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THE FOURIER TRANSFORM AS A NEW APPROACH OF EVALUATING THE INTERNAL COMBUSTION ENGINE INDICATOR DIAGRAM

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Abstract

In this paper, the authors present an introduction to the new method of evaluating the indicator diagram of internal combustion engine. For several years, it was observed that analyses of combustion processes have been hardly changed since they were conducted for the first time. At the moment, the diagrams are plotted more and more precisely owing to the new sensors and digital processors. Despite all of these high technical advantages, which were obviously unavailable in the past, theoretical approach for describing indicator diagram has not changed in significant way. Nowadays, the indicator diagrams are still evaluated very generally and are presented in much too idealistic way as a smooth curve of pressure changes, without any disturbances, which are being detected very easily now. Furthermore, it appears that performance improvements of the IC engines are in need of developing new methods for analysis and evaluation. The Fourier transform is a new way to look at the combustion process in the engines. It is basically a mathematical instrument for analysing different types of signals, which are transformed, from time domain into frequency domain. It enables identifying specific sinusoidal components of arbitrary signals and separates relevant ones from the noise. This allows one to see significant differences in two or more apparently similar signals and detect the crucial parts. If we treat pressure changes in time like a common signal, we can compute Fourier transform and see basic components of the diagram.

Keywords: *indicator diagram, Fourier transform, internal combustion engine*

1. Introduction

The indicator diagram analysing is one of the key method to evaluate the combustion process in the engine. The aim is to record the pressure changes of the working mixture at the compression, ignition and decompression phases in the cylinders. The recorded data is plotted into the indicator diagram. Most commonly, the pressure variable in this case is dependent on crankshaft angle, sometimes on time or piston position.

At the current available literature we can see, that processes of combustion are described very generally, based on theoretical and real engine cycles. Presented diagrams are shown as almost perfect graphs with smooth lines and no distortions, even if we currently know, thanks to much more accurate pressure sensors and processors, that locally, combustion process has a random characteristic with different kinds of disturbances, which are frequently omitted or ignored by researchers. Focusing on this imperfections supply information about engine performance [10, 11].

Despite all of the technical progression, the principles remain the same for over a hundred years [12, 13, 14, 15]. The importance of indicator diagrams has not diminished over the years, and the knowledge, which can be derived, is still essential for engine run evaluation. Based on these diagrams, we can establish the following factors [1]:

1. Whether the valves are correctly and evenly timed in order to insure the best distribution of mixture.
2. The power of the engine developed in the cylinder, but also the lost energy, such as: leakages, backpressure.

3. Whether the ports and passages are of proper sizes.
4. The condition of the piston and valves as it relates to the leakages.

2. Open and closed indicator diagrams

The indicator diagrams can be presented either as function of pressure dependent on volume of space above the piston crown, or as a function of pressure dependent on crankshaft angle.

The first ones are called closed indicator diagrams. They are mainly used for theoretical and real diagram comparison (Fig. 1), but they are not very useful in precise pressure determination. However, they can be used for mean indicated pressure calculation (Fig. 2).

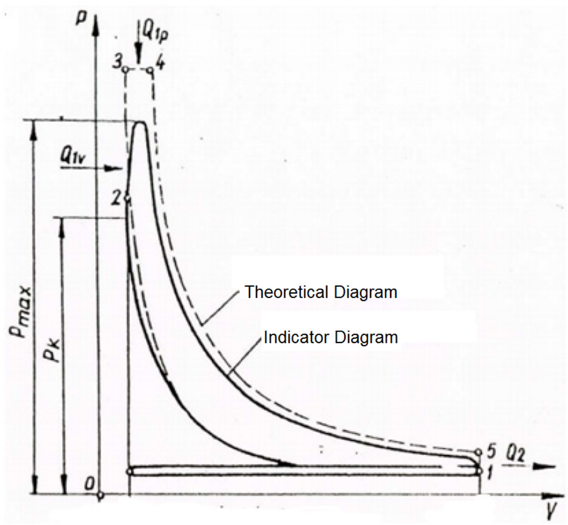

Fig. 1. Comparison of the theoretical and indicated diagrams [2]

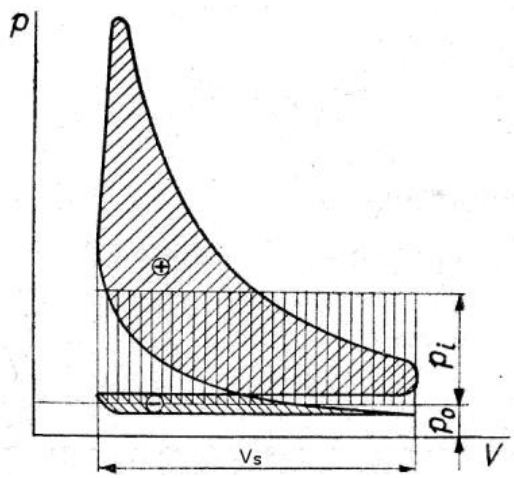

Fig. 2. Mean indicated pressure in Diesel engine [4]

The second ones are called open indicator diagrams (Fig. 3). They show curve of the pressure changes within at least one full engine cycle, which means 2 rotations (720°) of the crankshaft (in 4-stroke engine).

Open indicator diagram can supply us with important information such as maximum pressure, ignition time, speed of pressure build up, valve timing.

Real indicator diagrams differ from theoretical ones because of following conditions [4]:

– working mixture is exchanged in every cycle,
– compressing mixture has a different physical quality than decompressing one,

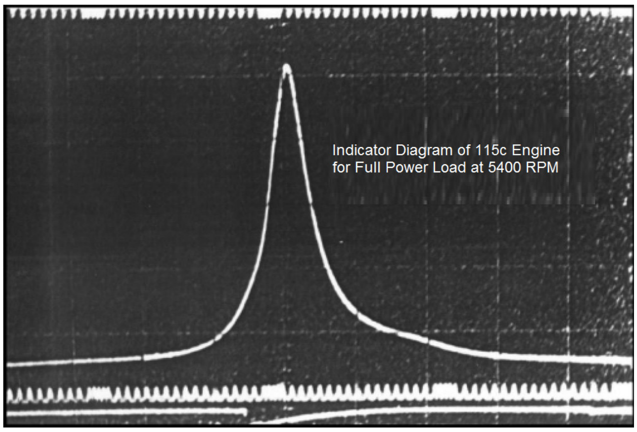

Fig. 3. Open indicator diagram [4]

- amount of mixture changes through the piston leakages,
- heat is not provided from outside, but from burning the mixture,
- heat exchange is not consistent with premises: p = const. and V = const,
- there are losses from incomplete combustion [16, 17, 18, 19, 20],
- mixture compressing and decompressing is not performed as an isentropic process.

3. Problems with diagrams evaluation

The combustion cycle is a random, unpredictable process, which in theory should be repetitive, but in practice shows, that every other graph is different (Fig. 4).

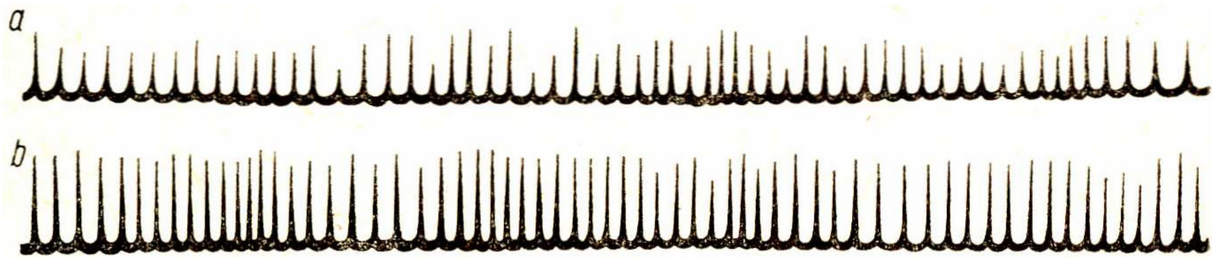

Fig. 4. Concentrated indicator diagrams: a – idle, b – high engine load [5]

The main reason why cycles differ from one another is that both cylinder filling and combustion are unequal. Due to these factors, in order to obtain reliable diagrams there is a need for using statistical averaging over multiple cycles.

4. The Fourier transform

The Fourier series is an expansion of a periodic function in terms of an infinite sum of sines and cosines, which basically shows that every random function can be decomposed into a sum of simple sinusoidal functions with different values of amplitudes and frequencies. The computation and study of Fourier series is known as harmonic analysis [6].

The Fourier transform is essentially a generalization of the complex Fourier series and after changes to an integral; the basic equations are [7]:

$$f(x) = \int_{-\infty}^{\infty} F(k)\, e^{2\pi i kx}\, dx\,, \tag{1}$$

$$F(k) = \int_{-\infty}^{\infty} f(x)\, e^{-2\pi i kx}\, dx\,. \tag{2}$$

The continuous Fourier transform is called the discrete Fourier transform and defined as [8]:

$$f(v) = F_t[f(t)](v) = \int_{-\infty}^{\infty} f(t)\, e^{2\pi i v t}\, dx \,. \tag{3}$$

For practical application, the discrete Fourier transform is calculated by an algorithm called the fast Fourier transform. It is a much more computationally efficient method for generating the Fourier transform, because it reduces the number of needed computations.

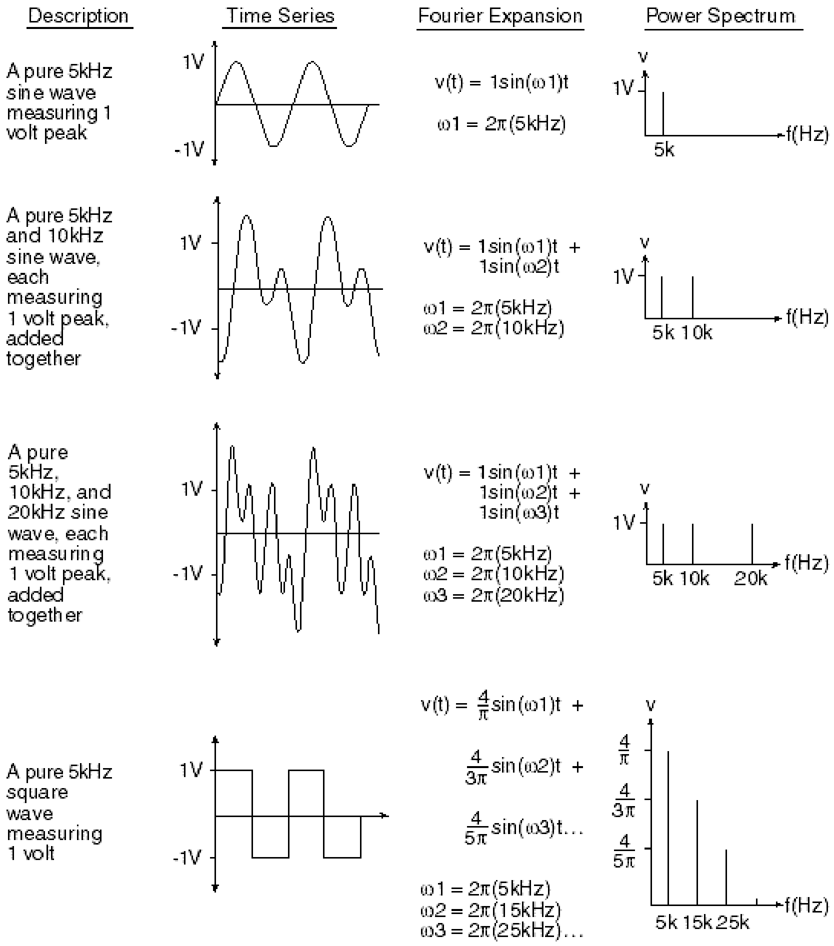

Fig. 5. The Fourier transform illustrated [9]

5. The ESC engine test

The European Stationary Cycle (ESC) test, also previously known as European Automobile Manufacturers' Association (ACEA) cycle, or Organisation Internationale des Constructeurs d'Automobiles (OICA) cycle, was introduced alongside the European Transient Cycle (ETC) and the European Load Response (ELR) by the Euro III emission regulation – Directive 1999/96/EC, effective year 2000 – for emission measurement from heavy-duty diesel engines.

The ESC test is a 13-mode, steady-state procedure that has replaced the ECE R49 cycle test. The test is performed on an engine dynamometer over a sequence of steady-state modes. In each mode, engine must be operated for the exact amount of time, completing engine speed and load changes in the first 20 seconds. All speeds need to be held to within ±50 rpm and torques within ±2% of the maximum torque at the test speed [3].

The test was performed on Volkswagen 1.9 TDI engine, code: AVB. This engine produces maximum power of 101 HP at 4000 rpm and 250 Nm at 1900 rpm. The 13-mode characteristic is shown in Fig. 7.

Tab. 1. The ESC modes description [3]

Mode	Engine Speed	Load, %	Weight, %	Duration
1	Low idle	0	15	4 minutes
2	A	100	8	2 minutes
3	B	50	10	2 minutes
4	B	75	10	2 minutes
5	A	50	5	2 minutes
6	A	75	5	2 minutes
7	A	25	5	2 minutes
8	B	100	9	2 minutes
9	B	25	10	2 minutes
10	C	100	8	2 minutes
11	C	25	5	2 minutes
12	C	75	5	2 minutes
13	C	50	5	2 minutes

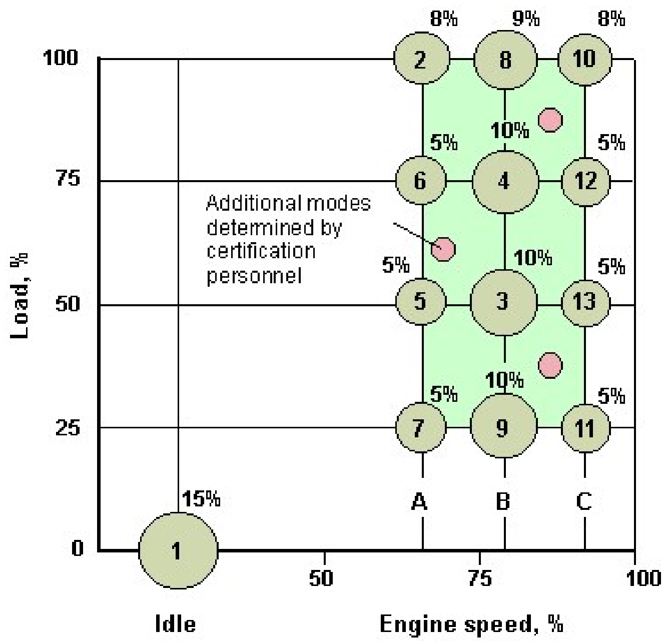

Fig. 6. The ESC characteristic diagram [3]

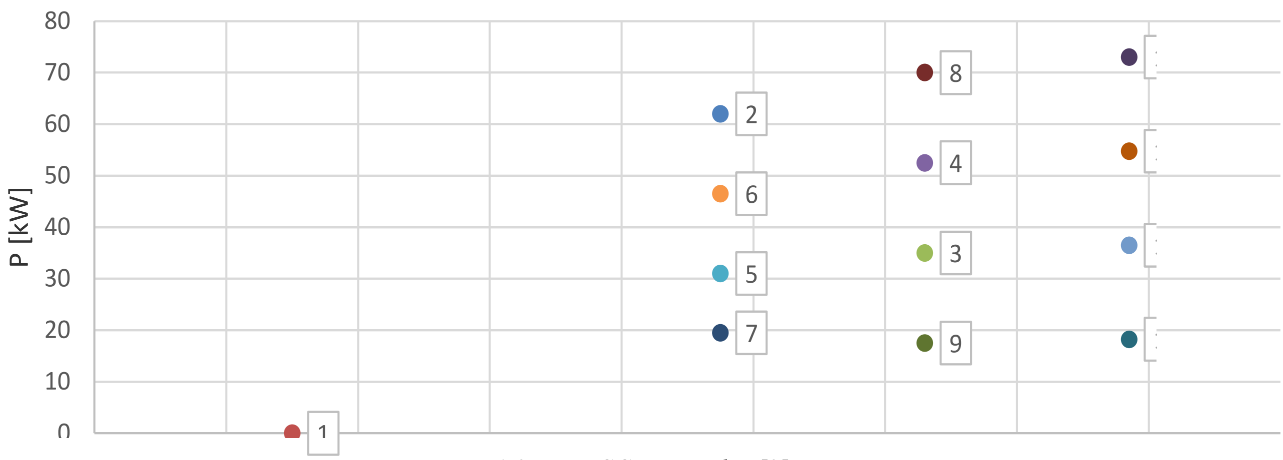

Fig. 7. VW 1.9 TDI ESC test modes [2]

6. The results of the ESC test

Below, we present examples of the 3-stage analysis, which was performed during the ESC test. First stage was to plot indicator diagram of each mode (Fig. 8 and 11). Next, we estimated the derivative of pressure changes in time (Fig. 9 and 12) and then, we computed the fast Fourier transform of this derivative (Fig. 10 and 13).

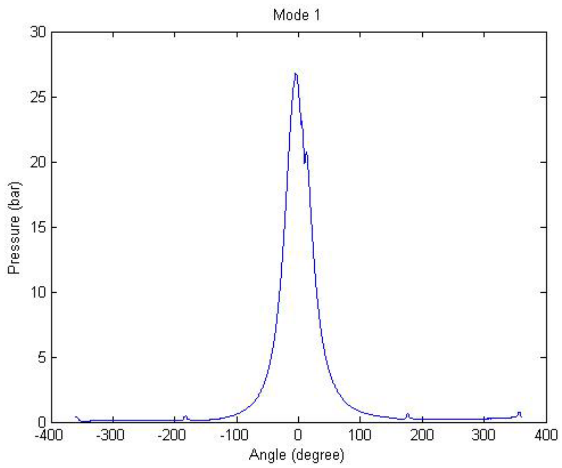

Fig. 8. The indicator diagram

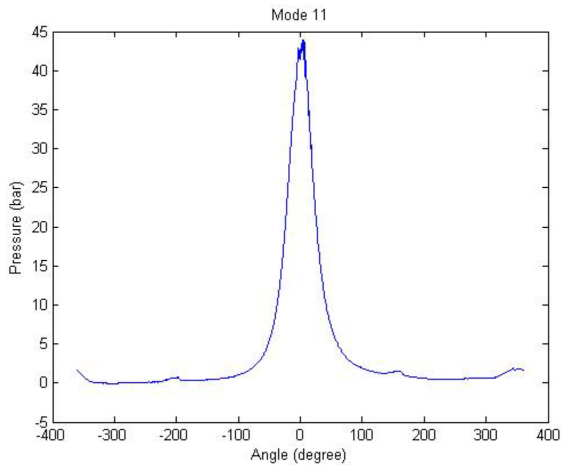

Fig. 11. The indicator diagram

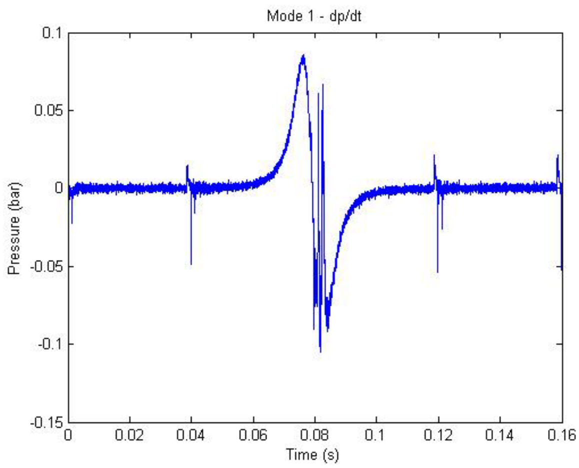

Fig. 9. Derivative of pressure change in time

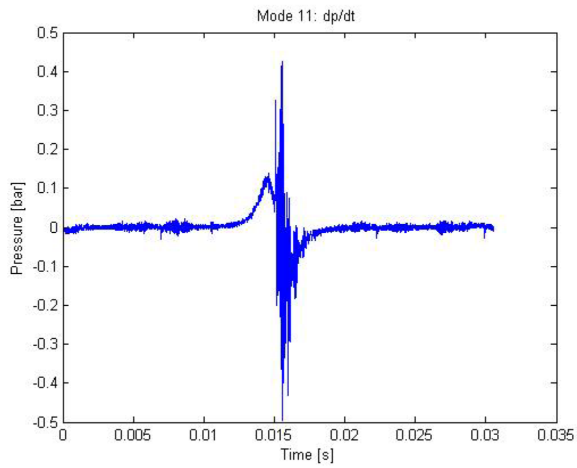

Fig. 12. Derivative of pressure change in time

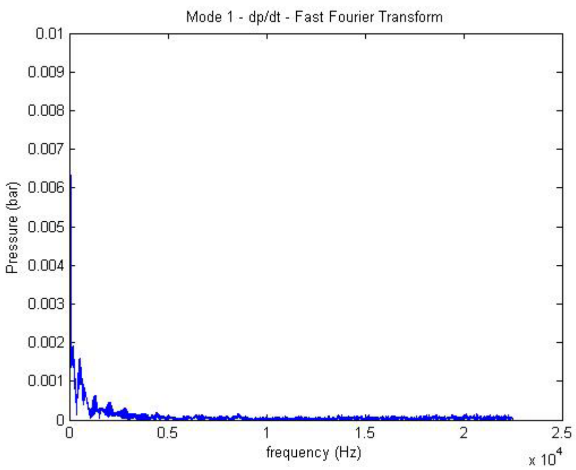

Fig. 10. The fast Fourier transform

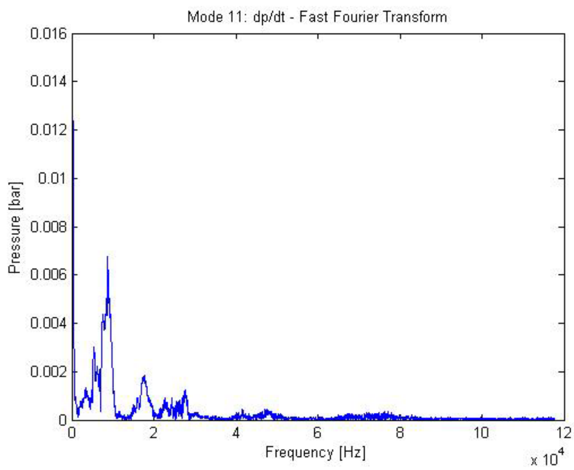

Fig. 13. The fast Fourier transform

Tab. 2. VW 1.9 TDI engine ESC modes values [2]

Mode	n [rpm]	P [kW]	Mode	n [rpm]	P [kW]	Mode	n [rpm]	P [kW]
1	750	0	6	2375	46.5	10	3925	73
2	2375	62	7	2375	19.5	11	3925	18.25
3	3150	35	8	3150	70	12	3925	54.75
4	3150	52.5	9	3150	17.5	13	3925	36.5
5	2375	31						

The results show differences between pressure changes in particular modes. The mode 1-idle speed contains only one important frequency, which stands out, while in mode 11 we can see other appearing frequencies. This suggests that characteristics of the pressure changes vary in every mode and becomes more complex with another load and engine speed. This method aims to present correlation between engine parameters in different states and related combustion processes.

7. Conclusions

The purpose of this preliminary study was to find and verify a new method for indicator diagram evaluation.

We believe that there is a strong need for exploring the new ways of describing engine performance and extracting additional information. The progress, which involves engine development, new emission regulations, reduced fuel consumption or downsizing, requires improved diagnosis, where the current state-of-the-art will become insufficient. Every attempt to establish a fresh method of engine analysis should be thoroughly tested and described. This approach is being currently developed.

Studies for this paper demonstrate that there is a high probability that Fourier transform method will be very useful in the indicator diagram analysis.

References

[1] Corp, C. I., *The interpretation of Indicator Diagrams*, Transactions of the Kansas Academy of Science (1903-), Vol. 20, pp. 239-244, 1905.
[2] Chmielewski, P., *Analiza statystyczna wykresu indykatorowego silnika o zapłonie samoczynnym,* Politechnika Wrocławska, Wrocław 2016.
[3] https://www.dieselnet.com/standards/cycles/esc.php.
[4] Fudalej-Kostrzewa, E., *Wykres indykatorowy silnika spalinowego*, Wydział Samochodów i Maszyn Roboczych, Instytut pojazdów, Politechnika Warszawska.
[5] Ustrzycki, A., *Ocena procesu spalania na podstawie wykresu indykatorowego*, Laboratorium Silników spalinowych – Materiały pomocnicze, Katedra Silników Spalinowych i Transportu, Politechnika Rzeszowska.
[6] http://mathworld.wolfram.com/FourierTransform.html.
[7] http://mathworld.wolfram.com/DiscreteFourierTransform.html.
[8] http://mathworld.wolfram.com/FastFourierTransform.html.
[9] https://www.dataq.com/data-acquisition/general-education-tutorials/fft-fast-fourier-transform-waveform-analysis.html.
[10] Jankowski, A., *Chosen Problems of Combustion Processes of Advanced Combustion Engine*, Journal of KONES, Vol. 20, No. 3, DOI: 10.5604/12314005.1136852, pp. 203-208, Warsaw 2013.

[11] Jankowski, A., Czerwinski, J., *Memorandum of Prof. A. K. Oppenheim and an Example of Application of the Oppenheim Correlation (OPC) for the Heat Losses during the Combustion in IC-Engine*, Journal of KONES, Vol. 17 No. 2, Warsaw 2010.
[12] Jankowski, A., Czerwinski, J., *Memorandum of Prof. A. K. Oppenheim and an Example of Application of the Oppenheim Correlation (OPC) for the Heat Losses during the Combustion in IC-Engine*, Journal of KONES, Vol. 17 No. 2, Warsaw 2010.
[13] Jankowski, A., *Heat transfer in combustion chamber of piston engines*, Journal of KONES Vol. 17 No. 1, pp. 187-197, Warsaw 2010.
[14] Jankowski, A., Kowalski, M., *Creating Mechanisms of Toxic Substances Emission of Combustion Engines,* Journal of KONBiN No. 4(36), DOI 10.1515/jok-2015-0054 pp. 33-42, 2015.
[15] Jankowski, A., *Laser Research of Fuel Atomization and Combustion Processes in the Aspect of Exhaust Gases Emission,* Journal of KONES, Vol. 15, No. 1 pp. 119-126, Warszawa 2008.
[16] Jankowski, A., *Test Stand for Modelling of Combustion Processes of Liquid Fuels,* Journal of KONES, Vol. 21, No. 2, DOI: 10.5604/12314005.1133885, pp. 121-126, Warsaw 2014.
[17] *Modelling of Combustion Processes of Liquid Fuels,* Journal of KONES, Vol. 19, No. 4, DOI: 5604/12314005.1138352, pp. 239-244, Warsaw 2012.
[18] Skrętowicz, M., Jankowski, A., Haller, P., Woźniak, J., Janas, M., *Risk Evaluation of Driver Exposure to Exhaust Fumes Inside the Passenger Car Cabin in Urban Traffic Conditions,* Journal of KONES, Vol. 23, No. 3, DOI: 10.5604/12314005.1216394 pp. 457-464, Warsaw 2016.
[19] Zurek, J., Jankowski, A., *Experimental and Numerical Modelling of Combustion Process of Liquid Fuels under Laminar Conditions,* Journal of KONES, Vol. 21, No. 3, pp. 309-316, DOI: 10.5604/12314005.1134559, Warsaw 2014.
[20] Zurek, J., Kowalski, M., Jankowski, A., *Modelling of Combustion Process of Liquid Fuels under Turbulent Conditions,* Journal of KONES, Vol. 22, No. 4, DOI: 10.5604/12314005.1168562, pp. 355-344, 2015.