QUID 2017, pp. 2557-2563, Special Issue N°1- ISSN: 1692-343X, Medellín-Colombia

MODELLING OF DIESEL ENGINE`S OPERATING CONDITIONS ON THE BASIS OF FUZZY LOGIC

(Recibido 05-06-2017. Aprobado el 07-09-2017)

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Abstract. In this paper, they considered the method for the development of linguistic variables to control the operating conditions of a diesel engine. Based on the terms, created linguistic variables and the results of the conducted experiments, they develop fuzzy rules of management. Using the Sudzen output and the obtained knowledge base of fuzzy rules, the control values are calculated. According to the proposed methodology, the analysis of the mathematical model of a diesel engine control is performed and realized as a software product.

Keywords: diesel, control, fuzzy logic, linguistic variable, fuzzy rules.

Citar, estilo APA: Iliukhin, A. & Khuzyatov, S (2017). Modelling of diesel engine`s operating conditions on the basis of fuzzy logic. *Revista QUID (Special Issue),* 2557-2563.

1. INTRODUCTION

The life cycle, the creation of new mechanisms and units, automotive and tractor engineering necessarily includes the testing. The development and the modernization of diesel engines is not an exception. During the tests of engines, technical solutions are checked which allow to ensure the increase of wear resistance of products, their reliability and durability. The importance of this process lies in the fact that failures and malfunctions of internal combustion engines (ICE) lead to vehicle and mobile aggregate idling, the repair of diesel engines is complicated and associated with a great deal of labor and time. It is possible to analyze the design technological solutions to increase the wear resistance and the reliability of parts and units of diesel engine systems only through the experimental tests of engines, which is a complex task requiring a large amount of labor for solution. One of the options for resource consumption reduction, both material and labor ones, is the development of an adequate mathematical model of diesel engine control, which allows to reduce the transition time from one operating mode to another, and also to increase the accuracy of operating mode control [Galiullin L.A., Zubkov E.V., 2011, Biktimirov R.L., Valiev R.A., Galiullin L.A., Zubkov E.V., Iljuhin A.N., 2014].

The development of a mathematical model of diesel engine control is a complex multidimensional task, associated with a large number of impacts on an engine, requiring complex calculations of a large number of adjustable coefficients. This process can be automated by an intelligent system introduction, based on fuzzy logic. The application of this approach makes it possible to obtain an engine model that takes into account all the necessary parameters of work on the basis of experimental data, and to adapt the database of fuzzy rules from one model to another in an automated mode without a man's participation [Zubkov E.V., Makushin A.A., Ilukhin A.N., 2009, Zubkov E.V., Makushin A.A., Ilukhin A.N., 2009].

2. MATERIALS AND METHODS

The material for the work was represented by the results of the engine 740-30-260 tests, with the engine number 82522592 and the HPFP number 732888 at the engine testing station of OJSC "KAMAZ-Diesel" PJSC "KAMAZ". During the tests, the HPFP regulator (parameter L) was controlled at a fixed external load of 10 Nm. and the rotation speed of an engine crankshaft (parameter n) and the load torque (parameter M) were measured (Table 1).

Table 1. Experimental data.

L, mm	0	5	10	15	20	25	30	35	40	45	50
n min^{-1}	600	935	1155	1355	1555	1760	1960	2165	2340	2425	2450
M Nm	73	101	120	126	125	118	113	111	110	110	110

In order to process the experimental data, they developed a mathematical model for operating conditions control of a diesel engine based on the knowledge base of fuzzy rules. The resulting knowledge base allows you to calculate the fuzzy value of an output variable depending on input parameters. An unclear output is used in order to transfer from an unclear value range to clear control parameters. In practice, five basic schemes of fuzzy inference are used: Mamdani, Tsukamoto, Sudzen, Larsen and a simplified scheme [S. Osovskiy, 2002, Galiullin L.A., Valiev R.A., 2015]. Let's implement the derivation of clear values based on fuzzy labels using Sudzen algorithm. The application of this algorithm allows to reduce the processing time of information and the use of the average summing value in it allows to obtain high accuracy for each linguistic variable.

The developed mathematical model was realized in the form of the software product "The editor of fuzzy inference systems".

3. RESULTS AND DISCUSSION

The use of fuzzy logic for the development of control systems makes it possible to obtain a mathematical model to control an object by experimental data processing in an automatic mode. This approach reduces a man's labor costs for a model creation, and also estimates the cumulative effect of each parameter on the final result of the calculations. Often when other methods are used, the secondary parameters are neglected, which leads to an erroneous result.

The development of fuzzy rules knowledge base begins with the development of a linguistic variable consisting of five objects: <x, T(x), U, G, M>, where

x is a proper name of a variable;

T(x) is the set of its values (term-set), which are the names of fuzzy variables, the definition domain of each of them is the set x. The set T(x) is called a base term-set or fuzzy marks of a linguistic variable;

U is the set of objects.

G is the syntactic procedure that allows to operate with the elements of the term set T, in particular, to generate new terms (values).

M is a semantic procedure that allows to transform each new value of a linguistic variable, formed by procedure G, into a fuzzy variable, i.e. to form a corresponding fuzzy set [Makushin A.A., Zubkov E.V., Gafiyatullin A.A., Ilyukhin A.N. 2010,Ilyukhin A.N., Zubkov E.V. 2007].

When experimental data is obtained (Table 1), a linguistic variable indicating the position of HPFP rail was determined via the letter L. This parameter can be measured quite accurately during a test. The base value L is determined by the range of HPFP regulator movement and makes 0 - 50 mm. In order to ensure the required accuracy, this range is divided into eleven terms (0.5.10 ... 50).

The next linguistic variable will be the position of a load device regulator, denoted by F. The loading device is a hydro-brake, the load change of which is carried out by the water level in a tank. Let's divide the basic range into five equal intervals of the external load Nm (0, 10, ..., 40) and the corresponding terms (0, 1, ... 4). The selected number of fuzzy marks satisfies the specified accuracy requirement.

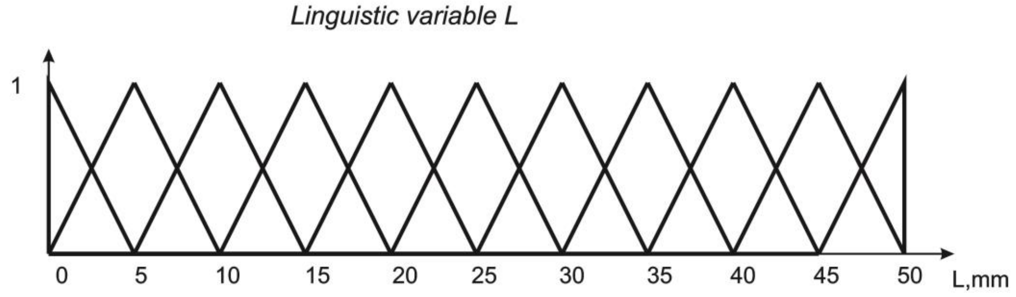
The rotation speed of an engine crankshaft is represented as a linguistic variable n, the base value makes 600 - 2450 min-1. The main influence that changes this parameter is the fuzzy set L, therefore we will divide the linguistic variable n into 11 fuzzy labels likewise. The values of the terms n were determined during the experiment (Table 1).

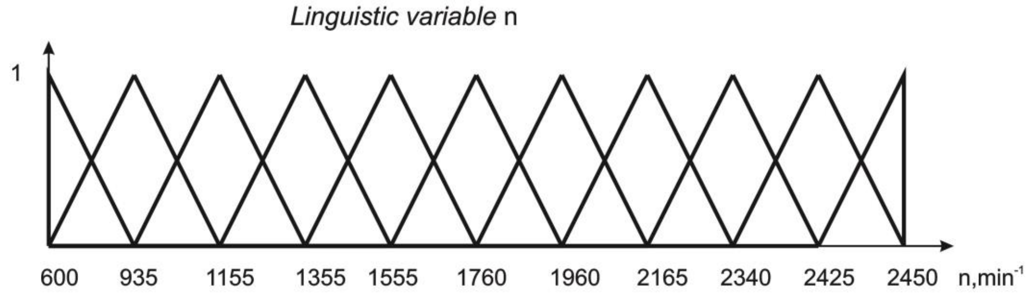
The magnitude of the engine torque M as well as n, depends on the linguistic variable L and, consequently, is divided into 11 fuzzy labels. The values of this characteristic terms will also be obtained during the tests (Table 1).

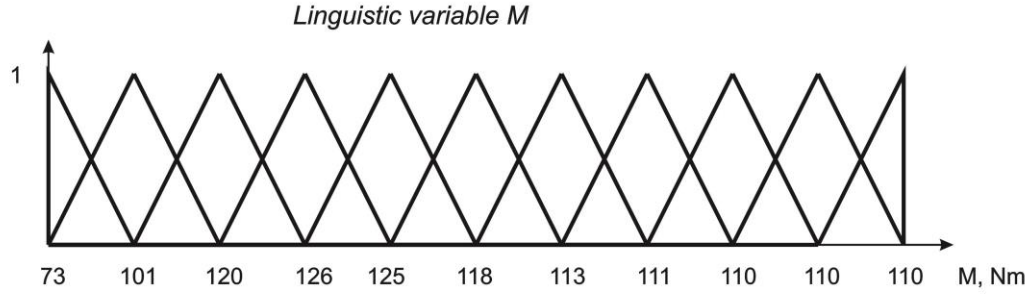
The development of the knowledge base that implements all types of tests requires the measurement of 11 values for the linguistic variable L and 5 measurements according to the linguistic variable F. The number of measured values will be 5 × 11 = 55. Each measurement is made after the bringing of ICE to a steady state, this process makes 15 minutes. Accordingly, 13.75 hours is necessary in order to find the time during which the knowledge base is filled, taking into account the reduction to the steady-state regime. In order to determine the adequacy of an engine management model, we will construct a knowledge base for one external load mode F = 10 Nm, which will reduce the experiment time to 2.75 hours. The received technique can be applied similarly to other values of external load and to build a complete model to control the operating modes of diesel engines.

Based on the results presented in Table 1, three linguistic variables L, n, M are created. The relationship between the base value and the obtained terms is made on the basis of the belonging function μ(x).

In practice, four functions of belonging are used: Gaussian distribution, bell-shaped function, triangular function and trapezoidal function. Linear dependencies have larger range of values in the linguistic variables under consideration. Thus, we choose the triangular function of belonging. This function of belonging describes linear sections better than other functions. The developed linguistic variables are shown on Figure 1.


Linguistic variable L


Linguistic variable n


Linguistic variable M

Using linguistic variables, it is possible to compile a knowledge base of fuzzy rules. The complete knowledge base will have the following form:

IF a_1 AND b_1 AND c_1 AND ... AND z_1 THEN f_i

IF a_2 AND b_1 AND c_1 AND ... AND z_1 TO f_i

……………………………………….

IF a_1 AND b_2 AND c_1 AND ... AND z_1 THEN f_i

IF a_2 AND b_2 AND c_1 AND ... AND z_1 THEN f_i

………………………………………

IF a_1 AND b_1 AND c_2 AND ... AND z_1 THEN f_i

IF a_2 AND b_1 AND c_2 AND ... AND z_1 THEN f_i

………………………………………

IF a_{m-1} AND b_n AND c_s AND ... AND z_v THEN f_i

IF a_m AND b_n AND c_s AND ... AND z_v THEN f_i

Where a_i, b_i, c_i, ... , z_i are the values of linguistic parameters.

f_i is the value from the range f_1, f_2, ... f_k, which determines the position of the control unit [Makushin A.A., Zubkov E.V., Gafiyatullin A.A., Ilyukhin A.N. 2010,Ilyukhin A.N., Zubkov E.V. 2007 ; / Zubkov E.V., Makushin A.A., Bakhvalova V.S., Ilyukhin A.N. 2009].

Using the principle of knowledge base development, the above and the linguistic variables presented on Figure 1 let's formulate a fuzzy control rule:

IF *N* OR *M* THEN *L*,

where *N* is the linguistic variable that determines the frequency of a crankshaft rotation;

M is the linguistic variable that determines an engine torque;

L is the linguistic variable that determines the position of HPFP regulator [Iliukhin, A.N. 2016].

The generated knowledge base of fuzzy rules has the following form:

IF *600* OR *73* THEN *0*;

IF *935* OR *101* THEN *5*;

IF *1155* OR *120* THEN 1*0*;

IF *1355* OR *126* THEN 1*5*;

IF *1555* OR *125* THEN 2*0*;

IF *1760* OR *118* THEN 2*5*;

IF 1960 OR *113* THEN 3*0*;

IF *2165* OR *111* THEN 3*5*;

IF *2340* OR *110* THEN 4*0*;

IF *2425* OR *110* THEN 4*5*;

IF *2450* OR *110* THEN 5*0*;

The obtained knowledge base on the basis of Sudzen's fuzzy derivation makes it possible to pass from the controlled fuzzy meaning to a clear one. By entering the input parameter a_i in the linguistic variable A, we calculate the values of the membership functions $\mu(a_i)$. A clear control value z with respect to the input parameter ai is calculated using the following formula:

$f_a = a_i \times \mu\ (a_i) + (a_i + 1) \times \mu\ (a_i + 1)$,

where x is a clear value of the linguistic variable A,

f_a is an output variable, a clear control value;

a_i and $a_i + 1$ are the terms related to the linguistic variable A;

$\mu\ (a_i)$ and $\mu\ (a_i + 1)$ is the value of the membership function of the variable x to the corresponding terms [Valiev R.A., Galiullin L.A., Zubkov E.V., Ilukhin A.N., 2015].

On the basis of above considered fuzzy conclusion mechanism and the constructed knowledge base of control fuzzy rules by a diesel engine operation, let's determine the necessary position of HPFP regulator for an arbitrary value of the crankshaft rotation [Galiullin L.A., Valiev R.A. 2016].

Let's take for example the crankshaft speed x = 1700 rpm. Based on the linguistic variable N, let's compute the values of all membership functions ($\mu(600)=0$; $\mu(935)=0$; $\mu(1155)=0$; $\mu(1355)=0$; $\mu(1555)=0,29$; $\mu(1760)=0,71$; $\mu(1960)=0$; $\mu(2165)=0$; $\mu(2340)=0$; $\mu(2425)=0$; $\mu(2425)=0$).

A clear output value is defined as follows:

$$l = \sum_{i=1}^{n} a_i \cdot \mu(a_i) = 23.55 \text{ mm.}$$

Where l is a clear value of the variable L,

a_i are the terms belonging to the linguistic variables N or M*;*

$\mu(a_i)$ is the belonging of the variable L to a corresponding fuzzy label.

4. CONCLUSIONS

Having applied the obtained method of fuzzy inference, let's develop a test program according to the standard [Galiullin L. A., 2014]. According to this standard, it is intended to measure the parameters of a diesel engine in a stationary mode with a step of 200 min-1. They calculate the corresponding value of HPFP regulator position for each value of engine speed of the diesel engine. All results are presented in Table 2.

N min^{-1}, calculated	600	800	1000	1200	1400	1600	1800	2000	2200	2400
L, mm	0	3	6,5	11,1	16,1	21,1	26	30,9	36	43,5

N min^{-1}, experimental	600	820	1120	1199	1394	1599	1800	2000	2205	2410
Absolute error, min^{-1}	0	20	20	1	6	1	0	0	5	10
Relative error, %	0,00	2,50	2,00	0,08	0,43	0,06	0,00	0,00	0,23	0,42

The resulting mathematical model of an engine corresponds to the real picture with a maximum error of 1.47 percent. This value is determined as the sum of the model error, maximum 1.4 percent at 800 min-1 and error of equipment makes 0.07 percent.

5. SUMMARY

The developed technique is implemented as a software product "The editor of fuzzy inference systems". The application of this program allows you to create various tests, which are the sets of diesel engine operation modes. The accuracy of diesel operation control modes on the basis of the developed mathematical model makes 1.47%, which is permissible from the point of view of the standard [Internal combustion engines of piston type.;2011], assuming a maximum error of 1.57%. Thus, time and material resources are saved to create a new type of test, based on the application of the same knowledge base.

6. ACKNOWLEDGEMENTS

The work is performed according to the Russian Government Program of Competitive Growth of Kazan Federal University.

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