The Possibilities of Using of the Engine Multidimensional Characteristic in Fuel Consumption Prediction

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Abstract

This paper presents the possibilities of using the multidimensional characteristic of engine in fuel consumption prediction. The multidimensional characteristic of engine has been defined. The quality and the scope of the proposed fuel consumption model have been estimated using verification tests according to the assumed engine operation test. The bed tests and simulation tests have been done using the same model of engine operation and their results have been included in this paper.

1. Introduction

Technological progress and the accompanying economic development have brought about a gigantic demand for energy in the 20th century. Cars as modes of transport currently constitute and in the future will represent ever greater consumers of the earth's energy resources. The gradual increase of liquefied fuels and gas-fuels consumption, which are the main carriers of energy in cars, transposes directly into huge emissions of CO₂ into the atmosphere (the main component of combustion products). Although CO₂ is not a toxic compound, its additional emission into the atmosphere is an undesirable event, because it causes an increase of the greenhouse effect. Burning of fuels also causes a significant reduction of the oxygen content in the atmosphere, which is replaced by CO₂. The severity of all these events is particularly marked in big cities, where car saturation is the highest [11]. A few directions marking the future tendencies of automotive engineering developments have been established in recent years. They facilitate fuel consumption reduction and reduction of the emission of CO₂ and other pollutants. The real alternative for vehicles with conventional propulsion (a heat engine only) currently are vehicles with a hybrid propulsion system (commonly used: a heat engine and a battery, which supports an electric motor) [4, 9, 12]. They have been accepted recently by potential customers, which has facilitated their serial production. The design of the hybrid vehicles combines the advantages of traditional vehicles (a wide range of operation and high power density – when the electric motor is added to the heat engine) and hybrid vehicles (low emission of pollutants and a low level of noise – when the electric propulsion is activated only). There are several proposals to reduce these vehicles mass, front surface and the drag coefficient \( c_x \) [8]. One of the targets of using the hybrid propulsion systems in these vehicles is the possibility of accumulation and partial consumption of energy, which is last during vehicle braking [4,12]. Using the hybrid propulsion systems in vehicles creates considerable possibilities of reducing: fuel consumption, pollutants emission and noise emission. It is therefore necessary to create effective modeling...
tools, which give the possibility of optimal design of this vehicle propulsion system and algorithms of its energy flow control [2]. This paper presents the possibilities of using the engine multidimensional characteristic, obtained during a bed tests of the engine in the creation of an effective model of fuel consumption. This model can be subsequently used in simulation tests of designed propulsion units with a specific focus on hybrid vehicles. The methods of model creation, which use static multidimensional characteristics, have already been applied in research projects, which are realized in the Technical University of Gdańsk in the Department of Internal Combustion Engines and Compressors.

2. THE MULTIDIMENSIONAL CHARACTERISTIC OF ENGINE

The multidimensional characteristic has been defined using the general dynamic relation, which is used in the theory of Bond Graph and State Equations [5], in the form of state equations (fig. 1):

\[
\begin{align*}
\dot{X} &= f_1(X,U) \\
Y &= f_2(X,U)
\end{align*}
\]  

![Fig. 1](image.png)  
*Fig. 1 The cause-effect model described by the state equations. U-vector of extortion (input), X-state vector, Y-output vector, Z-vector of disturbance, P-vector of sets and construction parameters.*

The output vector \( Y \) can incorporate elements of the state vector \( X \) and a set of the data, which will be used in simulation tests and optimization procedures. When a reciprocating engine is taken into consideration, the elements of vector \( Y \) can be different parameters, which describe the state of the engine. The most important parameters are:

1) angular speed : \( \omega \),
2) torque: \( M_o \),
3) temperature of cooling fluid: \( T_c \),
4) temperature of oil: \( T_{oil} \),
5) emission: \( CO \),
6) emission: \( HC \),
7) emission: \( NO_x \),
8) noise emission,
9) etc.: \( Y_m \).
Vector $Y$ in the state equations (1) has the general form:

$$Y = [\omega, M_o, T_c, T_{\text{oil}}, CO, HC, NO_x, \ldots, Y_m]$$  \hspace{1cm} (2)

When creating the static multidimensional characteristic, two energetic parameters are being distinguished from vector $Y$. They characterize the energy flux being transferred to the receiver (fig. 2) and make up the vector of the multidimensional characteristic:

$$Y_{MC} = Y^T - f(\omega, M_o, \text{ZERO}_3, \ldots, \text{ZERO}_m)^T$$  \hspace{1cm} (3)

where:

$$\text{ZERO}_i = 0 \quad \text{for} \quad i=3 \ldots m.$$  

The second element of the equation (3) eliminates the energy parameters ($\omega, M_o$) from vector $Y$.

$$\text{Fig. 2} \quad \text{Scheme of the system: thermodynamic process – crank system – energy receiver.}$$

The multidimensional characteristic of the engine is defined as the vector function of energy parameters:

$$Y_{MC} \bigg|_{T_c, \text{const}}^{\omega, M_o} = f(\omega, M_o)$$  \hspace{1cm} (4)

The reciprocated engine has then been treated as “black box”, where the vector coordinates of the multidimensional characteristic $Y_{MC}$ (3) are calculated using an approximation of data obtained in steady-state conditions. Identification of the model is possible using the basic research tools for engines: an engine test-bed, angular speed sensor, torque sensor and gas-analyzer.

The model of the engine, which is described in this paper will use two elements of the engine multidimensional characteristic only: the characteristic of fuel consumption:

$$G_e = f(\omega, M_o)$$  \hspace{1cm} (5)
and the characteristic of throttle opening angle:

\[ a_{th} = f(w, M_o) \]

The base function used for the approximation of functions (5) and (6) is the “Spline” type function [6], which consists of polynomials. They are linked in points called knots. There these polynomials have the same order \( N \), they are equal and they have the same value of derivatives of up to \( N-1 \). For final approximation of the data set the function of two parameters \( (w, M_o) \), linked in the directions: \( w \) and \( M_o \), has been used. The concept of this function has been worked out in the Internal Combustion Engines and Compressors Institute [3, 7].

3. VERIFICATION TESTS OF THE ENGINE MODEL

For the purposes of verifying the model of engine, the tests on the engine test-bed have been performed. The tests have been carried out according to the model of engine operation and their results have been compared with the results of simulation tests made using the same model of the engine operation. The test-stand has been equipped with a control system, which facilitates the realization of the given engine operation tasks and the recording of results in the domain of time. For the verification tests the SI engine has been used. This engine is the permanent equipment of the Laboratory of Department of Internal Combustion Engines and Compressors and it has been given by the firm Mercedes.

When carrying out the numerical simulation of the engine operation according to the chosen model of engine operation it is necessary to work out the model of engine, which consists of two characteristics: the fuel consumption: \( G_e = f(w, M_o) \) and the throttle opening angle: \( a_{th} = f(w, M_o) \). These characteristics have been worked out based on 39 measurement points. The tests have been performed according to the Polish Standards.

For the purposes of verifying the model of engine, the EU-/ECE-Driving Cycle (ECE) has been used. This test is an applicable certification test in Poland and the European Union. The ECE test is commonly used in certification tests and also in research and development, which should bring considerable advantages in cutting fuel consumption and reducing the negative effects of contemporary cars on the environment at the same time [1,10]. The ECE test has been shown on figure 3 a). On part b) of the same figure, a selected part of the ECE test for verification purposes has been shown. The selected part of the ECE test consists of steady-state engine operation (idle run), acceleration up to 50 km/h and operation at this velocity over a same time. As the verification tests concern the engine used in the car only, not whole the car, a reduction of the test conditions was necessary. The primary condition given as the run of car velocity over time: \( V = f(t) \), should be reduced to two functions: crankshaft angular speed: \( w = f(t) \) and throttle opening angle: \( a_{th} = f(t) \) both over time. These two functions finally define the operation point of the engine. For calculation purposes the sufficient model of the car, in the form of the Bond Graph and State Equations related to it has been used [5]. The final result of the simulation are two functions: \( w = f(t) \) and \( M_o = f(t) \) it was necessary to calculate the function: \( a_{th} = f(t) \) using the characteristic: \( a_{th} = f(w, M_o) \).
According to the prepared test of engine operation, the test on the engine test-bed has been performed. Directly from the engine control unit the courses: $a_{th}=f(t)$, $w=f(t)$ and $G_e=f(t)$ have been recorded. Two courses: $a_{th}=f(t)$ and $w=f(t)$ have been shown on figures 4 and 5. Course of the fuel consumption as a result of the experiment and the course gained from the simulation test have been given on fig. 6. The rate of fuel consumed by the engine during the test has been calculated according to the equation:

$$m_f = \int_{t_o}^{t_e} G_e \, dt$$  \hspace{1cm} (7)

where:
- $t_o$ - time of the test beginning,
- $t_e$ - time of the test end.

The rate of fuel consumed by engine during the test equals:

$$m_{f_0} = 3.85 \cdot 10^{-2} \text{ kg}.$$
For simulation purposes two courses have been used: $a_{th}=f(t)$ and $w=f(t)$ they have been recorded earlier on the test-bed (fig. 4 and 5). The calculated courses haven not been used because of additional errors in fuel consumption, which can take place as a consequence of imperfect test-bed control. The course of fuel consumption, which is based on the simulation during the test has been drawn on figure 6 (run b) with the course recorded during the tests on the engine test-bed (run a). The rate of fuel consumed during the test, according to the relation (7) as a result of the simulation amounts:

$$m_f = 3.62 \cdot 10^{-2} \text{ kg}.$$
4. CONCLUSIONS

Verification of the fuel consumption model has shown that using this model ensures a high compatibility of simulation results with the results of tests carried out on the engine test-bed during the completed test. The error in the estimation of fuel consumption for the complete test amounts – 6.1%. This is a very good result, because the test mostly consists of transient states (the model of the engine uses static engine characteristics). The biggest differences appeared under transient conditions (fig. 6). The prepared model of fuel consumption facilitates the obtention of results of the simulation in a short time, which is very important in numerical optimization tasks. The application of procedures for multidimensional characteristics approximation ensures a high level of accuracy in their approximation. The completed test confirms that the prepared model can be easily and widely used.

REFERENCES:
