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POWER CONSUMPTION OF ELECTRODYNAMIC VALVE ACTUATOR

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Abstract: *The presented analysis deals with a procedure how to compute electric energy consumption of electrodynamic valve actuator of combustion engine. The main aim of the electrodynamic valve control is to ensure independent valve lift and timing. Magnetic field of the actuator was determined using finite element analysis software. The paper also deals with an optimizing of the actuator coil. Forces from the flue-gas acting on valve is included in this model. Valve lift, coil current, voltage and electric energy consumption are graphically shown.*

Keywords: **Valve, Engine, Model, Electrodynamic, Consumption.**

1. Introduction

Designers strive to achieve the best engine performance. Variable valve control of combustion engine increases engine torque and reduces fuel consumption and emissions. Camless valvetrain can operate independently of the crankshaft of the engine, so the main advantage of the camless valvetrain is to provide independent valve timing. One of the possibilities of the independent valve control is an electrodynamic actuator connected to the valve. Each cylinder valve is actuated by the electrodynamic actuator. Electric energy is required to move the actuator.

2. Methods

The basic parts of this actuator are movable coil and stationary permanent magnet, shown in Figure 1. The coil is connected to the valve (Miyoshi, 1999). The coil moves in a cylindrical slot between the pole extensions of the magnetic circuit. The direction of the force can be easily changed by the opposite direction of the coil current. The force of the electrodynamic actuator is independent of the valve stroke. Stiffness of the spring is lower than conventional valve mechanism. The stiffness of the spring is selected to keep the valve closed when the differential pressure of the gases is 1 bar (higher pipe pressure than pressure in engine cylinder).

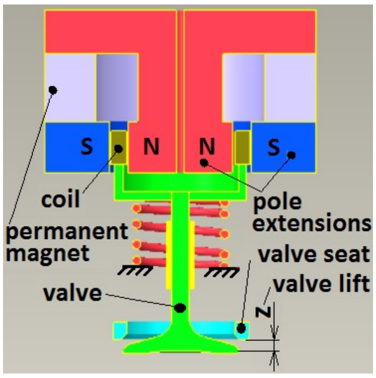

Fig. 1:Electrodynamic actuator

2.1. Mathematical model of electrodynamic actuator

The principle of the electrodynamic actuator uses the Lorentz force law (Tumanski, 2011). Lorentz force is the mechanical force acting on a current conducting wire and can be described as.

$$\vec{F} = I\left(\vec{\ell} \times \vec{B}\right) \tag{1}$$

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where ℓ is a vector of the length of wire. Direction of the vector ℓ is along the wire, aligned with the direction of conventional current flow *I*. If the magnetic field *B* is perpendicular to the direction of the conductor, the equation of motion is.

$$F(t) = B.I(t).\ell = (m_{valve} + m_{coil}).\ddot{z}(t) + k_{spring}.z(t) + F_{gas}(t) \qquad (2)$$

From the relationship (2), it is evident, that the force *F* increases with the increasing conductor length ℓ. However, with the increasing length of the conductor, it also increases conductor mass, hence the mass of the moving coil m_{coil}. This is disadvantageous because the acceleration of the valve must be quite considerable. Force also increases with increasing current flowing through the coil wire. However, with the increasing current, the energy losses in the conductor increase. The instantaneous conductor power loss P_{loss} is given by the relationship (3) (Sedlák, 2002).

$$P_{loss}(t) = RI^2(t) = \frac{1}{\gamma}\frac{\ell}{A}I^2(t) \qquad (3)$$

Where *R* is the resistance of the conductor, which can be determined using by the conductivity *γ*, conductor length ℓ and conductor cross-sectional area *A*. The optimization therefore consists of finding a length and cross-sectional area of the conductor in which the losses energy for the valve movement will be minimal. The instantaneous conductor power loss can be also expressed using by the coil mass and density of the coil material *ρ*.

$$P_{loss}(t) = \frac{1}{\gamma}\frac{\rho\,\ell^2}{m_{coil}}I^2(t) \qquad (4)$$

After expressing the current from equation (2) and inserting into equation (4), we obtain the equation (5) for minimum conductor power loss.

$$\frac{dP_{loss}}{dm_{coil}} = \frac{d}{dm_{coil}}\left[\frac{\rho}{\gamma B^2}\left(\frac{(m_{valve} + m_{coil})^2\ddot{z}^2}{m_{coil}} + \frac{2(m_{valve} + m_{coil})\ddot{z}K}{m_{coil}} + \frac{K^2}{m_{coil}}\right)\right] = 0 \qquad (5)$$

where *K* is given by the relationship (6).

$$K = k_{spring}.z + F_{gas} \qquad (6)$$

The result of optimization is the relationship (7).

$$m_{coil} = \sqrt{m_{valve}^2 + \frac{2m_{valve}K}{\ddot{z}} + \frac{K^2}{\ddot{z}^2}} \qquad (7)$$

For intake valve, the spring stiffness k_{spring} and the gas forces F_{gas} are negligible. The greatest losses occur at maximum engine speed where the dominant force is the accelerating force. The result of optimization is the relationship (8).

$$m_{coil} = m_{valve} \qquad (8)$$

Energy losses of the actuator for intake valve are the lowest if the coil mass m_{coil} is identical to the mass of the valve m_{valve}. It does not matter the cross-sectional area and length of the conductor, only the total mass of the coil is important. Valve mass, including coil connection and spring dynamic mass, is 45 g. Coil mass is also 45 g, so total moving mass is 90 g. Better material for conductor is aluminum than copper. Aluminum has 61 percent of the conductivity of copper, but has only 30 percent of the weight of copper, so the energy losses are reduced by 51 percent. The total resistance of the coil R is 164 mΩ. Coil resistance includes the resistance of two unipolar transistors.

2.2. Permanent magnetic circuit with air gap

Ansys simulation software was used to find the magnetic field of the actuator. The permanent magnet material is NdFeB N35. The results obtained with 3D simulation were further used in the mathematical model. Figure 2 shows the magnetic flux density of the actuator.

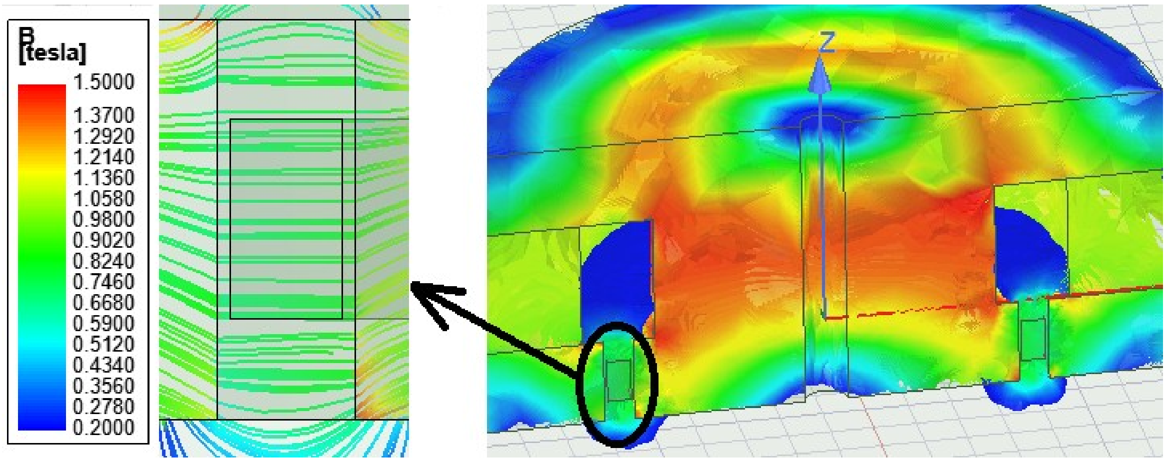

Fig. 2:Magnetic field in the air gap and in the conductor.

Magnetic flux density *B* is a little bit dependent on the magnitude and direction of the current and position of the coil. Its average value determined from the simulation is 0.74 T. Inductance of the coil *L* is 519 μH.

2.3. Solving the mathematical model

The coil consists of 30 turns of aluminum wire and the conductor diameter is 1.5 mm. The coil current is given by the equation (9) and can be calculated from the known valve stroke *z(t)*, valve acceleration $\ddot{z}(t)$ and gas forces F_{gas}.

$$I(t) = \frac{1}{B.\ell}\left[\left(m_{valve} + m_{coil}\right).\ddot{z}(t) + k_{spring}.z(t) + F_{gas}(t)\right] \tag{9}$$

Coil voltage U is calculated according to equation (10) (Souček, 2004).

$$U(t) = B.\ell.\dot{z}(t) + R.I(t) + L\frac{dI(t)}{dt} \tag{10}$$

Immediate power of the coil *P* can be calculated from the actual coil voltage and current values. The energy *E* is obtained according to the relationship (11).

$$E = \int P(t)dt = \int U(t)I(t)dt \tag{11}$$

For solving the mathematical model, it was used Matlab software. The graph below shows valve lift, coil voltage, current and input electric energy for the maximal stroke of the intake valve and the exhaust valve per one cycle.

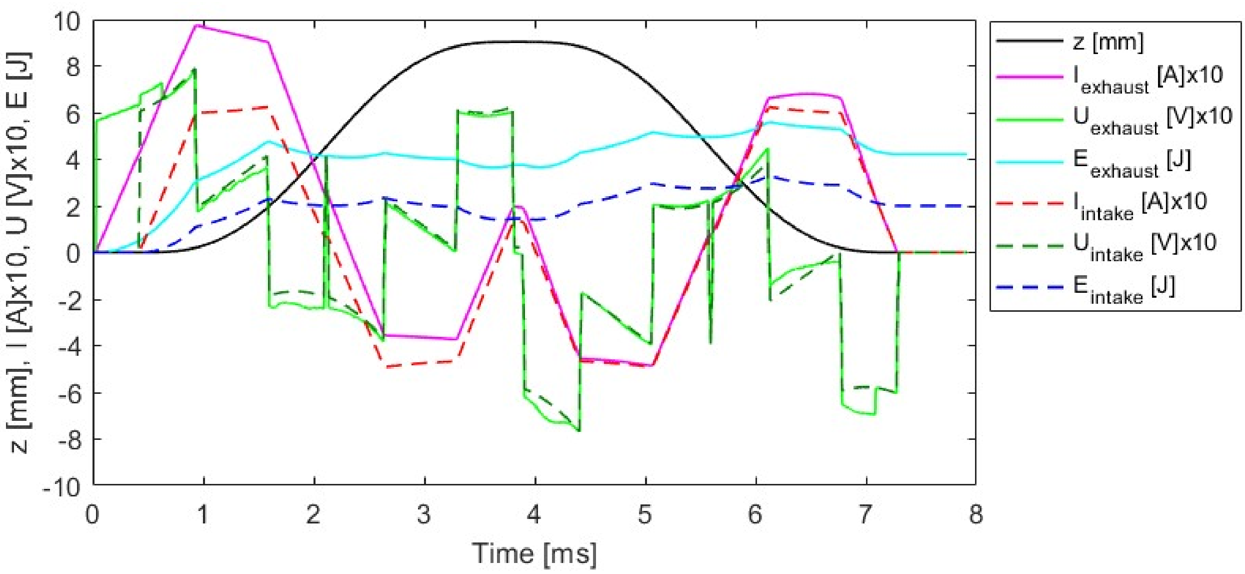

Fig. 3:One working stroke of intake valve (dashed line) and exhaust valve (full line) at 6000 RPM.

Figure 4 shows the exhaust valve input electric energy per one cycle depending on the engine speed and valve lift for two different coil mass.

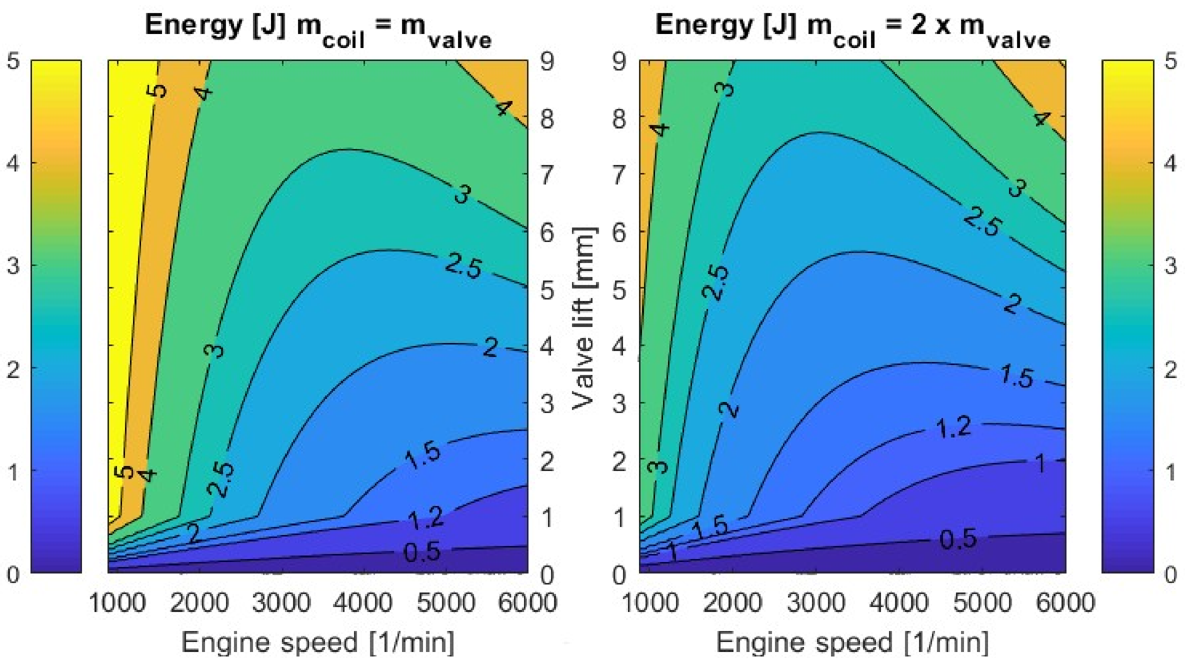

Fig. 4:Input energy for working stroke of the exhaust valve, $m_{coil} = m_{valve}$ *and* $m_{coil} = 2 \times m_{valve}$..

If the conductor area extends twice and the coil mass increases by 45 g, the input energy increases by 14 % at 6000 RPM, but at 2000 RPM, the input energy drops by 37 %.

3. Conclusions

This paper deals with the electrodynamic valve actuator simulation. Magnetic flux density determined from the finite element analysis software is 0.74 T. Finite element analysis software was also used to verify the actuator force. Results obtained using a 3D simulation match mathematical model. The non-linearity of the actuator force caused by the current is 8 % and non-linearity caused by the coil position is 5 %. Input electric energy for the maximal stroke of the intake valve is 2 J and input electric energy for the maximal stroke of the exhaust valve is 4.2 J per one cycle at 6000 RPM.

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