APPROACH OF CALCULATING THE AUTOMOTIVE GASOLINE INJECTOR ELECTROMAGNETIC PARAMETERS

Assoc.Prof. M.Sc. Bozhkov S. PhD.
Department of Transport Equipment, Todor Kableshkov University of Transport
Geo Milev str. 158, 1574 Sofia, Bulgaria

stbozhkov@vtu.bg

Abstract: *The electromagnetic fuel injectors automotive are the gasoline injection systems main elements. The injectors perform the gasoline injection and its time of open condition, i.e injection duration determines the fuel quantity per working cycle [1]. The injectors are activated by solenoid and inject the gasoline in the engine manifold at the system pressure [2]. The gasoline injectors ensure precise fuel metering according to engine work state. The injectors are controlled by control signals, whose parameters are defined by the engine management system. The control devices are power transistors (drivers) in the electronic control unit (ECU). The injectors synchronizing and speed activating has a special significance and influence upon the increasing of the power and efficiency and the decreasing of the harmful emissions of the automotive engines. The synchronization of the electromagnetic gasoline injectors is connected by one hand of the injection according engine work order and by the other – with equal fuel injection duration and injection quantity. Meanwhile the injectors work at such conditions, which imposed constant compensation and adaptation activities by the ECU. This circumstance is connected with requirements of speed activating, which is measured by indicators, such as minimal electromagnetic activating force and minimal opening and closing time. This paper is considered the method of calculating the electromagnetic parameters of the automotive electromagnetic gasoline injectors for manifold gasoline injection.*

Keywords: AUTOMOTIVE, INJECTOR, PARAMETERS, INJECTION

1. Introduction

A general layout of a typical automobile electromagnetic gasoline injestor is shown in Fig.1.

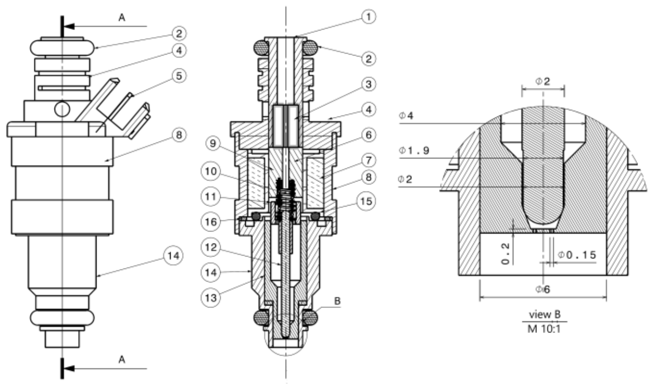


Fig.1. *General layout of a electromagnetic gasoline injector: 1-Inlet port; 2-O-ring; 3-Filter; 4-Cover; 5-Terminal; 6-Coil holder; 7-Coil; 8-Upper Housing; 9-Armature; 10-Spring; 11-Guide; 12-Needle; 13-Camera; 14-Lower Housing; 15-Internal O-ring; 16-Spacer Washer*

The fuel inlet port *1* and the lower housing *14* are sealed with O-rings *2*, respectively, to the fuel rail and the manifold. The filter *3* is located immediately after the inlet port in the cover *4*. The cover is provided with a housing for accommodating the electrical terminals *5* connected to the winding *7* located on the ciol holder *6*. The upper housing *8* together with the lower housing closes the magnetic circuit. The housings are made of steel with corresponding strength, electromagnetic and anti-corrosion properties.

Upon feeding the control signal, the armature *9* draws the guide *11* and the associated needle *12* by collapsing the spring *10* and the fuel passing through the injector interior and the open seat of the chamber *13* is injected through two holes Ø 0.15 mm. When the signal is interrupted, the spring returns the needle to the starting position, whereby the needle seals the seat in the chamber with its front head and interrupts fuel injection through the spraying holes. Excess fuel that is at a higher pressure returns to the fuel rack. The positioning and sealing between the upper and lower housing is via the spacer washer *16* and the inner O-ring 15.

The ECU driver [2,5] (most commonly the Motronic system) actuates the injector control signal (Fig. 2, diagram *a*). The current in the winding of the electromagnet increases (diagram *b*) and this leads to the needle lifting (diagram *c*). The maximum lift (full stroke) of the needle is achieved after t_{pk} (pickup time) [2]. The fuel is injected as soon as the needle starts to rise from the sealing seat. The total amount of injected fuel for one injection varies according to the characteristic shown in diagram *d*.

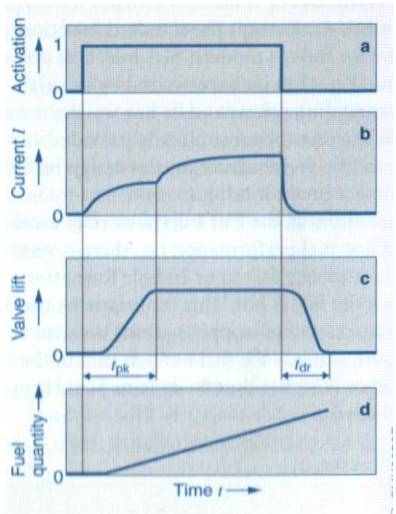


Fig.2. *[2] Activation characteristics: a-trigger signal; b-current through the winding; c-stroke of the needle; d-quantity of fuel injected*

The current through the winding decreases to zero when the control signal is terminated. The inertia of the moving parts (guide, needle, spring) causes the injector to close but with some delay. The injector closes completely after t_{dr} (drop-out time) [2]. When the injector is fully open, the amount of spraying fuel is proportional to time. The non-linear part of the injector opening and closing characteristic (t_{pk} and t_{dr} times) must be compensated for the entire injector actuation period (injection time t_{inj}, injection duration). The speed at which the needle is lifted also depends on the battery voltage.

A stainless steel is used to produce metal elements that come in contact with the fuel (i.e. gasoline) to ensure stable operation of the nozzle [2].

2. Approach

The force P with which the electromagnet attracts the guide and a related needle is determined by the formula [3]:

(1) $P = \dfrac{4(IW)^2 S}{\delta^2} 10^{-5}$, g,

where: IW is the number of amper-turns;

S – the cross section of the magnetic core, mm^2;

δ – the distance between the guide and the core (armature stroke), mm.

At a set force P, formula (1) is usually converted to determine the required number of amper-turns:

(2) $IW = 50\delta\sqrt{10\dfrac{P}{S}}$.

The cross section S of the automotive injectors is assumed to be the cross section of the injector housing that closes the magnetic circuit. The optimal value of S can be approximated by the expression:

(3) $S = \dfrac{P}{10}$, mm^2.

It can be seen from (3) that the cross section S is optimal, whereby every square millimeter weighs 10 grams force of gravity.

After determination of the amper-turns IW to obtain the force P, at the given working current I and voltage U, the number of windings of the coil and its resistance R can be calculated:

(4) $n = \dfrac{(IW)}{i}$,

(5) $R = \dfrac{U}{i}$, Ω.

According to the laws of theoretical electrical engineering [4], the current through the winding is changed by the formula:

(6) $i = \dfrac{U}{R}\left(1 - e^{-\frac{R}{L}t}\right)$, A,

where: L e is the inductance of the winding, H;

t – time, s.

The inductance L is related to the number of the turns of the coil by the formula:

(7) $n = K\sqrt{L}$,

where: K is a coefficient depending on the core material.

The coefficient K is taken from tables or nomograms [3]. Inductiveness can also be determined empirically by methodology in the special literature.

To obtain the power in Newtons, formula (1) is converted, according to a second law of Newton:

(8) $P = \dfrac{4(IW)^2 S}{\delta^2} 10^{-2} g$, N,

where: g is the earth acceleration, m/s^2.

3. Results

As a base model of the calculations an automotive electromagnetic injector is used, the scheme of which is shown in Fig.3.

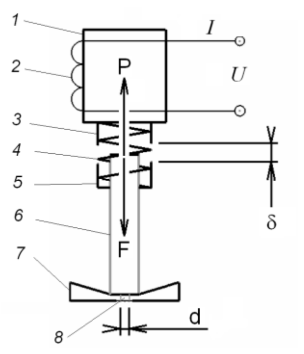


Fig.3. *Calculation scheme: 1-electromagnet; 2-winding; 3-armature; 4-spring; 5-guide; 6-needle; 7-housing; 8-injection hole; d-diameter of the injection hole; δ - stroke of the needle*

The electromagnetic parameters of the injector are presented in Table 1 together with the basic mechanical and hydraulic parameters.

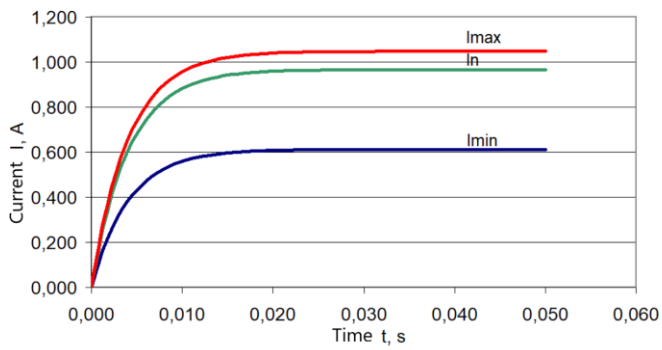
According to the above-mentioned dependencies calculations were made for the determination of the electromagnetic parameters, taking into account the influence of the voltage of the battery at the start of the engine. The minimum, nominal and maximum values of the voltage (U_{min}, U_n, U_{max}), the current (I_{min}, I_n, I_{max}) and the electromagnetic force (P_{min}, P_n, P_{max}) are given in Table 1.

Table 1: *Calculation parameters*

Parameter	Design.	Dim.	Value		
Electromagnetic Parameters					
Operating Voltage	U	V	U_{min}	U_n	U_{max}
			9,00	14,20	15,40
Operating Current	I	A	I_{min}	I_n	I_{max}
			0,612	0,966	1,048
Resistance	R	Ω	14,7		
Inductance	L	H	0,060		
Coil Turns	n		1000		
Needle Stroke	δ	mm	1,00		
Electromagnetic Force	P	N	P_{min}	P_n	P_{max}
			25,97	64,70	76,15
Mechanical Parameters					
Needle Mass	m_n	g	0,7191		
Guide Mass	m_g	g	1,000		
Spring Mass	m_s	g	0,2151		
Injection Hole Diameter	d	mm	0,15		
Injection Hole Number	m		2		
Spring Force	F	N	10		
Hydraulic Parameters					
Fuel Type			Gasoline A, B, C [7]		
Работно налягане на горивото	$p_{гориво}$	bar	1,5 – 4,5		
Плътност на горивото (25^{0}C)	$\rho_{гориво}$	g/cm^3	0,719		

The calculation results for the electromagnetic force P in dependence on the stroke of the needle δ are given in Table 2. Table 3 gives computational results for the electromagnetic force P according to time t.

Figure 4 shows the change in working current I, A.



Фиг.4. *Operating current characteristics*

The value of the electromagnetic force P for the three voltage values is calculated with a fully closed needle or maximum needle stroke, i.e. at δ = 1,00 mm. This is done in order to determine a force reserve for propelling the needle.

The maximum current value is reached for about t = 0.015 s, which applies to all three characteristics.

Table 2. *Calculation results for electromagnetic force P depending on the stroke δ of the needle*

δ, mm	P, N	Pmin, N	Pn, N	Pmax, N
1	57,42	25,97	64,7	76,15
0,98	59,79	27,04	67,37	79,29
0,96	62,3	28,18	70,21	82,63
0,94	64,98	29,39	73,23	86,19
0,92	67,84	30,68	76,44	89,97
0,9	70,89	32,06	79,88	94,02
0,88	74,15	33,54	83,55	98,34
0,86	77,63	35,11	87,48	102,97
0,84	81,37	36,81	91,7	107,93
0,82	85,39	38,62	96,23	113,26
0,8	89,72	40,58	101,1	118,99
0,78	94,38	42,69	106,35	125,17
0,76	99,41	44,96	112,02	131,84
0,74	104,85	47,42	118,16	139,07
0,72	110,76	50,1	124,81	146,9
0,7	117,18	53	132,05	155,41
0,68	124,17	56,16	139,93	164,69
0,66	131,81	59,62	148,54	174,82
0,64	140,18	63,4	157,96	185,92
0,62	149,37	67,56	168,32	198,11
0,6	159,49	72,14	179,73	211,54
0,58	170,68	77,2	192,34	226,38
0,56	183,09	82,81	206,32	242,84
0,54	196,91	89,06	221,89	261,16
0,52	212,34	96,04	239,28	281,63
0,5	229,67	103,88	258,81	304,61
0,48	249,21	112,72	280,83	330,53
0,46	271,35	122,73	305,78	359,89
0,44	296,58	134,14	334,21	393,35
0,42	325,5	147,22	366,79	431,71
0,4	358,86	162,31	404,39	475,96
0,38	397,63	179,85	448,08	527,38
0,36	443,04	200,38	499,25	587,6
0,34	496,7	224,65	559,71	658,76
0,32	560,72	253,61	631,86	743,68
0,3	637,98	288,55	718,91	846,15
0,28	732,37	331,25	825,28	971,34
0,26	849,38	384,17	957,13	1126,53
0,24	996,84	450,86	1123,3	1322,1
0,22	1186,32	536,57	1336,82	1573,41
0,2	1435,45	649,24	1617,56	1903,83
0,18	1772,16	801,54	1996,98	2350,41
0,16	2242,89	1014,44	2527,43	2974,73
0,14	2929,49	1324,99	3301,14	3885,37
0,12	3987,36	1803,46	4493,22	5288,42
0,1	5741,8	2596,98	6470,23	7615,32
0,08	8971,57	4057,78	10109,74	11898,94
0,06	15949,45	7213,83	17972,86	21153,66
0,04	35886,27	16231,12	40438,95	47595,75
0,02	143545,09	64924,47	161755,78	190382,98
0	########	########	########	########

At the beginning of the opening of the needle and the reduction of the gap *δ*, the electromagnetic force *P* increases by exponential law and theoretically bends to infinity at *δ* = 0,00 mm (fully open needle) - fig.5.

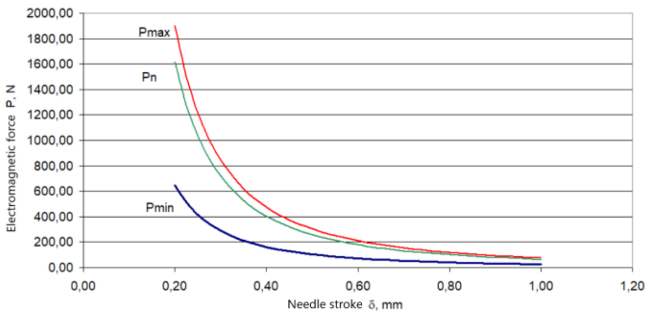


Fig.5. *Characteristics of electromagnetic force depending on the gap (needle stroke)*

The time to reach the maximum value of electromagnetic force is shown in Figure 6. The maximum value of electromagnetic force is reached for a time equal to that of the operating current, and has the same nature of increase.

In this way, the specific value of the electromagnetic force P can be determined for a particular interval and a period of time, as well as determining the time t_{min} to reach the required minimum value of the electromagnetic force P_{min} for the opening of the needle. Further it may be aligned with the frequency mode of the engine and hence be recorded in the control algorithm of the management system.

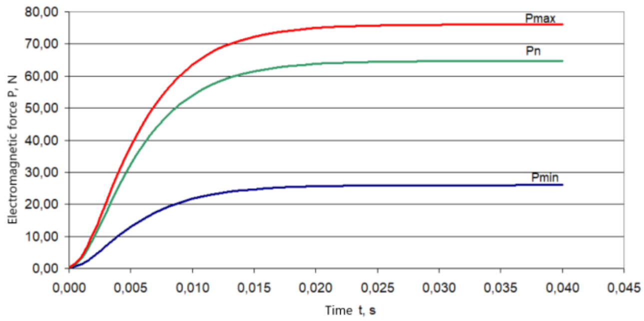


Fig.6. *Characteristics of electromagnetic force depending on the time in a fixed gap*

Table 3. *Calculation results for electromagnetic force depending on the time*

δ, mm	Pmin, N	Pn, N	Pmax, N	t, s
1	0	0	0	0
1	1,23	3,05	3,59	0,001
1	3,9	9,71	11,42	0,002
1	7,04	17,53	20,62	0,003
1	10,14	25,25	29,7	0,004
1	12,96	32,27	37,96	0,005
1	15,41	38,37	45,13	0,006
1	17,48	43,51	51,17	0,007
1	19,18	47,76	56,17	0,008
1	20,58	51,22	60,24	0,009
1	21,7	54,02	63,53	0,01
1	22,6	56,26	66,17	0,011
1	23,32	58,04	68,26	0,012
1	23,88	59,46	69,93	0,013
1	24,33	60,58	71,25	0,014
1	24,69	61,46	72,29	0,015
1	24,97	62,16	73,11	0,016
1	25,19	62,71	73,75	0,017
1	25,36	63,14	74,26	0,018
1	25,5	63,48	74,66	0,019
1	25,6	63,74	74,97	0,02
1	25,69	63,95	75,21	0,021
1	25,75	64,11	75,41	0,022
1	25,81	64,24	75,56	0,023
1	25,85	64,34	75,67	0,024
1	25,88	64,42	75,77	0,025
1	25,9	64,48	75,84	0,026
1	25,92	64,53	75,89	0,027
1	25,94	64,56	75,94	0,028
1	25,95	64,59	75,97	0,029
1	25,96	64,62	76	0,03
1	25,96	64,64	76,02	0,031
1	25,97	64,65	76,04	0,032
1	25,97	64,66	76,05	0,033
1	25,98	64,67	76,06	0,034
1	25,98	64,68	76,07	0,035
1	25,98	64,68	76,08	0,036
1	25,98	64,69	76,08	0,037
1	25,99	64,69	76,08	0,038
1	25,99	64,69	76,09	0,039
1	25,99	64,69	76,09	0,04

4. Parameters evaluation

It is of the utmost importance that the injector provides the required cyclic fuel quantity at the right time and with the exact predetermined angle of advance of the injection. In other words, the performance of the injector defined by the minimum electromagnetic force P_{min} and the minimum trigger time t_{min} [5]. The minimum electromagnetic force is defined in the previous section. The minimum trigger time is related to the needle movement rate and is determined by the following dependencies.

The needle motion is determined by:

$$V_{n_i} = \frac{P_{i-1} - F}{m_n} \Delta t + V_{n_{i-1}} \text{ , m/s,} \qquad (9)$$

where: Δt –time interval for needle motion, s;

V_{n_i} – needle speed at *i* interval, m/s.

The distance X traveled by the needle is determined of:

(10) $$X_{n_i} = \frac{P_{i-1} - F}{m_n} \Delta t^2 + V_{i-1}\Delta t + X_{n_{i-1}}, \text{ m},$$

where: X_{n_i} - distance traveled by the needle at i interval, m.

After replacing the values for the electromagnetic and spring force and the needle mass, values of time t are set, the minimum time t_{min} being defined as corresponding to that of $X_n > 0$ mm.

The calculated minimum trigger time t_{min} is compared to actual oscillograms of the injector operation along with the electronic control unit of the engine test bench. Oscillograms were taken when the engine was started (Fig.7), idle (Fig.8) and acceleration (Fig.9).

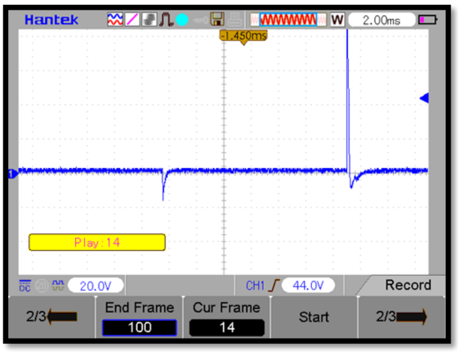


Fig.7. *Oscillogram of the injector control signal at the engine start*

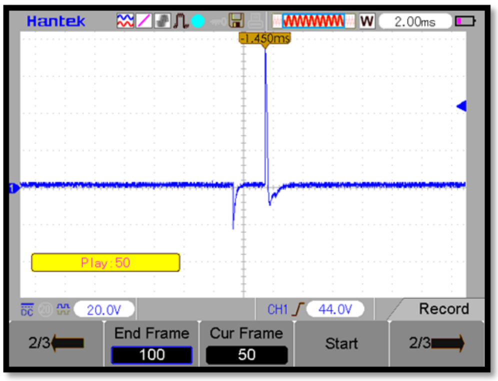


Fig.8. *Oscillogram of injector control signal at the engine idle speed*

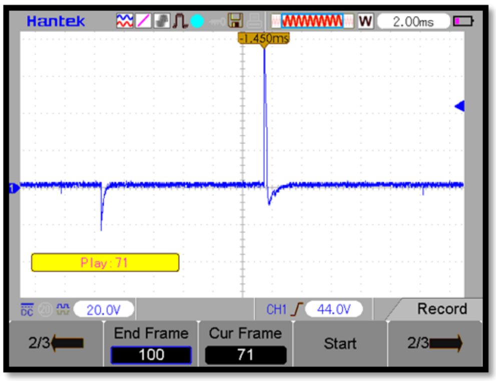


Fig.9. *Oscillogram of injector control signal at the engine acceleration*

According to the oscillograms the fuel injection time t_{inj} is as follows:

-start: t_{inj} = 14 ms;

-idle: t_{inj} = 3 ms;

-acceleration: t_{inj} = 12ms.

It should be noted that the recorded oscillograms are at zero engine load. When increasing the load on the engine, the value of the t_{inj} also increases.

It can be seen that t_{min} and t_{inj} have comparable values only at engine idle. In all other cases $t_{min} \ll t_{inj}$, which means that the calculations performed are of sufficient reliability.

5. Conclusion

An approach for calculating the electromagnetic parameters of automotive electromagnetic gasoline injectors for manifold injection (multi-point injection) is presented.

The criteria minimum trigger time t_{min} and minimum electromagnetic force P_{min} are proposed to assess the electromagnetic parameters of automotive electromagnetic gasoline injectors for manifold injection.

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