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POWER CONSUMPTION OF ELECTROMAGNETIC VALVE ACTUATOR

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Abstract: *The paper deals with mathematical modeling and numerical computing of electromagnetic valve actuator. It describes the computing method for an internal combustion engine valve mechanism. The presented approach considers real magnetic material of electromagnets. The mathematical model reflects the B-H characteristic of the core and movable armature and deals with losses of magnetic material. The controlled current in the electromagnet coil prevents the valve bouncing from its seat. Forces from the flue-gas acting on the valve are included in this model. Valve lift, coil current, voltage and electric energy consumption are graphically shown.*

Keywords: valve, engine, model, electromagnetic, consumption

1. Introduction

Camless valvetrains have great capabilities as new gas distribution devices for automobile engines. Since each individual valve is actuated independently, the valve timing, lift, event duration, and transition time can be optimized selectively for each operating condition. One of the ways to drive the combustion engine valves is an electromagnetic actuator. Each cylinder valve is actuated by the armature of the associated electromagnetic actuator. The switching times of the electromagnetic actuator takes a short time, which increases engine performance and reduces pumping losses. Electric power is required to move the actuator.

2. Methods

One form of known electromechanical actuators includes an armature that moves back and forth along a linear travel path between two electromagnet cores, shown in Figure 1. The armature functions as an actuating member and is operated against the force of two springs positioned on opposite sides of the armature. The armature is connected to the valve. In an unactuated state, the armature is positioned midway between the two cores by the opposing springs, (Newton, 2001). The armature, which by virtue of the forces of the return springs assumes its position of rest between the two electromagnets, is alternatingly attracted by the one or the other electromagnet and accordingly the cylinder valve is maintained in its closed or open position.

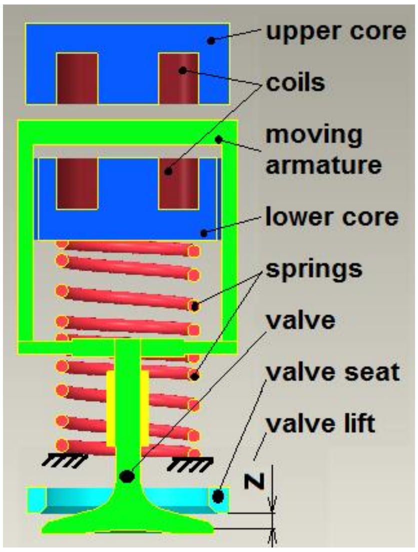

Fig. 1: Electromagnetic actuator.

2.1. Mathematical model of electromagnetic actuator

Core of the solenoid is E-shape with 20 × 32 mm center column. The lower core has two holes for connection armature to valve.

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The armature thickness is 8 mm. A coil consists of 60 turns of copper wire. Width of the actuator is 34 mm, so it will fit into the engine head of 1.6 MPI. Dimensions and number of coil turns were obtained using optimization to achieve minimal power consumption. The oscillation should be approximately at the natural resonance frequency of the spring/mass system. The total stiffness of both springs k for the period T is determined from equation (1).

$$k = 4\pi^2 \frac{m}{T^2} \tag{1}$$

Where the total moving mass m, including spring dynamic mass, is 173 g and period T was determined at 7.6 ms, corresponding to 6000 rpm. Mathematical model of the electromagnet considers the different cross-sections area of the core S_{CORE} and the movable armature S_{ARM}. Reluctance of magnetic circuit R_m for electromagnet 1 and 2 is given by the relationship (2) (Tumanski, 2011).

$$R_{m1,2} = \sum \frac{l_i}{\mu_i S_i} = \frac{l_{midle}}{\mu_0 \mu_{rCORE1,2} S_{CORE1,2}} + \frac{l_{ARM}}{\mu_0 \mu_{rARM1,2} S_{ARM}} + \frac{2y_{1,2}}{\mu_0 S_{CORE1,2}} \tag{2}$$

The relative permeability μ_r is calculated from Ampere's law (3), magnetic flux (4) and relationship between the magnetic flux density B and the magnetic field strength H (5).

$$NI = H_{CORE} l_{midle} + H_{ARM} l_{ARM} + H_{AIR} 2y \tag{3}$$

$$\Phi = \frac{NI}{R_m} = B_{CORE} S_{CORE} = B_{ARM} S_{ARM} = B_{AIR} S_{CORE} \tag{4}$$

$$B = \mu_0 \mu_r H \tag{5}$$

Relative permeability μ_{rCORE} is different from relative permeability μ_{rARM}. The mathematical model calculates the magnetic flux density according to the magnetization curve of the Fe-Co material VACOFLUX48 (VAC, 2016), whose maximum relative permeability is 18 000 and a flux density 2.3 T at 16 000 A/m magnetic field strength. The inductance of the coil L is given by the relationship (6) (Mayer, 2008).

$$L_{1,2} = \frac{N^2}{R_{m1,2}} \tag{6}$$

Magnetic force F_m is given by the relationship (7).

$$F_{m1,2} = \frac{dW_{m1,2}}{dy_{1,2}} = \frac{1}{2} \frac{dL_{1,2}}{dy_{1,2}} I_{1,2}^2 \tag{7}$$

Distance between moveable armature and individual electromagnets y_1, y_2 are given by the relationships

$$y_1(t) = z_0 + z(t) \tag{8}$$

$$y_2(t) = z_{MAX} + z_0 - z(t) \tag{9}$$

Where z_{MAX} is the maximum working stroke of the armature (ie the valve), $z(t)$ is the actual valve stroke and z_0 is the clearance between the armature and the core when the valve is closed. The equation of motion is.

$$m.\ddot{z}(t) + b.\dot{z}(t) + k.\left(z(t) - \frac{z_{MAX}}{2} \right) = F_{m1}(t) - F_{m2}(t) + F_{gas}(t) \tag{10}$$

The damping coefficient b is given by the relationship (11) (Ambekar, 2007).

$$b = 2\zeta \sqrt{k.m} \tag{11}$$

According to Drbohlav (2006), value for the damping ratio is ζ = 0.11. The maximum positive and negative coil voltage is 48 V. The total resistance of the coil R is 139 mΩ. Coil resistance is assumed at 150 °C of winding temperature and includes the resistance of two unipolar transistors. The differential equation of the coil current I is described by the relationship (12).

$$\frac{dI_{1,2}}{dt} = \frac{U_{1,2}}{L_{1,2}} - \frac{1}{L_{1,2}}\frac{dL_{1,2}}{dy_{1,2}}\dot{z}.I_{1,2} - \frac{R}{L_{1,2}}I_{1,2} \tag{12}$$

If the current reaches the target value, the current remains in saturation and the coil voltage U is calculated according to (13).

$$U_{1,2} = RI_{1,2} + \frac{dL_{1,2}}{dy_{1,2}}\dot{z}.I_{1,2} + L_{1,2}\frac{dI_{1,2}}{dt} \tag{13}$$

Immediate power of the coil can be calculated from the actual coil voltage and current values. The energy is obtained according to the relationship (14).

$$E = \int (U_1 I_1 + U_2 I_2)dt \tag{14}$$

Specific core power loss related to volume depends on the flux density B_m, thickness of the sample t, frequency f and resistivity of the material ρ according to the approximate relationship (Tumanski, 2011).

$$P = C_0 B_m^2 f + \frac{\pi^2 t^2}{6\rho}(B_m f)^2 + C_1 B_m f^{3/2} \tag{15}$$

The second part of equation (15) is related to the loss caused by eddy currents and can be reduced by decrease of thickness of the sheet and increase of the resistivity of the material. Magnetic materials of the electromagnet can be made of thin sheets. According to VAC (2016), the specific core loss is 58 W/kg (f = 400 Hz and B = 2 T) for a material thickness of 0.35 mm. The electromagnet weight is 540 g. For the maximal valve stroke, the loss energy is approximately 0.2 J.

2.2. Solving the mathematical model

For solving the mathematical model, it was used Matlab software. The graph below show valve lift, coil voltage, current and input electric energy for the maximal stroke of the intake valve per one cycle. Duration of the valve stroke is not dependent on engine speed.

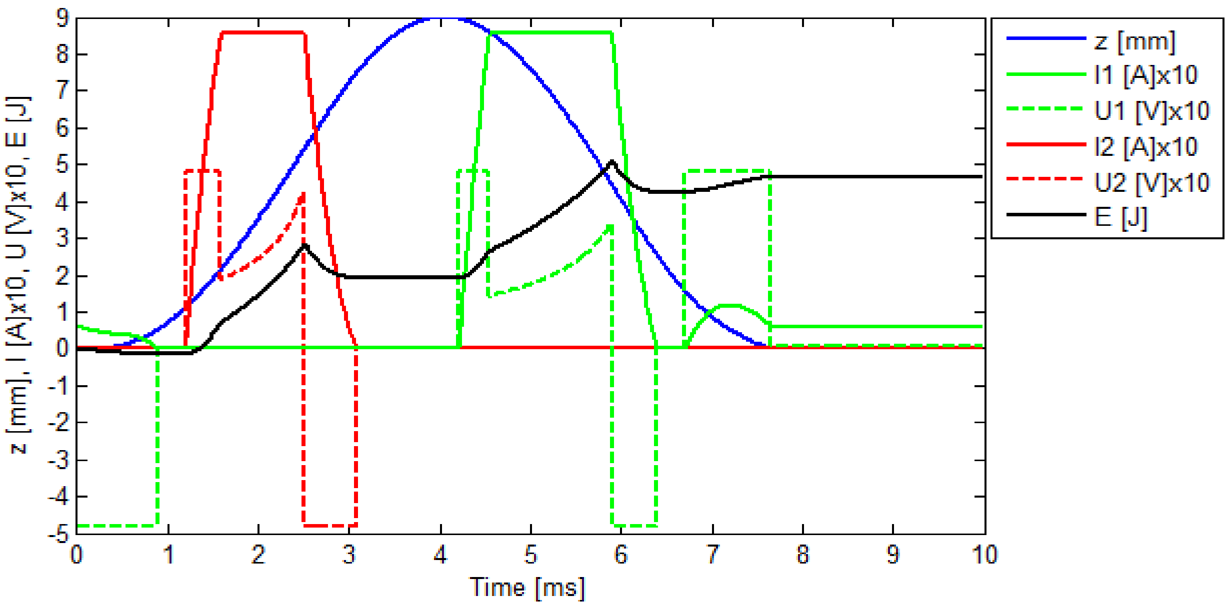

Fig. 2: The maximal stroke of the intake valve per one cycle.

The required stroke is achieved by the synchronized activate and deactivate electromagnets. The armature starts to move after switched off the upper electromagnet 1. To reach the maximum stroke, the lower electromagnet 2 is switched on. The lower electromagnet is switched off before the full stroke is reached. When the valve is fully opened, the upper solenoid is switched on. Before the valve goes into its seat, the upper solenoid is switched off and then switched on again. Higher energy consumption is achieved for the maximal stroke of the exhaust valve, as shown in Figure 3. Greater gas forces press on the exhaust valve and the lower electromagnet must be activated earlier.

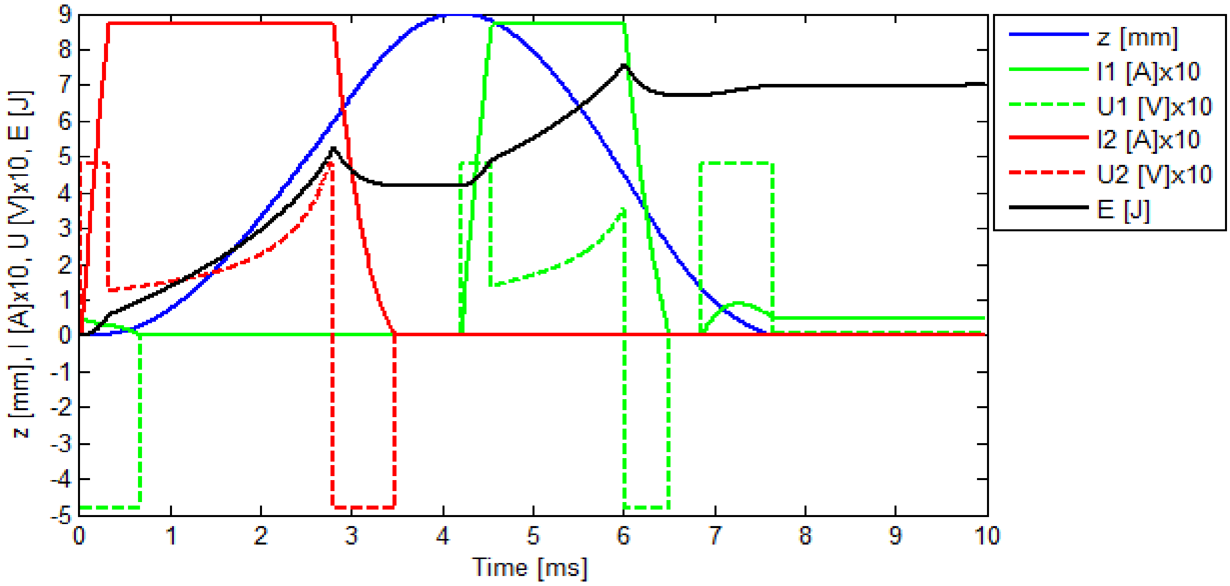

Fig. 3: The maximal stroke of the exhaust valve per one cycle.

2.3. Verification of the mathematical model

Ansys Workbench simulation software was used to verify the mathematical model. Results obtained using a 3D simulation match mathematical model. Figure 4 shows the flux density of actuator for the closed valve. Distance between the armature and the core is 0.1 mm. Force of the electromagnet is 634 N at a 6.1 A coil current. This force keeps the valve closed even the vacuum is in the engine cylinder. If the distance between armature and the core is 4 mm, the force of electromagnet is 334 N at a 86 A coil current.

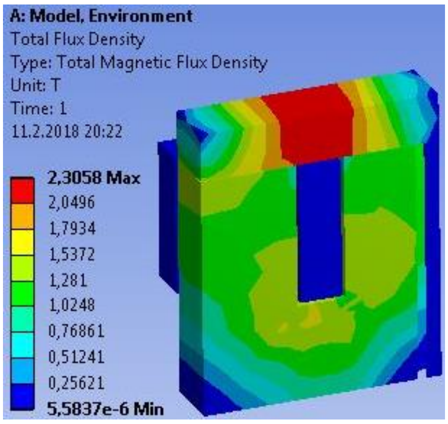

Fig. 4: 1/4 of electromagnetic actuator.

3. Conclusions

This paper deals with the electromagnetic valve actuator simulation. The mathematical model reflects the B-H characteristic of the core and movable armature and deals with losses of magnetic material. Loss of magnetic material is approximately 3 % of the total losses. Input electric energy for the maximal stroke of the intake valve is 4.7 J and input electric energy for the maximal stroke of the exhaust valve is 7 J per one cycle. When the valve is closed, the power consumption of the upper electromagnet is 5.2 W.

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