Statistics of indicated pressure in combustion engine.

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Abstract: The paper presents the classic form of pressure waveforms in the burn chamber of a diesel engine but based on strict analytical basis for amending the displacement volume. The pressure measurement results are obtained in the engine running on an engine dynamometer stand. The study was conducted by a 13-phase ESC test (European Stationary Cycle). In each test phase, 90 waveforms of pressure are archived. As a result of extensive statistical analysis, it was found that while the engine is idling, the distribution of 90 values of pressure at any value of the angle of rotation of the crankshaft can be described as uniform. In each point of characteristic of the engine corresponding to the individual phases of the ESC test, 90 of the pressure for any value of the angle of rotation of the crankshaft can be described as normal distribution. These relationships are verified using tests: Shapiro-Wilk, Jarque-Bera, Lilliefors, Anderson-Darling. In the following part, with each value of the crank angle, are obtained values of descriptive statistics for the pressure data. In its essence, the new method can be used to further analysis, especially the combustion process in the engine. It was found, e.g., a very large variances of pressure near the transition from compression to expansion stroke. This lack of stationarity of the process can be important both because of the emissions of exhaust gases and fuel consumption of the engine.

1. Introduction

The challenge facing the automotive industry, mainly reduce toxic exhaust emissions. This limitation must be achieved while reducing energy consumption. This means the need to raise the efficiency of drives.

Progress is seen in hybrid drives. Although this type of drive is unquestionable past and future are:

- The density of accumulated energy is too low - which means the need for unproductive by carrying extra weight in vehicles, and it must reflect negatively on the energy efficiency of vehicles.
- Casa charging is too long - at the same time prevents efficiently recover energy, e.g. in the braking process.
- There are no reports as to where the estimates have come up energy, especially electricity, in quantities enabling; meet the demand of modern transportation.

Until these problems are resolved intentional is still perfecting the classic power sources, especially combustion engines. The issue of improving the internal combustion engine is part of this work. It deals with questions related to the theoretical foundations of internal combustion engines associated with the course indicated pressure. Presents the classic form of indicator diagram engine but based on strict analytical basis for amending the displacement volume. This description has been verified measurement.
results course of the pressure in the combustion engine running on an engine dynamometer. The study was conducted by a 13-phase test ESC. In each test phase archived 90 waveforms indicated pressure in the later part of the work at each of the tested values of the angle of rotation of the crankshaft, values of descriptive statistics. Thus the data obtained, which in its essence, a new way to approach the issue of analysis indicator diagram can be used to further works, especially on the combustion process in the engine.

2. Pressure waveforms in the burn chamber of the engine
An indicator diagram showing the development of the internal combustion engine cylinder pressure as a function of engine crank angle \( p = p(\alpha) \) - called indicator diagram of an open - Fig. 1. If the pressure is shown as a function of the volume of the gases contained in the cylinder between the piston and cylinder head the \( p = p(V) \) - a function that is called the graph of the indicator closed - Fig. 2.

![Figure 1. Open indicator diagram test engine](image)

The transition from open to the graph chart contained requires knowledge of changes in the volume above the piston as a function of crank angle. Commonly known from the literature, however, is the basis of all the work, there is a dependency strict. Close relationship here is as follows describing calculation of fuel consumption [14].

The size of the geometric test engine necessary to determine the path of the piston is shown later in this article.

This relation was used to determine the piston travel in function of the angle of rotation of the crown and therefore also the determination of the relationship \( V_{rms} = V_{rms}(\alpha) \), and consequently, \( p = (V_{rms}) \).
An indicator diagram determined using the apparatus, the indication consisting of:

- a pressure sensor arranged in the combustion chamber,
- charge amplifier,
- a sensor of the angular position of the engine crankshaft, and
- DVR.

Indicated engine is thus brought virtually to the pressure prevailing in the working cylinder of the internal combustion engine depending on the angle of rotation of the crankshaft during one cycle. The real engine cycle differs quite significantly from the theoretical cycle. The engine exchanged the working medium after each cycle. Due to chemical reaction changes the number of moles of the thermodynamic medium is expanded and thus the factor have different physical properties compared to compressed medium. As a result of leakage of the combustion chamber of the thermodynamic medium amount of change no heat is supplied to the thermodynamic medium from the outside, but they result in the combustion of the fuel in the cylinder, – conduct heat input is not consistent with the assumptions $p = \text{const.}$ and $V = \text{const}$. There is a loss of incomplete and incomplete combustion of fuel, – compression and expansion factor is not done isentropic; in the initial period of the compression heat is supplied from the hot cylinder wall to the agent at a later stage during the expansion and compression heat is removed from the refrigerant to the cooler walls of the cylinder and its head,• no heat is dissipated from the refrigerant after it has completed its work, but the agent exiting the cylinder carries away a large quantity of thermal energy. All of this belies the thermodynamic assumptions underlying the creation known from the literature indicator diagrams and their subsequent analysis. By joining doa analysis obtained indicator diagrams, especially in terms of optimizing processes in the engine runs you should be aware of this.

3. Engine and his research

Parameters of the tested diesel engine

- Capacity: 1896 cm³
- Bore: 79.5 mm
- Stroke: 95.5 mm
• Compression ratio: 19.5
• Arrangement of cylinders: in line
• Number of cylinders: 4
• Number of valves: 8
• Injection system: pump injectors,
• The maximum power of engine: 100 kW.

The study was conducted using an engine dynamometer with the appropriate gear. Pressure measurement performed using the sensor.

4. Points characteristics of the ESC test
Engine test was carried out using engine dyno. Engine loaded by the ESC test. The detailed procedure determine the parameters of the test in clinical engine described in [15]. The values of engine speed and load corresponding shown in Figure 3. The size of the circles in the figure correspond to the share of the load in the total load in the assay.

![Figure 3. Points motor characteristics corresponding to the requirements of the ESC test.](image)

5. Averaged pressure Indicated
As a result of analysis (not presented here) we found that while the engine is idling (phase 1 test ESC), the statistical distribution of 90 of the pressure at each value of the crank angle, can be described statistically uniform distribution. While in the other phases of the test, 90 such values can describe a normal distribution. The verification tests were performed using the Shapiro-Wilk, Jarque-Bera, Lilliefors, Anderson-Darling.

Measuring the angle of rotation of the crankshaft was carried out with an accuracy of 0.1 degrees. As a result, during one cycle of the engine 7200 obtained the angle of rotation of the crankshaft and the same, the corresponding values of pressure. In each phase, the ESC test measurement was repeated 90 times. In each phase of the test obtained so 7200X90 = 648 000 of the crank angle and the corresponding pressure.

It must be emphasized that the pressure measured at one point in the combustion chamber. Location of measuring point due to the construction of the engine and was not in any way chosen.
Presentation of the whole experimental material is, in this work, for obvious reasons, impossible. To illustrate the results obtained are used merely an example of data 13, part of the test. This phase corresponds to the load of 50% at a speed of 4075 rpm.

At each value of the angle of rotation of the crankshaft 90 of pressure values were available. It was possible, therefore, to carry out statistical analysis of these values and setting the parameters of descriptive statistics. Selected results from these statistics are shown in Table 1.

**Table 1.** An example of the results of descriptive statistics 90 pressure at selected values of the crank angle in the 13th stage of the test ESC.

| CA [deg] | Average | Standard error | Median | Mode | Standard deviation | Sample variance | Kurtosis | Inclination | Range | Minimum | Maximum | Sum | Counter | Trust level (95%) |
|----------|---------|----------------|--------|------|--------------------|----------------|----------|-------------|--------|---------|---------|-----|---------|------------------|
| -10      | 41.35   | 0.02           | 41.33  | 41.29| 0.15               | 0.02           | 0.38     | 0.20        | 41.00  | 41.77   |         | 3721.92 | 90.00   | 0.03       |
| -9       | 42.36   | 0.02           | 42.32  | 42.32| 0.20               | 0.04           | 0.49     | 0.47        | 41.84  | 42.88   | 3812.05 | 90.00 | 0.04    |
| -8       | 43.41   | 0.07           | 43.21  | 43.12| 0.67               | 0.44           | 6.93     | 2.56        | 42.66  | 46.40   | 3907.34 | 90.00 | 0.14    |
| -7       | 44.33   | 0.12           | 43.88  | 43.75| 1.12               | 1.24           | 6.40     | 2.50        | 43.43  | 49.45   | 3989.55 | 90.00 | 0.23    |
| -6       | 44.68   | 0.09           | 44.34  | 44.31| 0.90               | 0.80           | 4.40     | 2.21        | 43.91  | 48.20   | 4021.54 | 90.00 | 0.19    |
| -5       | 45.01   | 0.12           | 44.53  | 44.53| 1.18               | 1.40           | 4.63     | 2.29        | 44.13  | 49.63   | 4051.32 | 90.00 | 0.25    |
| -4       | 45.11   | 0.14           | 44.55  | 44.55| 1.31               | 1.71           | 4.20     | 2.20        | 44.04  | 50.08   | 4059.50 | 90.00 | 0.27    |
| -3       | 45.12   | 0.17           | 44.43  | 44.43| 1.38               | 2.49           | 4.29     | 2.20        | 43.97  | 51.39   | 4061.08 | 90.00 | 0.33    |
| -2       | 45.14   | 0.20           | 44.22  | 44.13| 1.94               | 3.75           | 3.85     | 2.07        | 43.71  | 53.16   | 4062.44 | 90.00 | 0.41    |
| -1       | 45.41   | 0.25           | 44.19  | 44.00| 2.38               | 5.65           | 1.18     | 1.56        | 43.53  | 52.46   | 4087.27 | 90.00 | 0.50    |
| 0        | 47.66   | 0.31           | 47.04  | 46.8 | 258                | 8.85           | -0.88    | 0.52        | 43.38  | 54.36   | 4289.47 | 90.00 | 0.62    |
| 1        | 50.92   | 0.21           | 50.74  | 52.55| 1.95               | 3.81           | -0.10    | -0.23       | 45.15  | 54.64   | 4582.50 | 90.00 | 0.41    |
| 2        | 50.30   | 0.22           | 50.19  | 52.28| 2.12               | 4.49           | 0.48     | -0.09       | 44.33  | 55.31   | 4527.27 | 90.00 | 0.44    |
| 3        | 51.04   | 0.26           | 51.08  | 50.06| 2.44               | 5.95           | 0.01     | -0.23       | 44.38  | 55.87   | 4593.34 | 90.00 | 0.51    |
| 4        | 52.45   | 0.24           | 52.10  | 52.08| 2.28               | 5.20           | -0.47    | 0.26        | 47.23  | 58.24   | 4720.63 | 90.00 | 0.48    |
| 5        | 51.79   | 0.28           | 51.68  | 51.22| 2.66               | 7.07           | -0.08    | 0.08        | 46.05  | 59.37   | 4661.54 | 90.00 | 0.56    |
| 6        | 52.53   | 0.22           | 52.59  | 51.61| 2.13               | 4.55           | -0.05    | -0.43       | 46.01  | 56.14   | 4727.47 | 90.00 | 0.45    |
| 7        | 51.89   | 0.24           | 51.99  | 50.64| 2.24               | 5.04           | 1.43     | 0.26        | 46.46  | 59.95   | 4670.11 | 90.00 | 0.47    |
| 8        | 51.21   | 0.27           | 51.46  | 50.84| 2.60               | 6.77           | -0.16    | -0.35       | 43.58  | 56.44   | 4608.84 | 90.00 | 0.54    |
| 9        | 51.68   | 0.27           | 51.38  | 50.82| 2.52               | 6.35           | -0.33    | 0.48        | 46.52  | 58.49   | 4650.97 | 90.00 | 0.53    |
| 10       | 50.41   | 0.20           | 50.53  | 51.22| 1.94               | 3.76           | -0.55    | 0.09        | 46.85  | 54.95   | 4536.71 | 90.00 | 0.41    |
Figure 4. Averaged pressure indicated and range of variability of this pressure for selected values of the crank angle in a ambient of TDC in the 13th phase of the ESC engine test.

Mileage averaged pressure changes and changes the scope of this variation. For each value of the angle of rotation of the crankshaft is registered 90 pressure values, which are derived from 90 individual engine cycles. From a statistical point of view, these 90 pressure values are part of the general population. These 90 values can describe a normal distribution (out of phase idling). Determine can be further such parameters as kurtosis and skewness of the statistical distribution. An example thereof is given in Table 1 and Figure 5 are illustrated.

Figure 5. Kurtosis and skewness of pressure distributions for selected values of the angle of rotation of the engine crankshaft in the 13th stage of the test ESC.

It is characteristic that the value of kurtosis and skewness do not change their character before TDC piston (during the build-up of pressure). After TDC the pressure is maintained for a certain period in a
certain, fairly constant level, and the kurtosis and skewness oscillate about zero. If we analyze all the data relating to the 13th phase of the ESC test shown above observations are confirmed - Figures 6 and 7.

**Figure 6.** Averaged pressure Indicated and the scope of variation as a function of angle of rotation of the crankshaft engine to be tested in the 13-test phase ESC.

**Figure 7.** Kurtosis and skewness pressure distributions as a function of the angle of rotation of the engine crankshaft in the 13th stage of the test ESC. But this is not the correctness at all points of the characteristics of the engine. In the drawings 8 and 9 show the analyzed data with respect to all the test phases ESC.
Figure 8. Indicated averaged pressure as a function of the crank angle of the engine under test 13 then ESC test phases.

Figure 9. Kurtosis as a function of the angle of rotation of the crankshaft engine to be tested in 13 ESC test phases.

The data presented indicate that the processes in the vicinity of TDC between compression and expansion strokes are random processes with clearly non-stationarity. This lack of stationarity as a function of crank angle for the realization of a substantial part of the fuel energy conversion is not raised so far in the literature. Lack of stationarity has no basis in existing views on the implementation of the combustion process. This lack of stationarity is undoubted but also affects the transition temperature, and in the wake of the permanently reactions during the combustion and expansion of gases. This results in effects on the economy and engine emissions of toxic exhaust gas components. Progress in engine development requires an explanation of this phenomenon, his mastery and control it.
6. Conclusion
Was studied diesel engine on the engine test bench. Studies carried out in stationary conditions. The motor was loaded by the ESC test. In each phase of the test recorded 90 engine cycles. Was measured a crank angle and the corresponding combustion chamber pressure. Was obtained a database for statistical analysis. It was found that in addition to idle the engine, all the values indicated pressure for each crank angle can be described normal distribution. The parameters of this distribution change significantly with TDC neighborhood of the motor at the transition from compression stroke to a power stroke.
The data presented indicate that the processes in the vicinity of TDC between compression and expansion strokes are random processes with clearly non-stationarity. This lack of stationarity as a function of crank angle for the realization of a substantial part of the fuel energy conversion is not raised so far in the literature. Lack of stationarity has no basis in existing views on the implementation of the combustion process. This lack of stationarity is undoubted but also affects the transition temperature, and in the wake of the permanently reactions during the combustion and expansion of gases. This results in effects on the economy and engine emissions of toxic exhaust gas components. Progress in engine development requires an explanation of this phenomenon, his mastery and control it.
Based on the results presented in this work can draw the following conclusions:
1. Statistical analysis of waveforms processes in the engine can be a tool to assess the correctness of their implementation.
2. There was a lack of stationarity of processes in the engine.
3. Lack of stationarity of the processes is not well described in the literature.
4. Lack of analysis of instability can lead to erroneous process control in the engine, and thus also be an obstacle in achieving satisfactory performance of their work.

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