Design and Simulation of an Electromagnetic Valve Actuator Using COMSOL Multiphysics

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Abstract: In this paper an electromagnetic solenoid actuator (EMVA) consisting of an upper and lower electromagnet, a linear moving armature and two preloaded springs is considered as a potential approach in Variable Valve Actuation (VVA) Systems for Internal Combustion Engines. In opposition to common approaches the underlying EMVA make use of a permanent magnet in the upper electromagnet. The analysis of the upper electromagnet has been performed using finite element (FEM) simulation. Thereby an axially symmetrical 2D FEM model in COMSOL Multiphysics has been used taking into account all non-linear effects. The static force calculation has been applied using the virtual work method.

Keywords: Electromagnetic solenoid actuator, variable valve actuation, COMSOL Multiphysics, finite element method.

1. Introduction

Limited resources of crude oil and stringent emissions regulations are forcing the automotive industry to develop more efficient gasoline engines. In order to improve fuel economy and reduce exhaust emissions, variable engine valve actuation systems are considered. Notice that in conventional engines the valve's open and closing timings are fixed relatively to the engine crank angle and cannot be adjusted to engine load and speed.

There are several ways to implement variable valve trains [1]. Mechanical approaches such as the Valvetronic and Vanos-System by BMW and the VETEC-System by Honda make use of an adjustable camshaft. However, most research projects focus on the electromagnetic approach [2][3][4][5][6]. An electromagnetic solenoid valve actuator (EMVA) is considered in this paper.

2. General Requirements

The typical valve stroke curve is depicted in Fig. 1. The maximum lift $\hat{x} = 9$ mm has to be reached during the time $T = 3$ ms. The required maximum force depends on the used profiles for velocity v and acceleration a and on the mass m of all moving parts.

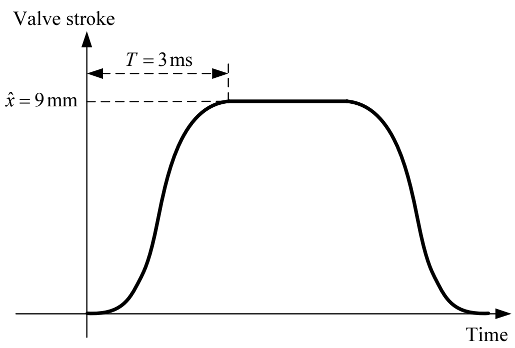

Figure 1. Valve stroke curve.

Assuming the profiles in Fig. 2 the equations for the valve stroke, velocity and acceleration within the interval $0 \le t \le T$ are given by

$$x(t) = \frac{\hat{x}}{2}\left(1-\cos\left(\frac{\pi}{\mathrm{T}}t\right)\right) \quad (1)$$

$$v(t) = \frac{\mathrm{d}x}{\mathrm{d}t} = \frac{\hat{x}}{2}\frac{\pi}{\mathrm{T}}\sin\left(\frac{\pi}{\mathrm{T}}t\right) \quad (2)$$

$$a(t) = \frac{\mathrm{d}v}{\mathrm{d}t} = \frac{\hat{x}}{2}\left(\frac{\pi}{\mathrm{T}}\right)^2\cos\left(\frac{\pi}{\mathrm{T}}t\right) \quad (3)$$

respectively.

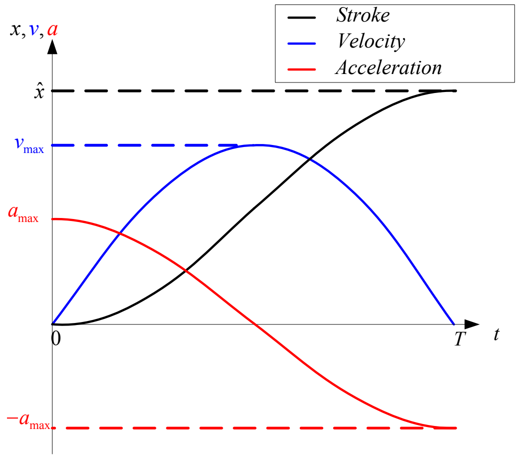

Figure 2. Used profiles for stroke, velocity and acceleration.

From Eq. (3) the maximum acceleration is determined by

$$a_{\max} = \frac{\hat{x}}{2}\left(\frac{\pi}{\mathrm{T}}\right)^2 \approx 4950\,\frac{\mathrm{m}}{\mathrm{s}^2}. \qquad (4)$$

The outer dimensions of the actuator may not exceed 36 mm (width), 60 mm (depth) and 100 mm (height).

3. EMVA Principle of Operation

The EMVA is a solenoid consisting of an upper and lower electromagnet, a linear moving armature and two preloaded springs (see Fig. 3). Mechanically this actuator is a resonant oscillating device with inherent damping in which energy is alternating between potential energy stored in the springs the kinetic energy of the moving armature. The two basic tasks of the electromagnets are to hold the armature in either the open or the closed position and to return energy that is dissipated during motion due to friction and work against the pressure of the exhaust gas.

Fig. 4 compares the lift profile of conventional valve train with the electromagnetic valve train. Thereby the variation of the closing time is shown. The air mass which is aspirated during the intake stroke can be regulated without a throttle valve by varying the opening period.

Furthermore with an EMVA system the opening and the closing events can be shifted with respect to the crankshaft angle, which allows an optimization of the combustion process depending on the engine load and speed.

In the opened and closed positions electrical power is needed to enable the electromagnets to hold the armature against the spring stiffness. During operation the duration of the closed state is much greater than the one of the opened state. That's why a new EMVA is considered in Fig. 5.

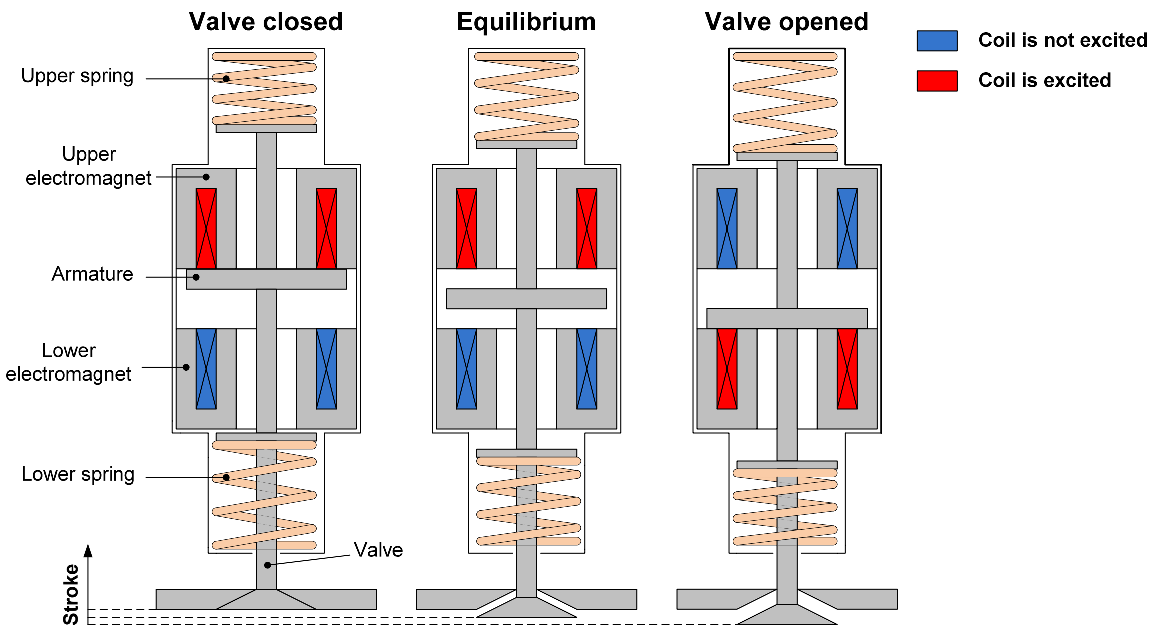

Figure 3. EMVA Principle of Operation.

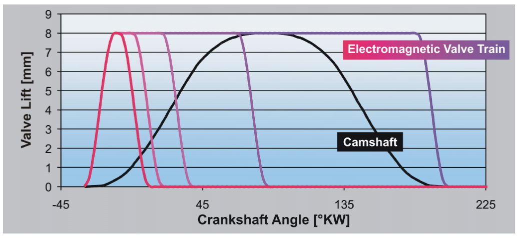

Figure 4. Variation of Valve closing time.

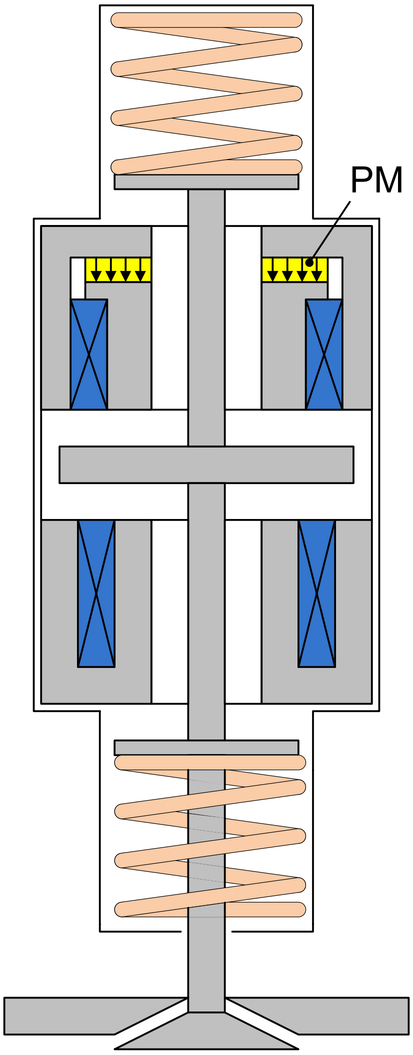

Figure 5. EMVA with permanent magnet.

The new EMVA make use of a permanent magnet in the upper electromagnet to support the magnetic field of the coil in the closed position.

4. Simulation

In the following simulation only the upper electromagnet is considered. Thereby an axially symmetrical 2D FEM model in COMSOL Multiphysics is used (see Fig. 7).

The nonlinear B-H curve in Fig. 6 has been used for all steel parts. This curve can be expressed as

$$B = a \cdot \operatorname{asinh}(b \cdot H) \tag{5}$$

with $a = 0{,}27\ \mathrm{T}$ and $b = 0{,}045\ \frac{\mathrm{m}}{\mathrm{A}}$.

The use of this analytical expression instead of a lookup table leads to a faster convergence of the simulation in COMSOL.

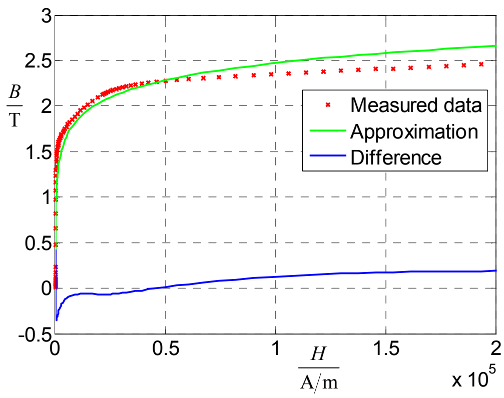

Figure 6. Used B-H curve.

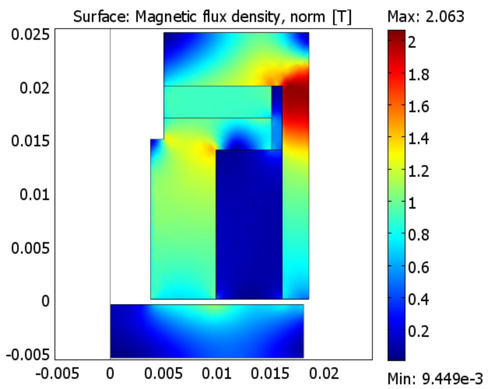

Figure 7. FEM Model of the upper electromagnet.

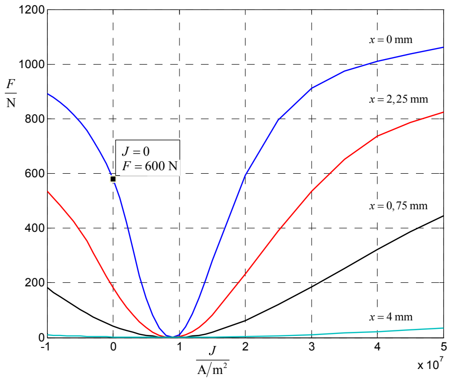

Figure 8. Static force calculation.

The calculation of the static force versus current density has been applied using the virtual work method. The results are presented in Fig. 8 for four armature positions.

It can be seen that in the closed position the force is 600 N when the coil is not excited. This is due to the permanent magnet.

5. Conclusions

In the common EMVA electrical power is needed to enable the electromagnets to hold the armature against the spring stiffness. In this paper a new EMVA making use of a permanent magnet in the upper electromagnet to support the magnetic field of the coil in the closed position has been considered.

The FEM simulation in COMSOL Multiphysics has shown that the force due to the permanent magnet is 600 N. This means that less electrical power is needed to hold the armature. However, in opposition to common EMVA, electrical power is needed to release the armature. Furthermore using the permanent magnet leads to less space for the coil.

6. References

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