A SIMULATION STUDY OF THE INFLUENCE OF THE GAS EXCHANGE ON THE WORKING CYCLE OF A SINGLE-CYLINDER DIESEL ENGINE

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Abstract: *This article presents the results of numerical experiments with the simulation model created to study the processes of the operating cycle of an internal combustion engine in the software environment of MATLAB with Simulink. The influence of the laws of motion of the intake and exhaust valves and related time-sections for processes intake and exhaust on the working cycle and performance of a four stroke single-cylinder diesel engine is obtained.*

Keywords: INTERNAL COMBUSTION ENGINES, WORKING CYCLE, GAS EXCHANGE, MATHEMATICAL MODELING AND COMPUTER SIMULATION

1. Introduction

The mathematical model of the operating cycle of internal combustion engines (ICE), is a system of ordinary differential equations, derived from ICE theory, thermodynamics, hydrodynamics and mechanics. With the system of differential equations are described operating substance parameters during periods of the intake process, compression, expansion and exhaust process. It includes the equation for the dynamics of combustion and heat and the equation of continuity [1, 2, 5].

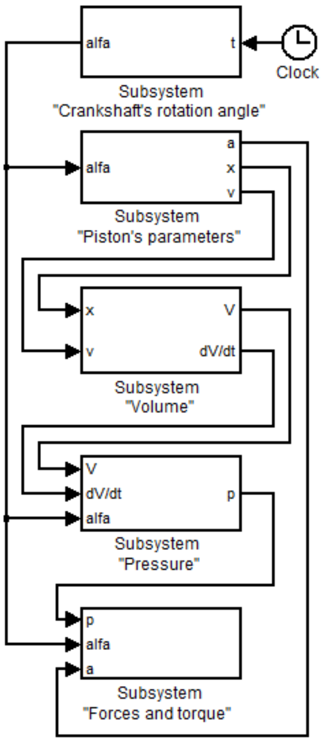

Fig. 1 *Simulation model of ICE*

The simulation model (fig. 1) of four-stroke ICE in Simulink [3, 4] is realized, based on mathematical description of the successively implemented processes of the operating cycle of ICE [1, 2, 5]. In the auxiliary script file to the simulation model is described, initialized and calculated the necessary constructive and regime parameters of the engine and the operating substance.

In structural terms, the simulation model consists of several subsystems: subsystem to determine the angle of rotation of the crankshaft as a function of time, subsystem to determine the kinematic parameters of the piston – path, velocity and acceleration, subsystem to determine the operating volume, subsystem to determine the pressure of the operating substance and subsystem to determine the forces acting on crankshaft mechanism units, as well as on torque of ICE. Individual subsystems are described in details in [3].

The simulation model of ICE [3], allows possibility for calculating the parameters of four or two stroke ICE with valve timing, valve-contour or contour gas distribution [4].

The phases and the parameters of the constituent processes, and the kinematic parameters of the piston are a function of the angle of rotation of the crankshaft α, [deg], which is considered to be an argument, and is given by

$$\alpha = 6nt \qquad (1)$$

where n, [1/min] is the speed of the crankshaft and t, [s] is the time.

The values of the parameters at the crankshaft position in top dead center (TDC), when the intake and exhaust valves are partially open, are accepted for initial conditions in a four-stroke cycle.

The transformation of t into α is performed in "Alfa" subsystem, the kinematic characteristics of the piston are calculated in the second subsystem "Pistons parameters", and the volume of the working space and its derivative - in the third subsystem "Volume", which are presented in [3].

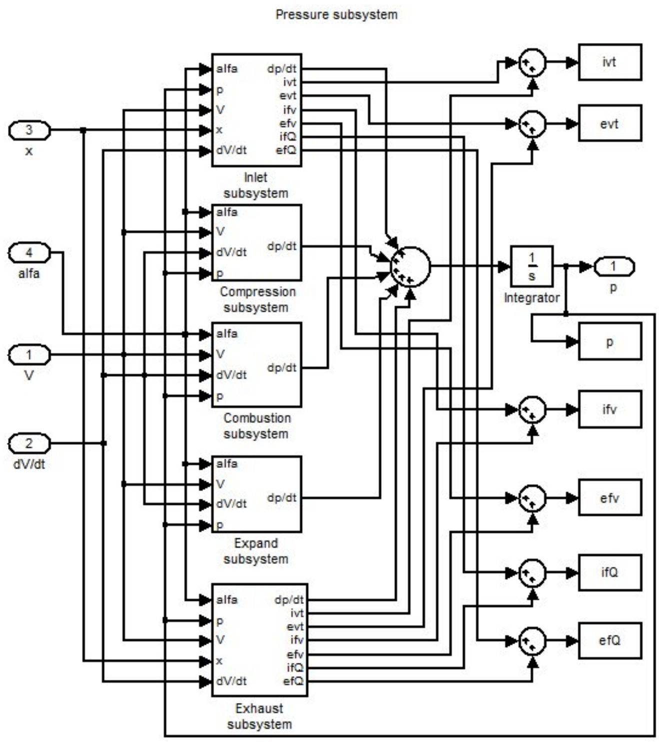

Fig. 2. *"Pressure" subsystem*

In "Pressure" subsystem, shown in Fig. 2, is calculated the derivative of the pressure and its numerical integration, at the succession of the processes of the operating cycle of the four-stroke or two-stroke ICE, with a selected valve timing system, and with the application of the following basic functional and logical dependencies.

The derivative of the pressure of the working substance in the filler is calculated from the formula

$$\frac{dp}{dt} = 6n\left(a_p \frac{\mu f}{V} z_s - bc_1 \frac{p}{V} \right), \qquad (2)$$

where μ - coefficient of the flow; f, [m2] - area of the passage section with open valve; p, [Pa] - pressure; V, [m3] - volume;

$$a_p = kp_\kappa \sqrt{2\frac{k}{k-1} R_в T_\kappa} \qquad (3)$$

$$z_s = \left(\frac{p}{p_\kappa} \right)^{\frac{1}{k}} \sqrt{1 - \left(\frac{p}{p_\kappa} \right)^{\frac{k-1}{k}}}, \qquad (4)$$

when $\frac{p}{p_\kappa} \le \beta_{кр.} = \left(\frac{2}{k+1} \right)^{\frac{k}{k-1}}$, and $-\alpha_{вк} \le \alpha \le 180 + \beta_{вк}$ for four-stroke engine;

when $\frac{p}{p_\kappa} \ge \beta_{кр}$, $z_s = \left(\frac{p}{p_k} \right)^{\frac{1}{k}}$;

$$b = \frac{\pi k V_h}{360} \qquad (5)$$

where k is the exponent of the adiabatic and V_h, [m^3] – swept volume;

$$c_1 = \frac{\sin(\alpha + \beta)}{\cos \beta} \qquad (6)$$

$$\beta = arc\sin(\lambda \sin \alpha) \qquad (7)$$

as $\lambda = R / L$, R, [m] – radius of the knee and L, [m] – length of the rod.

The flow velocity,

$$\text{when } \frac{p}{p_\kappa} \ge \beta_{кр} \;\; w_s = \sqrt{2R_в T_\kappa \frac{k}{k-1} \left(1 - \frac{p}{p_\kappa} \right)^{\frac{k-1}{k}}} \qquad (8)$$

$$\text{and when } \frac{p}{p_\kappa} \le \beta_{кр} \;\; w_s = \sqrt{2R_г T_0 \frac{k}{k-1}} \qquad (9)$$

The overall look of the dependences, for determination of the time cross-section of the intake valve while moving according harmonious law is as follows:

$$f = \mu_{iv} \left(1 - \cos\left(\alpha \frac{360^\circ}{daf_1 + daf_3} \right) \right) h_{iv} \pi D_{iv} \qquad (10)$$

where μ_{iv} is the coefficient of the hydraulic losses during filling;

daf_1 - the rotation angle of the crankshaft, corresponding to the time of the intake valve full opening;

daf_2 - the rotation angle of the crankshaft, corresponding to the constant and the maximum open position of the intake valve;

daf_3 -the rotation angle of the crankshaft, corresponding to the time of full closing of the intake valve;

h_{iv} - the full stroke of the intake valve;

D_{iv} - the diameter of the intake valve;

ω - the angular velocity of the crankshaft of the engine.

The flow rate is calculated by the formula

$$Q_v = \mu f w_s \qquad (11)$$

The calculations are performed in the "Inlet" (Fig. 3) and "Exhaust" subsystems, that are in "Pressure" subsystem, represented by functional relationships (2), ..., (11), applied to the process of the discharge, in a reciprocal relation to pressure. "Exhaust" subsystem has the same structure and relationships as "Inlet" subsystem, therefore it is not displayed.

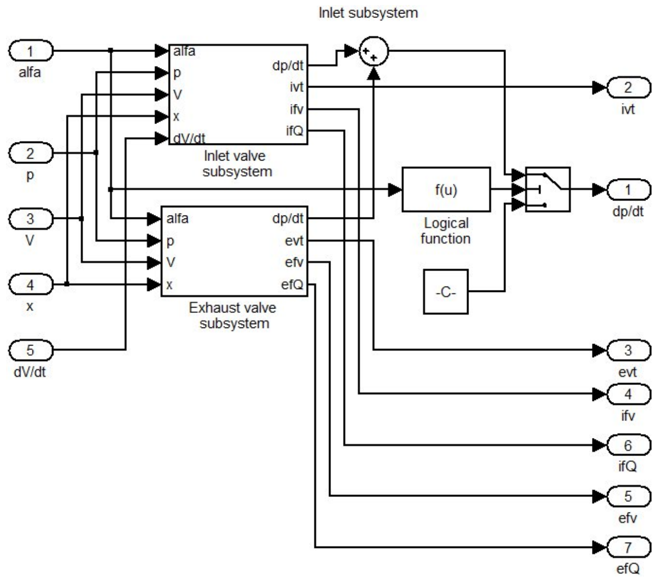

***Fig. 3.** "Inlet" subsystem*

Fig. 4 represents "Inlet valve / window" subsystem, from the "Inlet" subsystems. It implements a number of conditions and logical calculation of the derivative components of the cross-sections in time pressure, speed and consumption during exhaust, and velocity and flow rate of filling or purging.

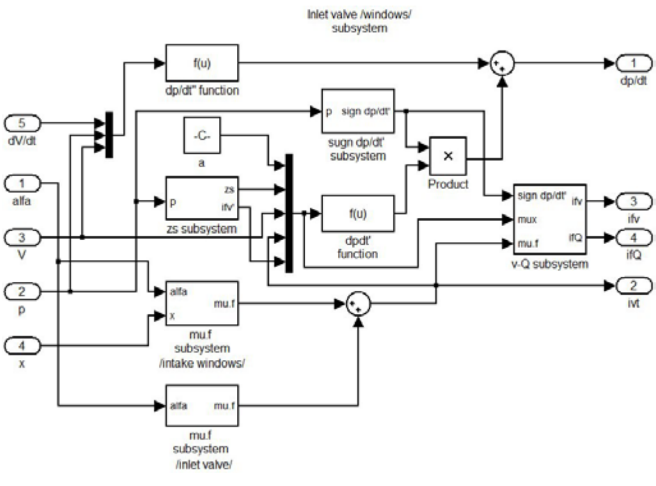

***Fig. 4.** "Inlet valve / window" subsystem*

The subsystem for the variation of the cross-section in time of the intake valve (Fig. 5) is a component of the subsystem for determination of the working substance pressure during the intake and exhaust processes. It consists of blocks for out-of-phase shift of the angle of rotation of the crankshaft with the related switches and the associated logic functions controlling them.

The percentage of the horizontal section of the valve's law of motion is defined in a script file in the simulation model and is assigned, in relative value in comparison with the total duration of the valve opening.

In cases where there is no horizontal section, the law of motion of the valve is accepted as cosinusoidal and in the presence of a horizontal section, the front and rear part are described as half cosinusoid in order to have a shockless movement of the valve.

In the case of a large percentage of the horizontal section it is necessary to ensure a guaranteed closing of the valves, especially in larger rotational speed of the crankshaft. This is achieved by using springs with suitable elastic constants.

The options where the horizontal section has the largest percentage, in which the front and rear sections are close to a straight line, are carried by electromagnetic valve drive.

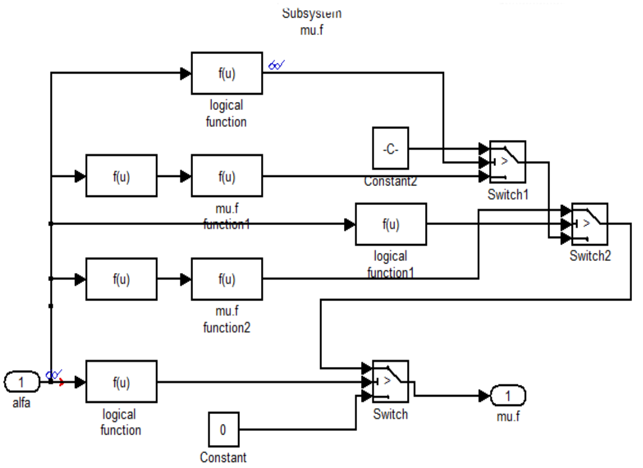

Fig. 5. *Subsystem cross-section in time of the intake valve of the internal combustion engine*

The subsystem for determining the cross-section in time of the exhaust valve is similar to that of the inlet.

The simulation model provides the opportunity to select the version of the law of motion of the corresponding valve, including with a horizontal section at a fully open valve.

2. Formulation of the problem

The aim of this work is to study the influence of the laws of motion of the intake and exhaust valves and their respective sections in time for filling and discharge processes on the cycle of four stroke single-cylinder diesel engine.

3. Simulation results and analysis

The simulation study is conducted for the four stroke single-cylinder diesel engine [6], whit direct injection and air-cooling, which has the following parameters and criteria: piston stroke - 72 mm; diameter of the cylinder - 86 mm; compression ratio – 19; average effective pressure - 546 kPa, effective power - 5,7 kW; maximum torque - 18,7 Nm and specific fuel consumption - 275,1 g/kWh at 3000 rpm.

With one of the examples of the variety of the laws of motion, the total duration of the valve opening remains constant, i.e. the cross-section in time for the respective valve remains. In this example, the start of the opening and the end of the closing of the valve changes - with a delay or advance - Fig. 6. It is possible to optimize the engine performance through the use of appropriate law for gas distribution in each established spinning frequency. In this case, the camshaft must rotate relative to the crankshaft in the various operating modes of the engine.

Fig. 7 shows the indicator diagrams, constructed with the results obtained at various angles of opening of the valves. With the increase of the outstrip in the opening of the valve, increases the maximum pressure of the cycle, and vice versa.

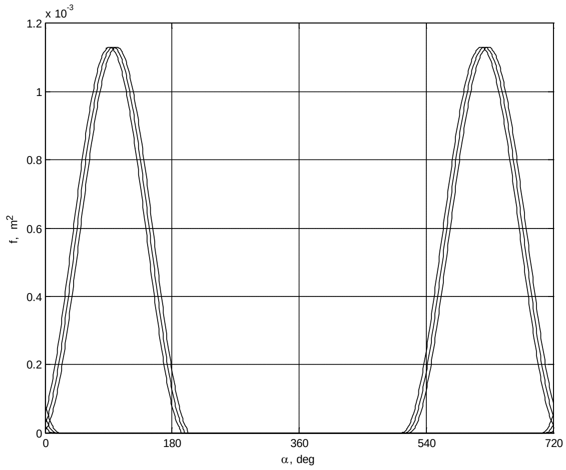

Fig. 6. *Cross-sections in time of the valves at different angles of opening*

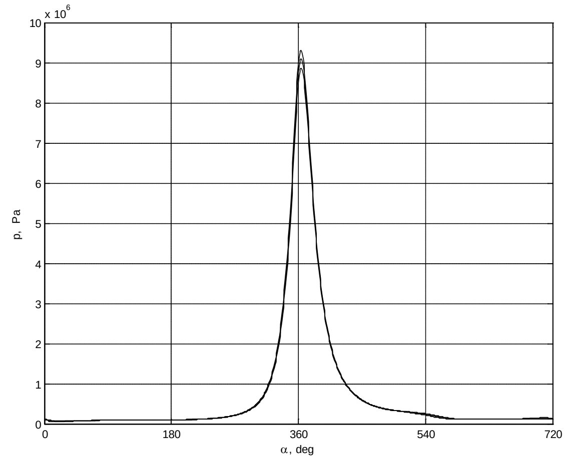

Fig. 7. *Expanded indicator diagrams at different angles of opening of the valves*

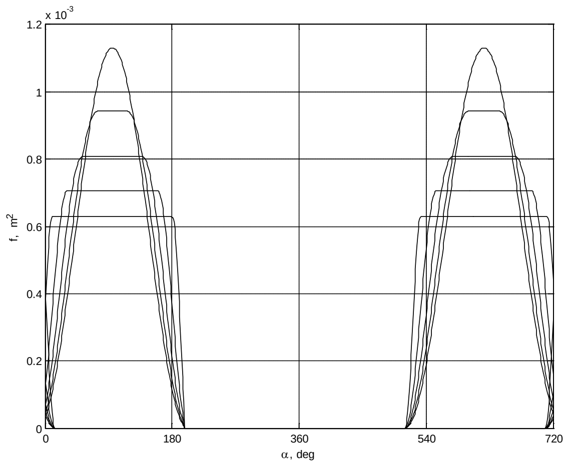

Fig. 8. *Phases of the gas exchange at a constant value of the cross-section in time of the valve and the relative duration of the horizontal section 0, 20, 40, 60, 80%*

The availability of the horizontal section in the law of motion of the valves, and respectively a change of the maximum stroke of the valve (Fig. 8), so as to maintain a constant value of the cross-section in time of the valve, results in a change in the maximum pressure of the cycle, as well as a change in the power and torque of the engine. The displayed in Fig. 9 variants of the cross-section in time modification, can be carried out by changing the camshaft of the engine or by an electromagnetic drive. The maximum pressure of the cycle is obtained at maximum relative value of the horizontal section and at the smallest valve stroke (Fig. 9).

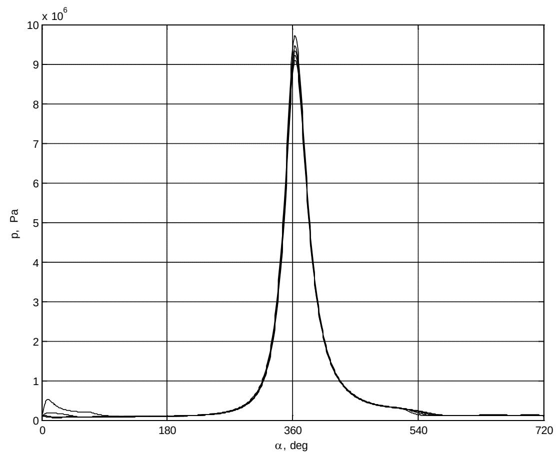

Fig. 9. *Expanded indicator diagrams at a constant value of the section of the valves in time*

Another variant of the change of the law of motion of the valves, associated with modification of the cross-section in time of the valves, i.e. different length of the horizontal section and constant maximum valves' stroke, it is shown in Fig. 10.

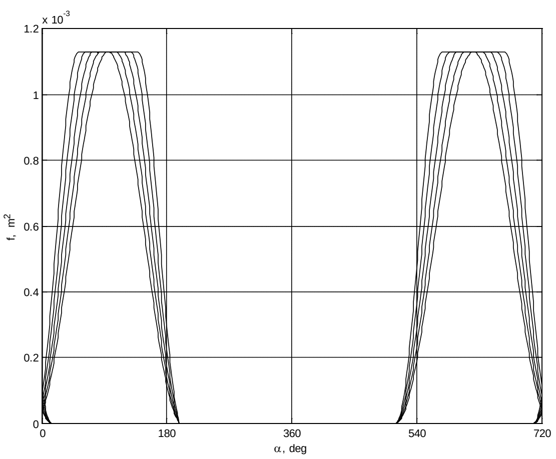

Fig. 10. *Phases of the gas exchange at a variable value of the cross-section of the valves in time, and relative duration of the horizontal section 0, 10, 20, 30, 40%*

Based on the obtained results, graphically shown in Fig. 11, it can be concluded that the maximum value of the pressure of the working substance is obtained with the longest duration of the horizontal section, i.e. with a maximum cross-section of the valve in time, realized through its electromagnetic propulsion.

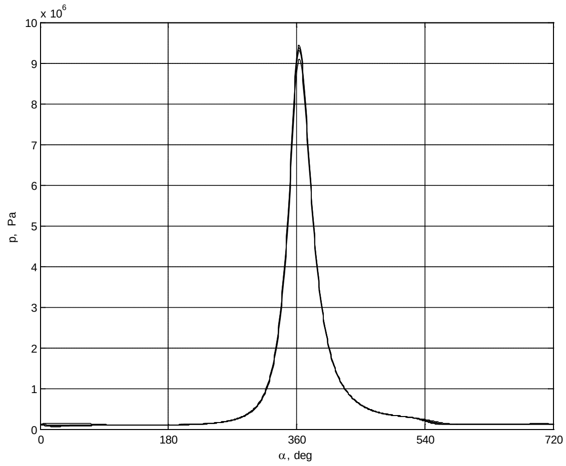

Fig. 11. *Expanded indicator diagrams for various sections of the valves in time*

1. Conclusion

With thus created simulation model, created to study the processes of the operating cycle of an internal combustion engine in MATLAB with Simulink, the influence of the laws of motion of the intake and exhaust valves and their respective cross-sections in time for filling and discharge processes on the working cycle of four stroke single-cylinder diesel engine.

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