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A comparison of the fuel consumption characteristic in dynamic states with the general characteristic of the combustion engine

The paper presents a comparison of the fuel consumption characteristic in dynamic states with the general characteristic. It was proven that the use of the general characteristic to calculate the fuel consumption in dynamic operating states is limited because under certain conditions the results are incorrect. This is due to the fact that this characteristic is based on data obtained from the engine test bench measurements in static states. In contrast, the characteristic in the dynamic states is determined on the basis of data from both static and dynamic states characterized by variable engine speed and torque. It reflects the nature of the internal combustion engine much better because it takes into account the specificity of its work. Development of such characteristic is possible through the use of artificial neural network trained in a supervised mode to analyze the data collected during tests on the engine test bench. The purpose of this paper is to quantitatively compare the results obtained by each of the characteristics in different operating states of the engine. The analysis takes into account both the trajectory between the successive work points as well as time in which the change occurs.

Key words: *dynamic states, fuel consumption, artificial neural network*

Porównanie charakterystyki zużycia paliwa w dynamicznych stanach pracy z charakterystyką ogólną silnika spalinowego

W artykule przedstawiono porównanie charakterystyki zużycia paliwa w stanach dynamicznych z charakterystyką ogólną. Wykazano, że wykorzystanie charakterystyki ogólnej do obliczania zużycia paliwa w dynamicznych stanach pracy jest ograniczone, gdyż w pewnych przypadkach daje wyniki obarczone istotnymi błędami. Wynika to z faktu, że jest ona wyznaczana w oparciu o dane z pomiarów w stanach statycznych na hamowni silnikowej. Inaczej jest w przypadku charakterystyki w stanach dynamicznych, która jest sporządzana w oparciu o dane pomiarowe ze stanów zarówno statycznych jak i dynamicznych. Wierniej oddaje ona charakter pracy samochodowego silnika spalinowego, gdyż uwzględnia specyfikę zjawisk w nim zachodzących. W artykule wykazano, że wykorzystanie sztucznej sieci neuronowej uczonej w sposób nadzorowany do analizy danych zgromadzonych w trakcie badań na hamowni silnikowej pozwala na opracowanie takiej charakterystyki. Przedstawiono także ilościowe porównanie wyników otrzymywanych przez każdą z charakterystyk w różnych stanach pracy silnika spalinowego. Przeprowadzona analiza uwzględnia zarówno trajektorię przejść między kolejnymi punktami pracy jak i czas w którym ta zmiana zachodzi.

Słowa kluczowe: *stany dynamiczne, zużycie paliwa, sztuczne sieci neuronowe*

1. Introduction

Internal combustion engines used in automotive vehicles operate primarily in dynamic operating states. In an urban traffic it can be up to 95% of total time [11]. This is due to the specific nature of the road traffic, where the speed and acceleration of the car (and consequently the engine speed and torque) is affected by many variable factors, e.g.: traffic lights, the slope of the road, road traffic and the way they are controlled by the driver.

Determination of any general characteristic in dynamic operating states is difficult, because operating parameters in such conditions depend on inertial elements, changes in the air-fuel ratio, the dynamic phenomena occurring in the flow of fluids etc. In such states, the engine torque is not based directly on throttle position and engine speed at a given time, the fuel flow intensity is also not a function of the operating state. This leads to significant difficulties in the data analysis from such states and determining general characteristics [5]. Hence measurements in static states are commonly performed [11]. On a basis of such measurements engine general characteristics are determined. One of them is general characteristic of specific fuel consumption.

However, dynamic phenomena have strong influence on exhaust emissions [7], the fuel consumption [9, 10], or driving force [6]. It forces researchers to seek new opportunities for the preparation of more precise general characteristics in these states. There are many attempts to determine such characteristics. Chosen examples refer to:
– exhaust emissions with use of multinomial functions of the third order based on the measurement data from a chassis dynamometer [8],

– fuel consumption and torque in dynamic operating states based on measured data from engine test bench with use of ANN [13],
– Harmful emissions in CI engines with use of ANN [7].
– Engine efficiency based on data from the measurements of the vehicle parameters in real traffic conditions [10].

Determination of the general characteristic of the fuel flow intensity in dynamic operating states is also possible when the engine operating parameters are taken into account in time intervals, rather than considered as a function of the operating state at the time. The result is that the fuel flow intensity depends on a few engine speed and torque values in successive moments of time. This type of analysis is possible with use of ANN, which has appropriate number of inputs and outputs and is trained with proper training algorithm. The method is described in details in the works of author [1, 2, 3, 4]. Such an approach has many advantages: the analysis applies only to the engine thus the effect of transmision parameters is excluded, fuel flow intensity can be calculated in every case and not only for specific cases where n = const. or M = const., ANN uses data from the test bench measurements, and not for example road measurements, thus minimizing the impact of random external factors on the accuracy of the calculations. The purpose of this work is to compare quantitatively results obtained by the characteristic in dynamic states and general characteristic.

2. The specificity of dynamic working states

Fuel flow intensity in dynamic states is affected by three main factors. The first one is a change of air-fuel ratio. In the static operating states majority of modern spark ignition engines work on stechiomertic mixture. But when the engine speed and load increase the ECU switches to range of rich mixture as shown in Fig. 1.

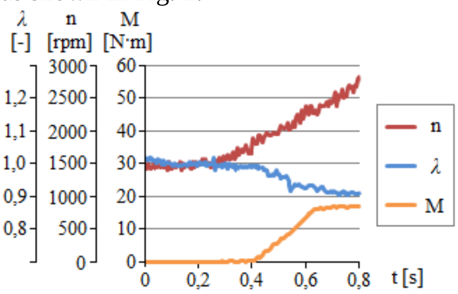

Fig. 1. Change in mixture composition in dynamic working state

The second factor is the increase in the kinetic energy of moving parts of the engine. These elements are mainly: the crankshaft (I_{crank}), camshafts (I_{cam}), crankshaft system (I_{pst}), flywheel (I_{fwheel}), water pump (I_{cpmp}), oil pump (I_{oilp}) but also oil (I_{oil}) and coolant (I_{cool}) shown in Fig. 2.

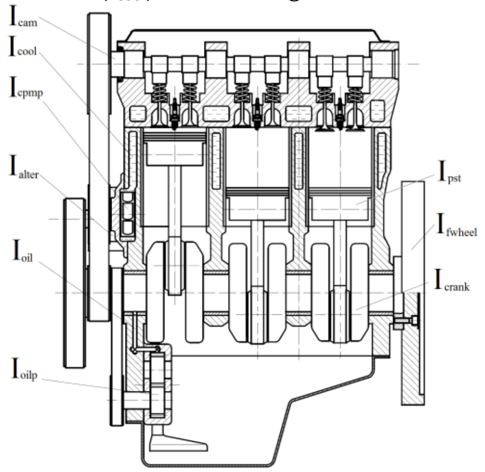

Fig. 2. Inertial elements in combustion engine

These elements have a significant impact on the fuel flow intensity especially when working with a small load and with a large angular acceleration. In such cases a large part of the energy derived from the mixture combustion is used to increase the kinetic energy of these elements in comparison to the energy transmitted to the transmission. The third factor is the delay Δt in engine response to increase of fuel flow intensity, as shown in Fig. 3.

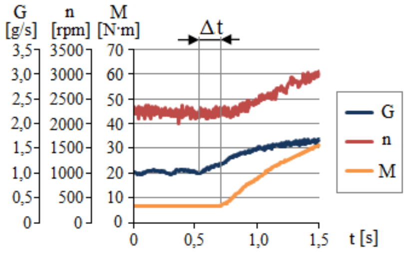

Fig. 3. Engine response delay to the change in fuel flow intensity

Certainly, the time interval Δt is not constant and depends on engine speed, load and the speed of changes in throttle opening angle. In the described method time interval Δt is not designated as a separate variable. ANN indirectly determines this time during the training process.

3. Measurement methodology

Presented characteristic in dynamic states in determined based on measurement data from the engine test bench, which allows to perform measurements of the fuel consumption in dynamic operating states. In order to develop the characteristics of the fuel flow intensity in dynamic states is necessary to ensure appropriate training set for ANN. Such set must primarily contain measurement data from all possible operating states the engine might work in. In addition, measurements must cover the entire engine work field. The whole method of measurements is described in details in [2]. Measurements were performed on spark ignition engine with a displacement of 899 cm^3 and effective power of 29 kW at nominal operating temperature.

4. Measurement data analysis with use of ANN

Data analysis was carried out with use of ANN. It allows determination of multidimensional non-linear relationships between variable inputs and outputs. In this particular case the ANN with 6 inputs, 8 neurons in the hidden layer and one output was used (Fig. 4).

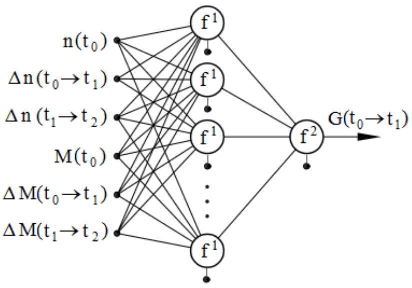

Fig. 4. Artificial Neural Network

Training set was constructed based on 180 measurements in the dynamic states and 120 measurements in static states. Sampling time was set to 0,1 s. As a result 13900 training subsets were obtained. Due to the large number of data the ANN was trained with use of Lavenberg – Marquardt algorithm. Graphs of mean-square error Q during training process are shown in Fig. 5, whereas the ANN model fit to the measurement data is shown in Fig. 6.

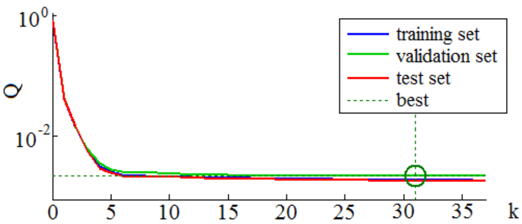

Fig. 5. Graph of errors for each subset during the ANN training

R-values close to unity indicate a very good fit of the ANN model to the collected data. This means that assumed intervals of 0,1 s, and the presentation of data to the network are correct, because ANN was able to determine a non-linear input-output relationship.

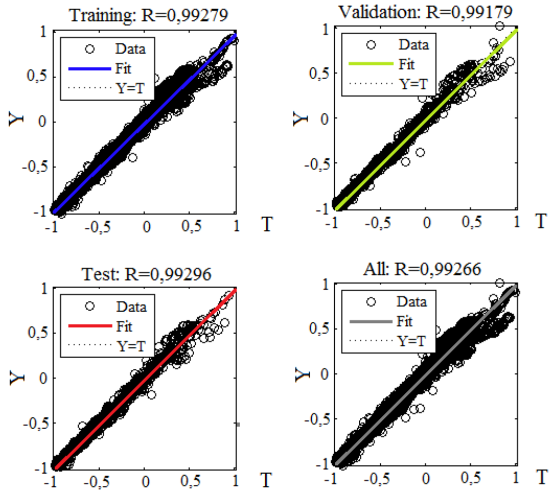

Fig. 6. ANN data fit after training process

Axis ranges (-1, 1) in Fig. 6 result from scaling all measurement data to such an interval. This is necessary in order to ensure proper effectiveness of ANN training. After the training process the ANN (Fig. 4) with the corresponding values of weights becomes fuel consumption characteristic in the dynamic states. Such network can be simulated by any input values (from the engine operating range) for which fuel flow intensity is calculated.

5. Comparison of fuel consumption characteristic in dynamic states with general characteristic

General characteristic provides an easy and fast way to determine the field of engine work with the best efficiency. But it refers only to static working states. Nevertheless, it is often used to calculate the fuel consumption in dynamic operating states, which is not accurate approach [9, 10]. Fig. 7 shows the general characteristics of the tested engine with marked curves of constant specific fuel consumption g_e.

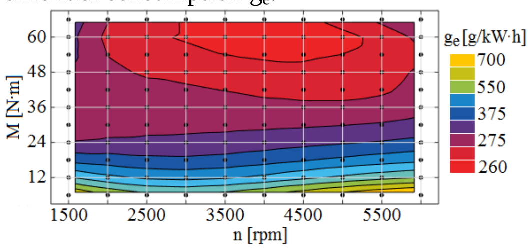

Fig. 7. General characteristic of tested engine

Hereinafter the fuel consumption characteristic in dynamic states and general characteristic were used to calculate the amount of fuel consumed by the engine during the transition between the two operating points 1 and 2, through a particular course within a certain time t. Only cases of increasing speed and/or torque were taken into account, and therefore the amount of fuel computed by the characteristic in dynamic states is always greater than the one calculated with use of the general characteristic. In case of general characteristic the transition between two points is considered as a series of static operating states lasting 0,1 s. The graphs show the error δ defined as follows:

$$\delta = \frac{m_{dyn} - m_{stat}}{m_{stat}} \cdot 100\% \qquad (1)$$

where:

m_{dyn} - mass of the fuel consumed by the engine during the transition from state 1 to 2 at time t, calculated by the characteristic in dynamic states,

m_{stat} - mass of the fuel consumed by the engine during the transition from state 1 to 2 at time t, calculated by the general characteristic.

Case studies were carried out as follows: the first three (Fig. 8 - Fig. 10) refer to increase in engine speed at a constant torque. Another three (Fig. 11 - Fig. 13) refer to the torque increase while maintaining constant speed. In the seventh case both engine speed and torque increase (Fig. 14). In every case several times t of transition were considered. In all cases the whole range of engine work field was covered. Drawings a) show the trajectory of the engine transition from the state 1 to state 2 (arrows show the direction), while drawings b) illustrate an error δ as a function of transition time t between these points. Angular acceleration and torque increments are constant throughout transition.

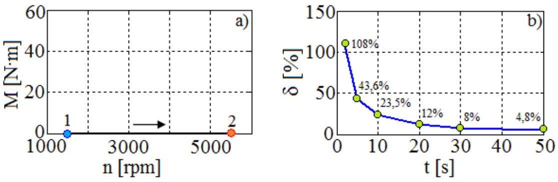

Fig. 8. Engine speed increase with no load

Fig. 8 – Fig. 10 clearly indicate that the longer the transition time t the smaller the error δ. This means that the result calculated by the characteristic in dynamic states is closer to the result of general characteristic. It is in line with expectations because for long times t engine work can be described quite precise as series of static states. In the case of engine work with no load error δ is smaller than 5% at 50 s and further, while at work with full load it is 20 s and further.

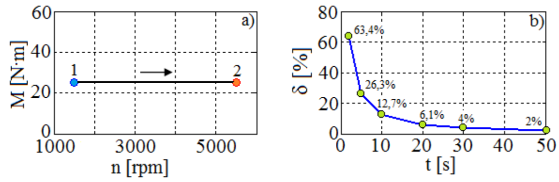

Fig. 9. Engine speed increase with middle load

Furthermore, the analysis of Fig. 8 – Fig. 10 leads to the conclusion that the greater the engine load the smaller error δ is. Between the operation with no load and with a maximum load difference is almost 100%. This can be explained by the fact that in the case of a large engine torque the share of kinetic energy of moving elements is relatively small in comparison to the total energy produced by the engine.

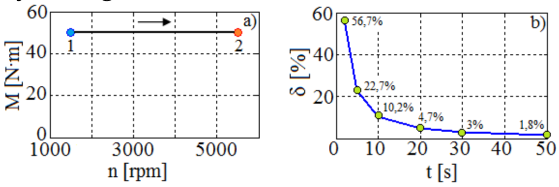

Fig. 10. Engine speed increase with full load

In any case, the relationship between the error δ and time t is highly non-linear, which is especially noticeable in the time interval t = 2÷20 s.

The following three graphs (Fig. 11 - Fig. 13) show the cases of increasing torque at constant speed.

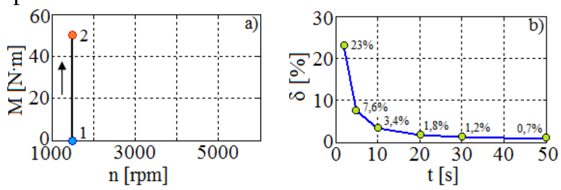

Fig. 11. Engine torque increase at small speed

In this case (Fig. 11 - Fig. 13) there is also a tendency to reduce the error δ with lengthening the time t of transition. Whereas in this cases the errors are 4 - 5 times smaller than those in Fig. 8 – Fig.10. This means that changes in the kinetic energy of the moving parts have a much greater impact on the fuel flow intensity under dynamic operating states than change of the mixture composition and delay in engine response to a change in fuel flow. The error δ smaller than 5% is achieved here already at the time of the transition of about 5 seconds for medium and heavy load. In the low load range the error δ smaller than 5% is obtained after 8 s.

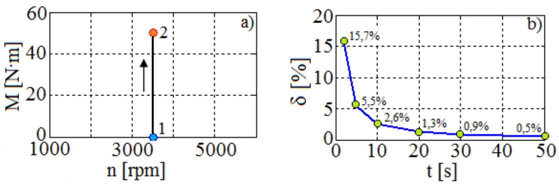

Fig. 12. Engine torque increase at middle speed

Like in the first three cases (Fig. 8 – Fig. 10), here also the following dependencies are noticeable: the error δ decreases with increasing load and that error δ is highly non-linear function of time in time range 2÷20 s. Considering that changes in the engine torque (depending on acceleration lever position) are very quick so such a change usually occurs in less than 2 s. It results in situation that in every real life situation error δ is always greater than 10%.

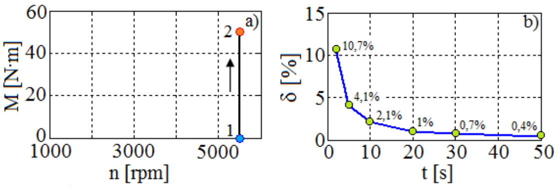

Fig. 13. Engine torque increase at top speed

Fig. 14 illustrates the transition between points when both engine speed and load increase. This is a general case of engine work state. All three factors described in section 2 have an influence on fuel flow intensity. In general case the transition through the whole engine work results in a very large error. Error is smaller than 5% until 30 s. Taking into consideration the fact that in real traffic conditions drivers realize full throttle opening very quickly, the error is always greater than 10%.

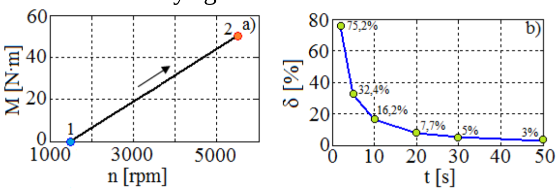

Fig. 14. Increasing engine speed and torque at the same time

Then, using the developed characteristic in the dynamic states values of error δ were determined in three ranges of speed and load (Fig. 15) in the fields of: small (range 1: 1500÷2500 rpm), the middle (range 2: 3000÷4000 rpm) and high (range 3: 4500÷5500 rpm) speed. In contrast, Fig. 16 shows the differences when changing the torque at constant speed in the range of small (0÷10 N·m), middle (20÷30 N·m) and large (40÷50 N·m) torque. Bar graphs show the values of the error δ which is defined according to the formula (1).

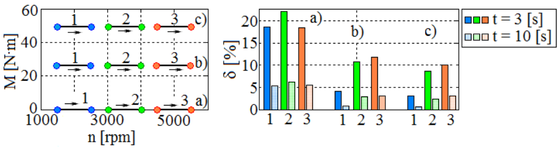

Fig. 15. Engine speed increase at constant torque in different speed ranges

Fig. 15 shows that the smallest error δ is always obtained when the engine works in the range of low engine speed and under large load. Unfortunately small error δ below 5% is guaranteed when the time equals at least 10 s. Only for operation without load there is no clear relationship between the error δ and speed. Similarly as described earlier, longer transition means smaller error. At t = 10 s the error is always less than 6% but changes in engine speed of 1000 rpm usually occur much faster in a real life conditions.

Then cases of the torque increase were analyzed.

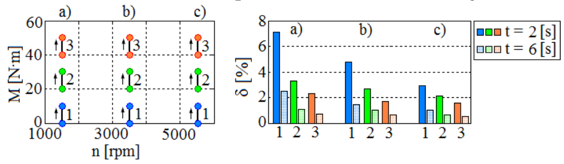

Fig. 16. Engine torque increase at constant speed in different ranges

Fig. 16 shows, like in the previous cases, that the largest error is obtained when engine works at small speed and with small load. Similarly with time of transition – the longer the time the smaller the error. For a particular load increase error is always the smallest when the engine speed is in the highest range.

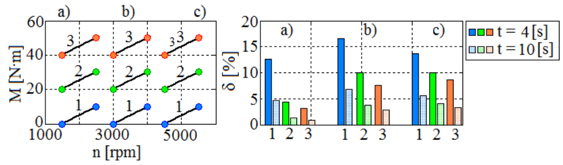

Fig. 17. Engine speed and torque increase in different torque ranges

Fig. 17 illustrates the general case in which both operating parameters change. The relationships between errors, trajectory and time are similar to those mentioned previously.

6. Summary and conclusions

The article shows that the method of ANN can be used to determine the fuel consumption characteristics in dynamic states. It is extremely important because, as shown in the article, the use of the general characteristic in such applications is very limited. The conclusions of the calculations performer in the article are as follows:

– General characteristic always calculates smaller fuel consumption than characteristic in dynamic states determined with use of ANN (while increasing engine speed and/or load).

– The differences are the largest in the range of small engine load, when increase in kinetic energy of moving parts is similar to energy transmitted to the transmission.

– For real life traffic conditions the error is always too large to use general characteristic. It gives reasonable answers only when the time of transition is long enough to assume that transition is series of static states.

– General characteristic gives the smallest error when used to calculate fuel consumption in cases of torque change at constant speed, rather than in cases of engine speed change at constant torque.

Nomenclature/*Skróty i oznaczenia*

ANN Artificial Neural Network/*Sztuczna Sieć Neuronowa*
f^1 hidden layer transfer fuction/*funkcja przniesienia warstwy ukrytej*
f^2 output layer transfer fuction/*funkcja przniesienia warstwy wyjściowej*
g_e specific fuel consumption/*jednostkowe zużycie paliwa*
G fuel flow intensity/*natężenie zużycia paliwa*
k ANN training steps/*kroki uczenia sztucznej sieci neuronowej*
M engine torque/*moment obrotowy silnika*
n engine speed/*prędkość obrotowa silnika*
Q mean square error/*błąd średniokwadratowy*
t time of transition between two points on engine work field/*czas przejścia między dwoma punktami na charakterystyce silnika*
T target value/*wartość wyjściowa ze zbioru uczącego*
Y ANN output/*wyjście sieci neuronowej*

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