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Static and Dynamic 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. 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 nonlinear effects. The calculated static characteristics are implemented in a SIMULINK model to simulate the dynamics of the EMVA.

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

1. Introduction

In recent years, one of the main focuses within the automotive industry was improving fuel economy and reducing exhaust emissions. In order to achieve this purpose 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 an electromagnetic valve actuator (EMVA) [2][3][4][5].

2. General Requirements

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

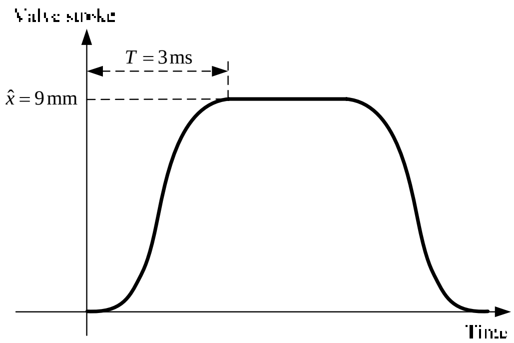

Figure 1. Valve stroke curve.

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

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

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

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

respectively.

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

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

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

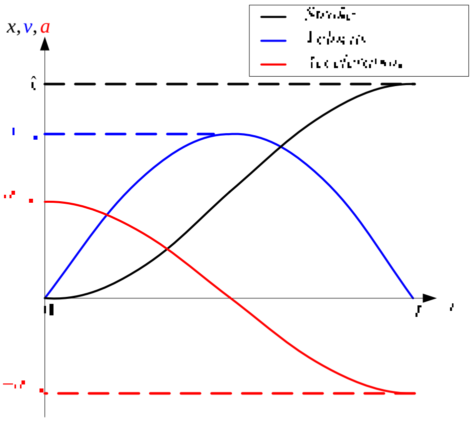

Figure 2. Used profiles for stroke, velocity and acceleration.

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.

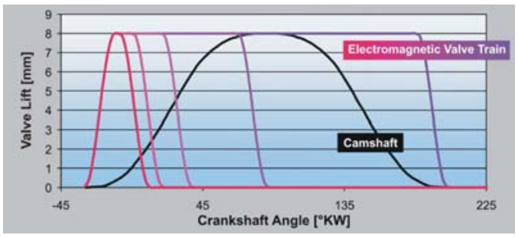

Figure 4. Variation of Valve closing time.

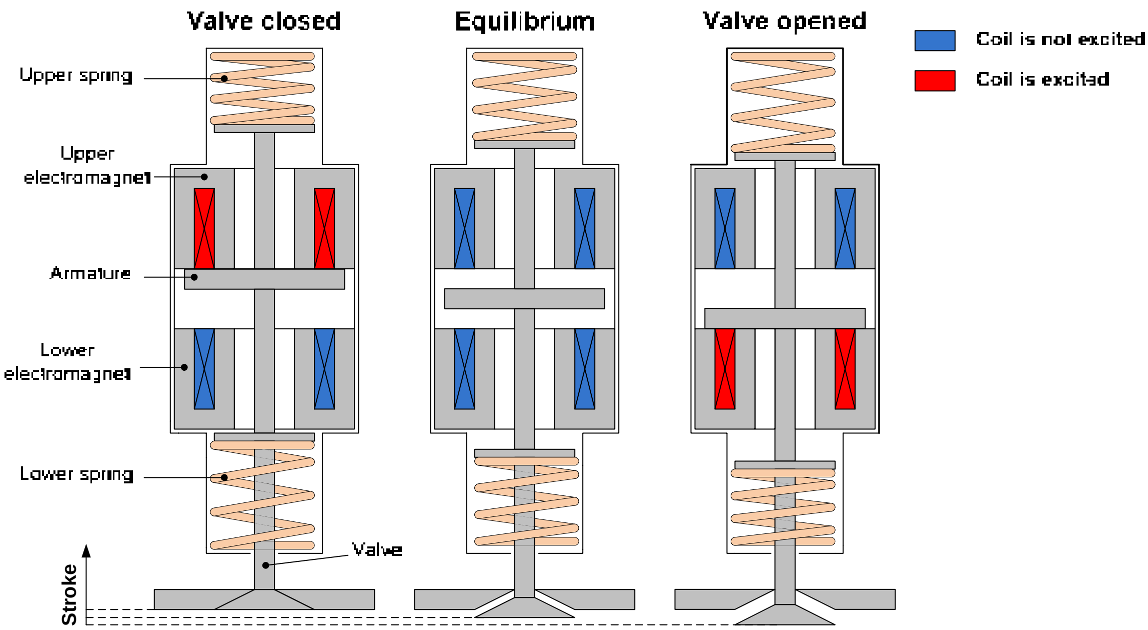

Figure 3. EMVA Principle of Operation.

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. 5).

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 $b = 0{,}045\ \dfrac{\mathrm{m}}{\mathrm{A}}$.

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

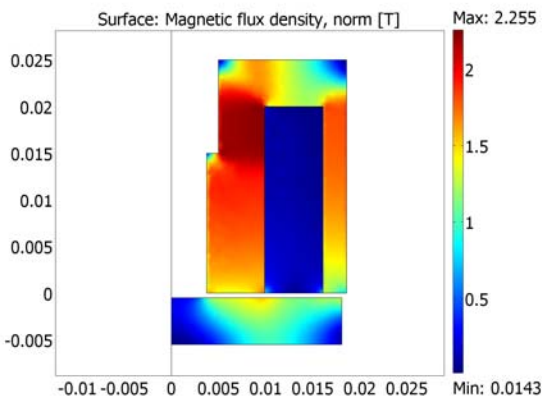

Figure 5. FEM Model of the EMVA.

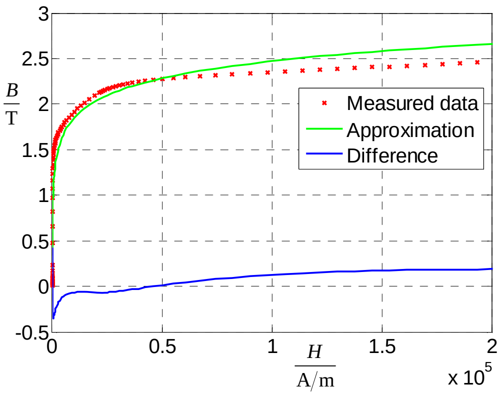

Figure 6. Used B-H curve.

The results of the static force and flux linkage characteristics are depicted in Fig. 7 and Fig. 8.

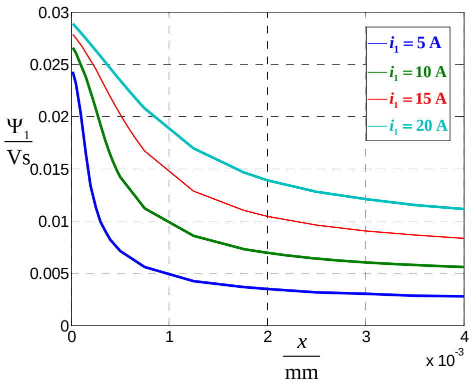

Figure 7. Flux linkage.

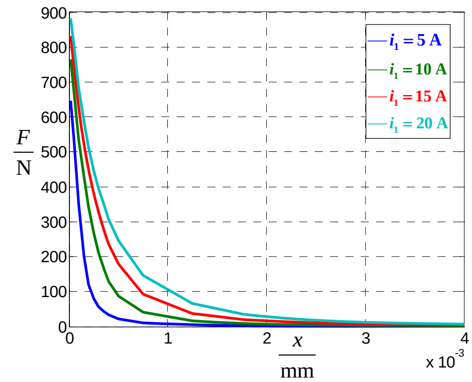

Figure 8. Electromagnetic force.

5. Simulink Model for Dynamics

The derivation of the Simulink model is based on the electrical equations

$$u_1 = R \cdot i_1 + \frac{d\Psi_1(i_1,x)}{dt} \tag{6}$$

$$u_2 = R \cdot i_2 + \frac{d\Psi_2(i_2,x)}{dt} \tag{7}$$

and on the equation of motion

$$m\,\ddot{x} = F_1(x,i_1) + F_2(x,i_2) - k \cdot x \tag{8}$$

with

u_μ :	Input voltage of electromagnet μ
i_μ :	Current of electromagnet μ
Ψ_μ :	Flux linkage of electromagnet μ
$F_\mu(x,i_\mu)$:	Electromagnetic force μ
k :	Spring constant

Thereby damping, friction, eddy currents and the mutual inductance have been neglected. The state equation describing the model can be written as

$$\begin{pmatrix} \dot{\Psi}_1 \\ \dot{\Psi}_2 \\ \dot{v} \\ \dot{x} \end{pmatrix} = \begin{pmatrix} u_1 - R \cdot i_1(\Psi_1, x) \\ u_2 - R \cdot i_2(\Psi_2, x) \\ \frac{1}{m} \cdot \left[F_1(x, i_1) + F_2(x, i_2) - k \cdot x \right] \\ v \end{pmatrix} \quad (9)$$

$F_1(x,i_1)$ and $F_2(x,i_2)$ are directly provided by the FEM simulation as a 2D matrices and can be implemented in Simulink as a 2D lookup tables. However, the matrices $\Psi_1(i_1,x)$ and $\Psi_2(i_2,x)$ have to be transformed in $i_1(\Psi_1,x)$ and $i_2(\Psi_2,x)$. The Simulink model is presented in Fig. 9 with the input variables u_1 and u_2 and the output variables x, v and a. In [6] a model is presented considering friction, damping and eddy currents.

6. Conclusions

An electromagnetic valve actuator (EMVA) has been designed and presented. Its static characteristics are calculated using an axially symmetrical 2D FEM model in COMSOL Multiphysics. Thereby the nonlinear magnetic behaviour of all steel parts has been considered.

Finally, a Simulink model has been presented to simulate the dynamics of the EMVA based on FEM results.

7. References

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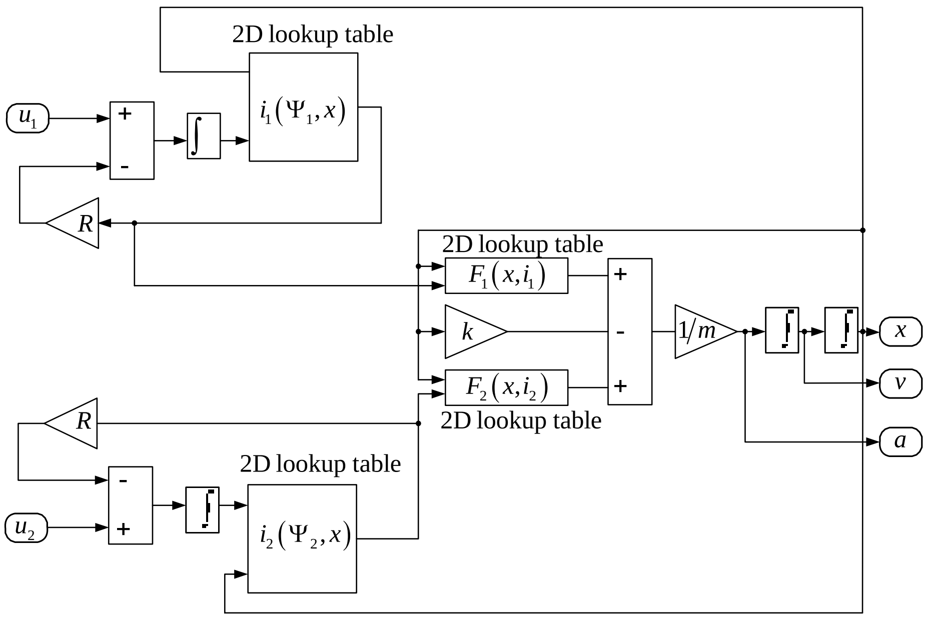

Figure 9. Simulink model for dynamics.