THE USE OF VIBRATION SIGNALS AND RBF NEURAL NETWORKS IN THE PROCESS OF IDENTIFICATION OF PRESSURE IN INTERNAL COMBUSTION ENGINE CYLINDER

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Abstract: *In recent years the number of vehicles using the roads all over the world constantly increases. Continuous progress in the field of new technologies causes that they become cheaper and cheaper in the production and at the same time more accessible. In order to balance the positive and negative effects of motorisation development, world organisations introduce stricter and stricter regulations concerning safety and natural environment protection. Currently, there are many tests in progress on the development of internal combustion engines which are all mainly conditioned by ecological aspects. All is aimed at constructions which are the most eco-friendly and at the same time which have best technological parameters. In order to maintain proper functioning the presently produced engines are steered with a lot of electronic sensors which are installed in the vehicle. At present, failure symptoms found in the signal, are more and more often studied with the aid of artificial intelligence methods. The major issue referred to in the literature related to methods of artificial intelligence is the method for creating data used in the process of neural network operations. The ability to set up models is the guarantee for a successful process using neural networks. The paper presents an attempt of identification of pressure in internal combustion engine cylinder by measuring the engine block accelerations based on these, building patterns for radial artificial neural networks (RBF).*

Keywords: DIAGNOSTIC SYSTEM, ENGINE, ARTIFICIAL NEURAL NETWORKS

1. Introduction

Modern internal combustion engines of cars use integrated ignition-injection systems. By choosing the right value of the ignition advance angle the criterion of maximum turning moment should be taken into account together with simultaneous low level of harmful substances emission in car fumes. The value of ignition advance angle has direct influence on the run of fuel blend peak firing pressure in cylinder.

Correct process of combustion in ZI engines starts at the moment of fuel-air blend ignition. It is initiated with an ignition spark which is formed between the electrodes of ignition plug. Created flame disperses on the whole charge. The process begins in a laminar way and then continues in a turbulent way. The speed of flame dispersion is dependent on the type of fuel, its composition, temperature and the speed of blend movement.

During the process three stages can be distinguished:
- first stage – from the moment the ignition spark appears to the moment of pressure increase caused by the reaction of oxidation,
- stage two – from the moment of pressure increase as a result of combustion to the moment of the when the maximum pressure value in a cylinder occurs,
- stage three – from the moment of maximum pressure value occurrence to the termination of giving off the heat energy.

First stage includes ignition delay and creation of the area of the flame range. Next the process of fuel oxidation may develop without the inlet of energy from the outside. The time length of this stage depends strictly on the properties of the blend. It is longer with the decrease of compression degree and ignition energy.

In the second stage the heat is created rapidly and in the form of a flame spreads all over the combustible blend. The time length of this stage depends mainly on:
- ingredients of the blend,
- ignition advance angle,
- degree of compression,
- geometry of combustion chamber,
- location of the ignition plug,
- rotational speed of engine,
- degree of blend swirl.

In the third stage, in high temperature, the fuel after-burns in combustion chamber.

Detailed information connected with combustion process in internal combustion can be found in [7, 9, 20, 21].

Heat which is created as a result of combustion of a part of blend led to not burned part may lead to creation of next ignition centres. From the created centres the flame may spread with a speed much higher than the one in normal conditions (20-40 m/s).

The effect of this is the occurrence of a disadvantageous phenomenon called engine knocking (pinging).

The reason of such phenomenon is:
- too high compression degree,
- too soon ignition of the blend,
- too low octane number of the fuel,
- overheating of engine,
- too small degree of blend swirl in combustion chamber,
- too big filling of the cylinder.

Intensity of engine knocking (pinging) depends on:
- degree of compression,
- shape of the compression chamber,
- location of the ignition plug,
- ignition advance angle,
- engine load.

Liability to engine knocking (pinging) increases particularly with the increase of engine walls temperature.

It results from the fact that such process occurs mainly during a rapid acceleration of the engine and by big loads of the engine. Engine knocking (pinging) causes the increase of dynamic loads of crankshaft system. Such loads may eventually lead to a damage of bearings. Increased heat exchange between the working gas and the walls of the combustion chamber causes the increase of temperature of the head, valves and pistons which leads to shortening the life of the whole internal combustion engine.

In order to prevent the engine knocking (pinging) the limitation of the ignition advance angle is applied. In order to limit the probability of engine knocking occurrence the following methods are used:
- use of fuel with the right octane number,
- properly chosen compression degree,
- properly designed shape of combustion chamber.

In practice two different methods are used to identify the process of combustion. First of them assumes the direct measurement of the pressure in a cylinder. However, this method is expensive and requires changes in the construction of the motor head. Also in this case, a proper shape of the sensor tip is required as well as the choice of the location of the sensor and maintenance of the geometry of the combustion chamber. The advantage of this method is the direct measurement of the pressure which allows for easy identification of the combustion process occurring in the engine.

Second method assumes the use of the vibroacoustic effects which occur during engine knocking and which are transmitted by the engine elements. In this case the vibration signals measured on the head or on the engine frame may be used and on their basis identify the occurrence of engine knocking. The method in which the signals are measured is easier and cheaper here, but requires the use of complicated mathematical analyses in order to detect engine knocking. Undoubtedly, a huge signal deformation occurs here together with influence of other engine parts on the shape of the registered signal [1, 3, 4, 12].

Example courses of pressure in cylinder in case of nondetonational burning and knocking burning are showed at the picture 1 and 2.

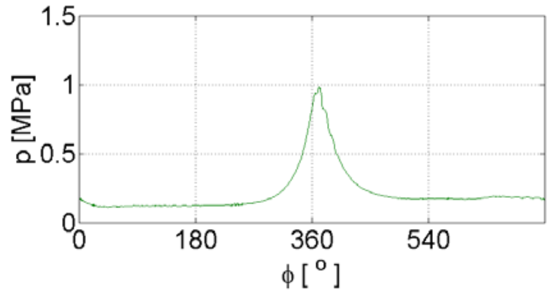

Fig. 1 Course of pressure in cylinder in case of nondetonational burning

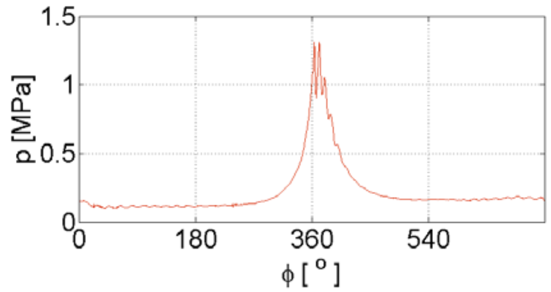

***Fig. 2 1 Course of pressure in cylinder in case of knocking burning*.**

The description of the notions connected with identification of engine knocking in internal combustion engines can be found in [7, 9, 21]

2. Description of the conducted tests

In the experiment it was attempted to initial determine the course of pressure in the combustion process on the basis of registered vibration signal.

The object of test was a 4-cylinder internal combustion engine ZI (installed in a vehicle) with capacity of 1.6 dm^3 fueled with *LPG* gas and petrol.

Tests were conducted in engine test bench type FLA 203 by Bosch company, which made testing of vehicles with single axle drive possible.

During tests the following aspects were registered:
- signal of vibration acceleration in parallel direction to the cylinder axis,
- signal of vibration acceleration in perpendicular direction to cylinder axis,
- signal of combustion pressure,
- signal of the crankshaft rotation angle with marker of upper dead centre of piston position.

Vibration signals were registered with the use of piezoelectric sensors placed on the frame in the area of the fourth cylinder.

Signal of combustion pressure was measured on the fourth cylinder. To perform this a piezoelectric quartz pressure sensor type 6121 was used with charge amplifier type 5011 by Kisler company. Applied converter enables the measurements in particularly difficult conditions which are to be found in combustion chamber. It has measurement range from 0-25 MPa and may work in temperature range from -50 do +350^{o}C without the need of additional cooling application.

Signals were registered with the use of multi-channel measuring device which enabled synchronous sampling with high frequency. The device cooperated with an application created in LabView environment.

Tests were conducted for rotation speed of engine which equaled:
- 1500 rotations/minute,
- 2000 rotations/minute,
- 2500 rotations/minute,
- 3000 rotations/minute,
- 3500 rotations/minute,
- 4000 rotations/minute.

Additionally for idle run registered vibration signals for engine working speed 800 rotations/minute and 4000 rotations/minute.

Measure cycle was repeated twice when an engine was on conventional petrol – petrol (*Pb*), and alternative fuel – *LPG* gas.

Registered vibration signals undergone decomposition process with the use of discrete wavelet transform. Tests were conducted for ten levels of decomposition.

Wavelet analysis consists of signal decomposition and presenting it in the form of linear combination of basic functions, called wavelets. The feature which distinguishes this method of signal analysis from other methods is the multi-stage signal decomposition, variable resolution in time and frequency domain and possibility to use basic functions other than harmonic functions [10-12, 15].

Discrete Wavelet Transform of the signal $x(t)$ is marked as scalar products $x(t)$ and sequence of basic functions $\psi(t)$:

$$DWT = \int_{-\infty}^{+\infty} \psi(t) \cdot x(t) dt$$

As a result of multi-level signal decomposition, the signal approximation is achieved on given level a_k and a detail sum on next levels d_l:

$$x(t) = a_k(t) + \sum_{l=1}^{k} d_l(t)$$

where:
d_l – detail of signal, high-frequency signal element,
a_k – signal approximation, low-frequency signal representation.

Together with the increase of signal decomposition level the participation of details decreases, which causes that with the decrease of resolution, the contents of details in signal approximation decrease.

Discrete Wavelet Transform gives an opportunity of decomposition and selective reconstruction (synthesis) of the signal in the whole range of the analysis. It can be equalled to signal filtration with constant relative bandwidth [10-12, 15].

The tests assumed that the signal of combustion pressure will be determined with the use of signals achieved from vibration signals decomposition on ten levels. However, due to the fact that the tests registered combustion pressure only for one cylinder the attempt of combustion process identification was performed only in a chosen range of the crankshaft angle corresponding with the occurrence of the combustion process in a given cylinder.

The tests assumed to use the neural networks taught on data coming from vibration signals to determine the combustion pressure. Therefore, the registered signals were properly processed with the use of normalization and scaling processes [2, 10, 14, 17, 18, 23].

Example vibration signal which was decomposed with the use of discrete wavelet transform is shown in fig. 3.

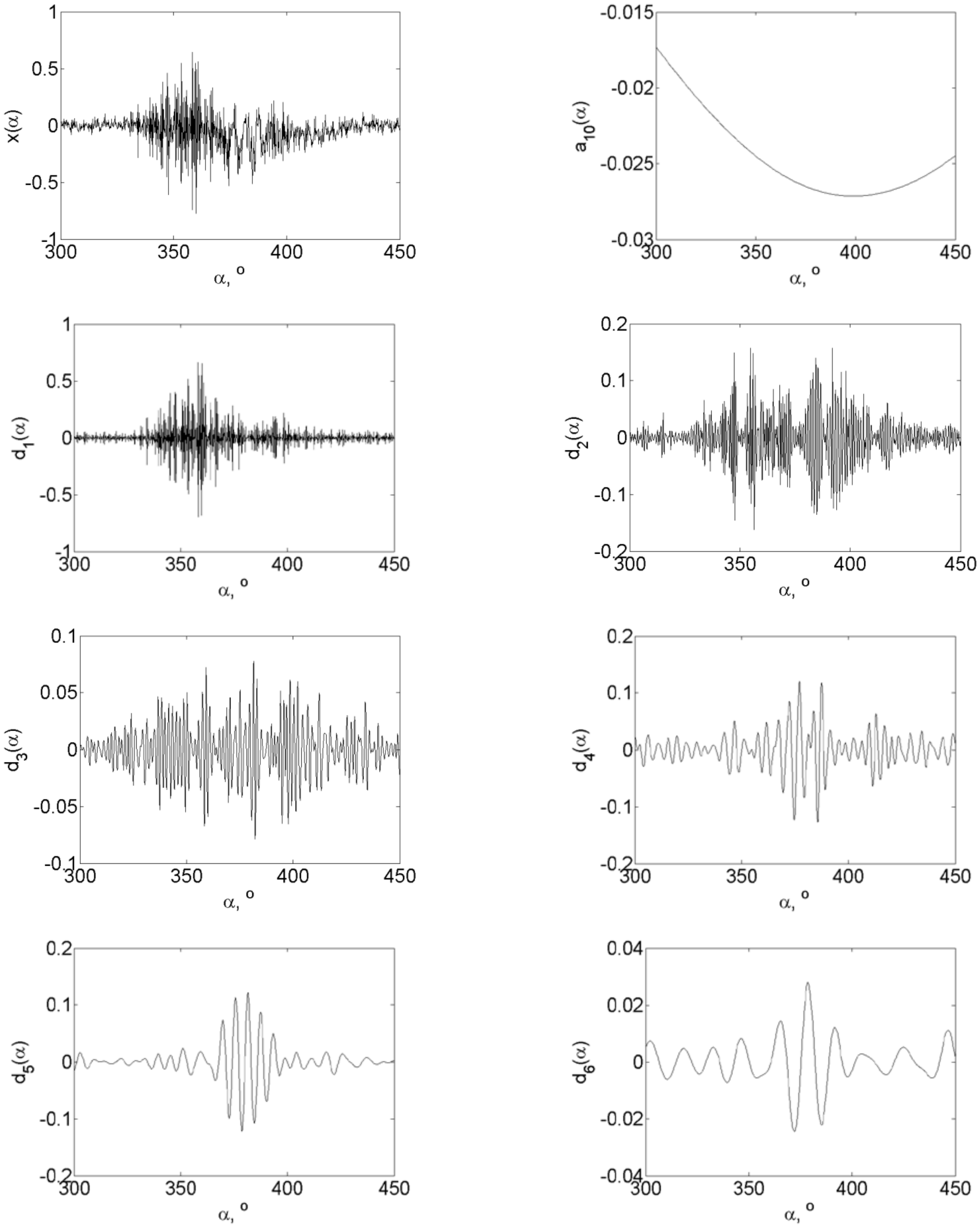

Fig. 3 *Vibration signal decomposed with the use of discrete wavelet transform.*

Signal values achieved for ten decomposition levels were the input data for neural networks (radial basis function) [2, 10, 14, 17, 18, 23]. The values of combustion pressure were expected to be achieved on the network output.

While using such network type, proper smoothening coefficient γ should be selected. It represents the radial deviation of Gauss functions and is a measure of the range of neurons in the hidden layer. This value, when too low, causes the loss of knowledge generalizing property by the network, and, if too high, prevents the correct description of details. Similarly to the radial networks, the value of γ coefficient is determined experimentally [14, 18]. In the experiments the performance of the network for 86 various values of γ coefficient were checked.

3. Results of the tests

Experiments were conducted for vibration signals measured in parallel and perpendicular direction to cylinder axis and for 52 basic wavelets. Influence of basic wavelet choice on the correctness of combustion pressure value determination for the signal measured in parallel direction (a_x) and perpendicular direction (a_y) to the cylinder axis are shown in fig. 4 and 5.

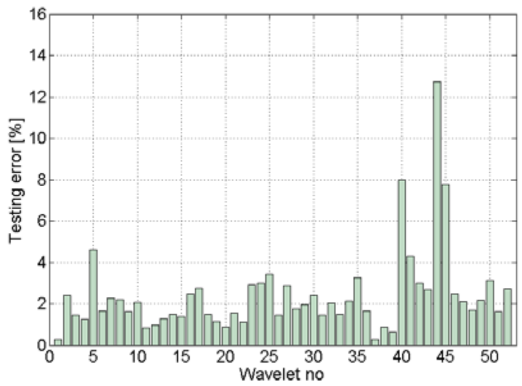

Fig. 4 Influence of basic wavelet on the correctness of the combustion pressure value for vibration signal measured in direction parallel to cylinder axis (Pb, 2000 rotations/min).

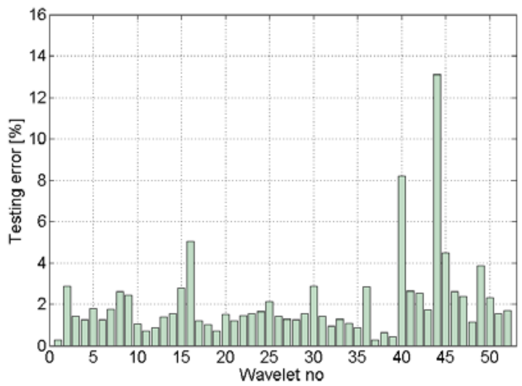

Fig. 5 Influence of basic wavelet on the correctness of the combustion pressure value for vibration signal measured in direction perpendicular to cylinder axis (Pb, 2000 rotations/min).

Made experiments showed strong dependence value identification correctness of burning pressure on factor γ selection for neural network type RBF (Fig. 6).

Analyzing the γ factor influence on error value, noted that for majority of examined variants in which identified burning pressure using one speed (between 8), one kind of petrol (between 2) and one way of signal registration (between 2) and one way of signal registration (a_x or a_y), for another wavelets noted similar character of changes.

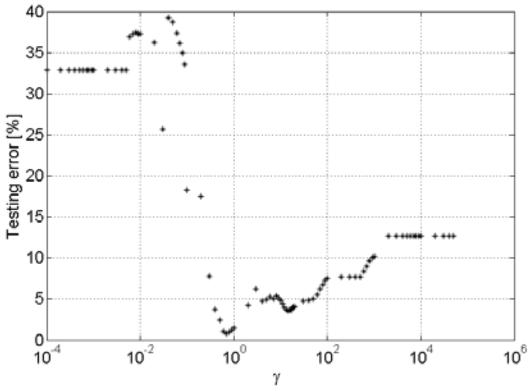

Fig. 6 Example of influence of coefficient γ on testing error.

The best results reached for the next examined variants was:

- 0,21% – *Pb*, 1500 rotations/min, a_x,
- 0,29% – *Pb*, 2000 rotations/min, a_x,
- 0,38% – *Pb*, 2500 rotations/min, a_x,
- 0,49% – *Pb*, 3000 rotations/min, a_x,
- 0,74% – *Pb*, 3500 rotations/min, a_x,
- 0,62% – *Pb*, 4000 rotations/min, a_x,
- 0,26% – *Pb*, 800 rotations/min, idle run, a_x,
- 0,54% – *Pb*, 4000 rotations/min, idle run, a_x,

- 0,21% – *LPG*, 1500 rotations/min, a_x,
- 0,29% – *LPG*, 2000 rotations/min, a_x,
- 0,41% – *LPG*, 2500 rotations/min, a_x,
- 0,46% – *LPG*, 3000 rotations/min, a_x,
- 0,67% – *LPG*, 3500 rotations/min, a_x,
- 0,61% – *LPG*, 4000 rotations/min, a_x,
- 0,24% – *LPG*, 800 rotations/min, idle run, a_x,
- 0,60% – *LPG*, 4000 rotations/min, idle run, a_x,

- 0,21% – *Pb*, 1500 rotations/min, a_y,
- 0,29% – *Pb*, 2000 rotations/min, a_y,
- 0,38% – *Pb*, 2500 rotations/min, a_y,
- 0,50% – *Pb*, 3000 rotations/min, a_y,
- 0,74% – *Pb*, 3500 rotations/min, a_y,
- 0,62% – *Pb*, 4000 rotations/min, a_y,
- 0,27% – *Pb*, 800 rotations/min, idle run, a_y,
- 0,54% – *Pb*, 4000 rotations/min, idle run, a_y,

- 0,22% – *LPG*, 1500 rotations/min, a_y,
- 0,28% – *LPG*, 2000 rotations/min, a_y,
- 0,41% – *LPG*, 2500 rotations/min, a_y,
- 0,46% – *LPG*, 3000 rotations/min, a_y,
- 0,67% – *LPG*, 3500 rotations/min, a_y,
- 0,61% – *LPG*, 4000 rotations/min, a_y,
- 0,23% – *LPG*, 800 rotations/min, idle run, a_y,
- 0,60% – *LPG*, 4000 rotations/min, idle run, a_y.

Analyzing received results it can be said that the biggest influence on received minimum error values of engine speed had the engine speed during which tried to identify the burning process. The highest speed the worst results was received. The reason for this can be decreasing number of registered signal test samples for engine courses with increasing speed with founded constant frequency of signal sampling. From received results we cannot see the significant influence of used petrol, and direction of signal registration on minimum error values.

5. Conclusion

The vehicles of today are full of most modern systems which serve to increase safety and comfort and reduce the negative impact on the environment. At the same time the works are continued on further development of such technologies which can be noticed in various scientific papers [2-4, 11-13, 15, 16, 24]. Development of branches connected with most modern technologies does not limit the conduction of basic research works which lead to similar measurable effects such as, for example, increase of safety by increase of the durability of the power transmission system elements [5, 6, 8, 19, 22].

The article presents results which aimed at determination of combustion pressure in cylinder of internal combustion engine with the use of neural networks which were taught on data coming from measured vibration signals. Results achieved in the experiment are on satisfactory level and are the basis to continue further experiments.

Conducted experiments have shown a huge dependence of correct identification of combustion pressure on the choice of the coefficient γ for the radial neural network (RBF).

It was also noticed during the tests that the choice of the right basic wavelet used during signal decomposition with the use of discrete wavelet transform has a big influence on the determined value of combustion pressure. The best results were achieved for basic wavelets of haar and reverse biorthogonal type.

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