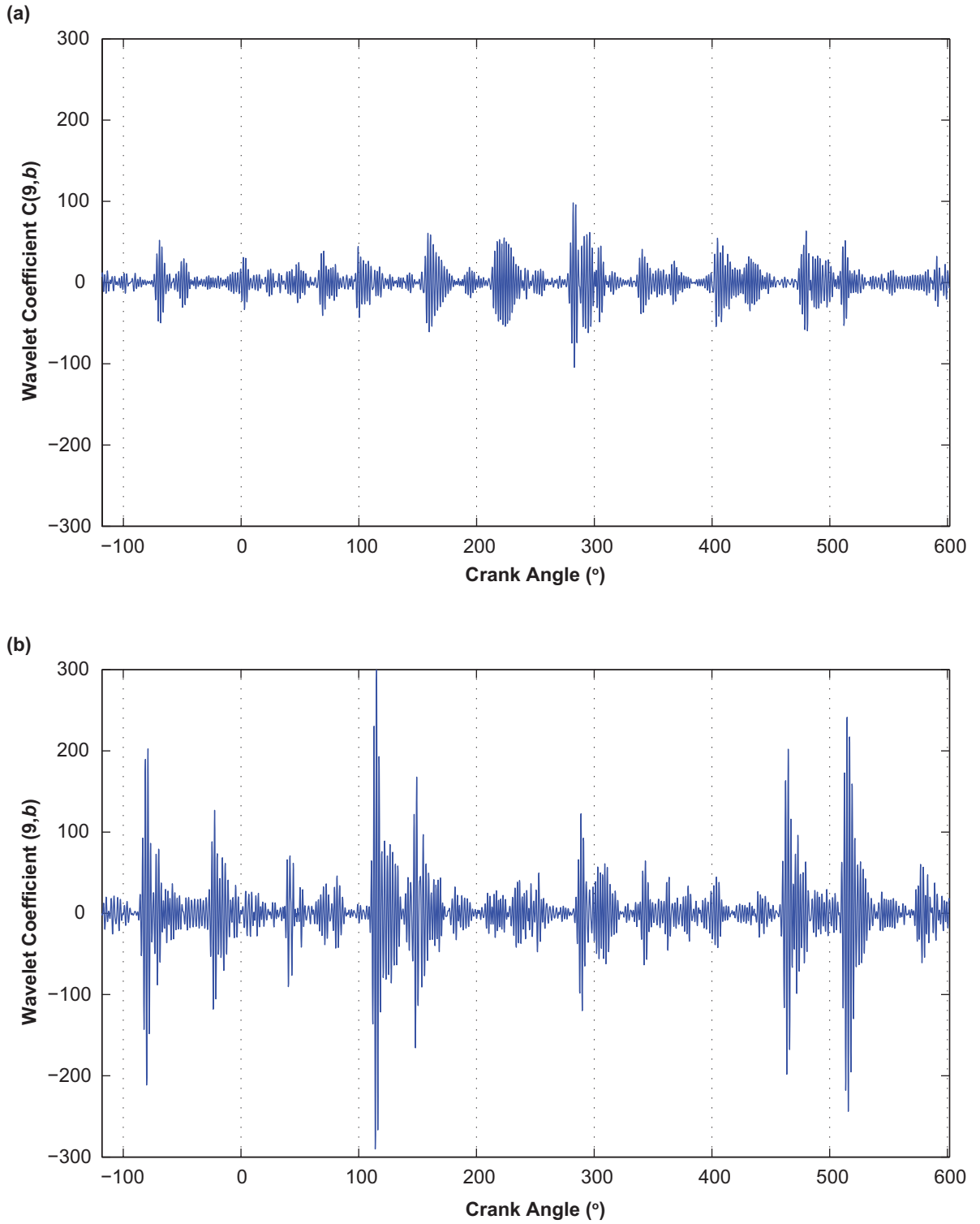


Figure 13. Vibration signal filtered with db4 wavelet, scale coefficient $a = 9$: (a) base model, (b) defective head gasket [21].

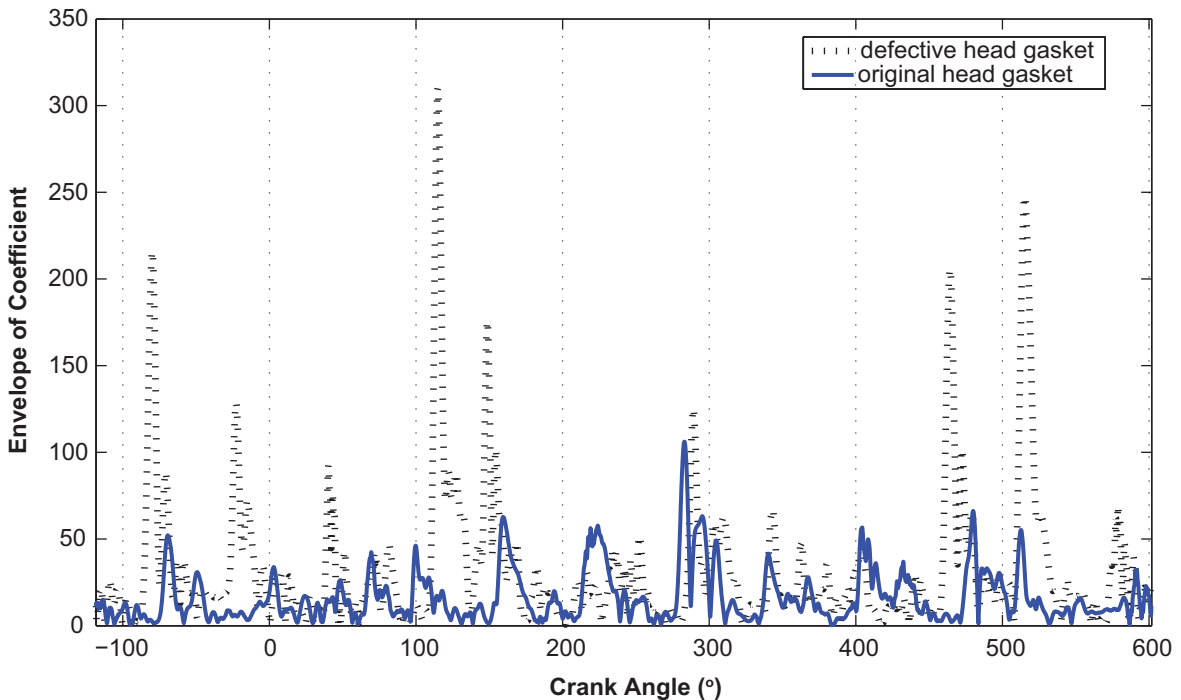


Figure 14. Envelopes of signal filtered with db4 wavelet, scale coefficient $a = 9$ [21].

4. CONCLUSIONS

To improve road transport safety, this article proposes a method of diagnosing mechanical defects of a vehicle driving system based on comparing a current vibration signal with a reference model. This model is described at a very high level of abstraction. It can be used in diagnosing some mechanical defects of subassemblies, provided the parameters are properly identified. Vibration signals measured in two places of the driving system (on the engine head and on gearbox housing) were used in designing the base model.

The model is adaptive, i.e., the diagnostic program obtains a base model after each change of an element of the driving system. Then, the program compares the recorded, properly processed signal with this model. Submodels are described in the frequency domain with the vector of the numbers denoting amplitudes of the spectrum components, determined on the basis of the driving system data.

The submodel of the head vibrations of the internal combustion engine is more difficult to describe. The wavelet model obtained by decomposing a discrete signal can be used. This model

is supplemented with the time notation of the envelope of the acceleration signal of engine vibrations. The envelope signal must be examined in time ranges characteristic for successive vibration responses of the engine to the operations of valves, ignitions, injections, etc. [22].

As a result of the algorithm of signal processing, the diagnostic measures that are developed are more current than the measures determined with base models. The diagnosis consists in testing the hypothesis.

The model was designed and verified with a series of tests on the driving system of a Fiat Punto with a four-cylinder spark ignition engine, capacity of 1.2 L, mileage of ~400 000 km. The fact that this vehicle was not new, confirmed the applicability of the method, since the vibration characteristics of a driving system change over time and defects are delayed. Komorska provides further information on this method [13]. The reliability of this method is still under investigation, because the process is lengthy and costly. The main problem consists in determining appropriate threshold limits to avoid unnecessary alarms. This problem must be solved before the method is used.

The described model was also adapted for the driving systems of low-mileage Ford Fiesta and Renault Thalia with internal combustion engines of 1.4 cm³. Irrespective of the differences in the level of generated vibrations, the character of vibration waveforms in various engines is similar. Moreover, changes in the characteristics of vibration generated by the defects studied are similar.

The proposed model can be used to diagnose other defects for which the vibroacoustic signal is sensitive. This requires further studies and modifications of the program. Diagnostics can be done off-line, whereas the aim of these procedures is to diagnose on-line or on-board. The proposed system can thus supplement existing on-board diagnostic systems, significantly improving vehicle reliability and road transport safety.

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