Transient Analysis of an EMVD Using COMSOL Multiphysics

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Abstract: In this paper an EMVD (Electro-Mechanical Valve Drive) for combustion engines is redesigned to achieve a fail-safe behavior when power loss occurs. The Magnetic Field interface and the Moving Mesh interface of COMSOL Multiphysics 4.2 are used to build up a transient model. This model also includes the calculation of eddy currents.

Keywords: EMVD, ACDC, Moving Mesh, Eddy Current

1. Introduction

Due to the purpose of minimizing the pollution and the fuel consumption by vehicles the automotive industry is searching for new concepts. Most concepts focus on technologies which may totally replace the conventional combustion engine in decades. In order to cover this gap the conventional combustion engine is being improved. To reduce fuel consumption different mechanical or hydraulic systems are replaced by electrical engines, which are more flexible. Electrical pumps and steering systems are already on the market. Even though the mentioned systems improve the efficiency of the vehicle they do not improve the combustion itself. To improve the combustion a more flexible valve opening and closing is needed. This allows the control of the fuel-air mixture without the use of a throttle. In most of the combustion engines the movement of the valves is fixed to the contour of the cams and the rotational speed of the crankshaft, but the cams are optimized for a specific working point. This reduces the possible power and fuel saving in a wide range [1].

An improvement is the EMVD (Electro-Mechanical Valve Drive), which can control the opening and closing of the valves independently from the rotation of the crankshaft [2].

A very common actuator concept is the combination of two solenoids which are placed adverse (Fig. 1). The solenoids pull a plate, which is connected to the valve. This allows an independent movement of the valves from any other component of the engine. But the independent movement of the valves is also a risk, as the piston can damage valves which are in wrong position. A power loss could result in a total loss of the motor, as all valves would return to their rest position at half stroke.

To avoid this situation a permanent magnet is used to hold the valve in the upper position. The prices for magnetic material are rising rapidly. Therefore the size and the flux of the additional permanent magnet are altered to achieve the best design regarding costs and fail safe security. Additionally the eddy currents are modeled.

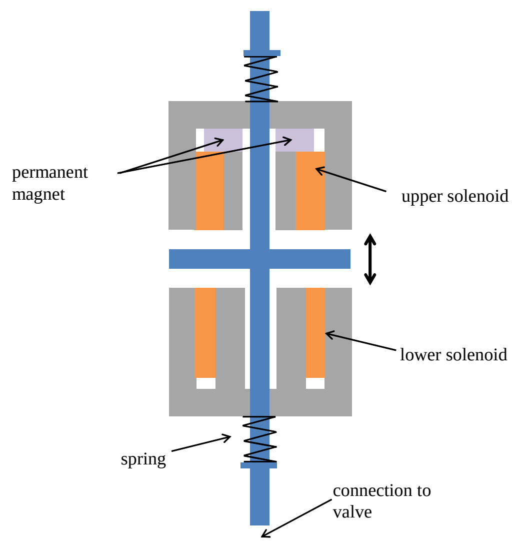

Figure 1. The EMVD based on two solenoids.

2. Modeling the EMVD in COMSOL Multiphysics

The modeling process in COMSOL Multiphysics starts with the combination of three physics interfaces. The Magnetic Fields (mf) interface of the AC/DC-Toolbox is used to solve Maxwell's Equations which describe the magnetic field. The Moving Mesh interface is used to make the mesh deformable. Finally the Global ODEs and DAEs (ge) interface is used to define the deformation inside the Moving Mesh interface by defining an equation for the acceleration of the valve plate.

The geometry is directly drawn in COMSOL Multiphysics as parametric definitions are supported. The geometry of the actuator is augmented by additional rectangles which improve the simulation results. This is explained in the subsection 2.2.

2.1 The Magnetic Fields interface

The Magnetic Fields interface is used to solve the Maxwell Equations which in this transient magnetic 2D analysis are:

$$\nabla \times H = j \qquad \text{Eq. 1}$$

$$\nabla \times E + \frac{\partial B}{dt} = 0 \qquad \text{Eq. 2}$$

$$\nabla \cdot B = 0 \qquad \text{Eq. 3}$$

$$\nabla \cdot D = \rho \qquad \text{Eq. 4}$$

Figure 2 marks the defined boundary conditions. The first two boundary conditions are set automatically by COMSOL because of the predefined 2D axisymmetric space dimension. The magnetic isolation feature avoids the penetration of the magnetic field at the borders. The symmetry condition reduces the model from 3D to 2D. Therefore the calculation period is reduced drastically.

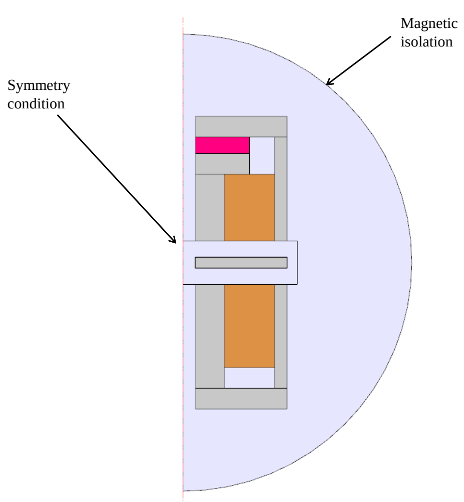

Figure 2. Boundary conditions of the Magnetic Field interface

Beside the boundary conditions there are those conditions which apply for domains. Ampère’s Law is used to implement the material data and describe the magnetic behavior of the domains.

The relation between B- and H-Field inside a material is not always constant or linear. In this case the magnetic circle has steel inside which result in a strong nonlinearity. This is shown in Fig. 3.

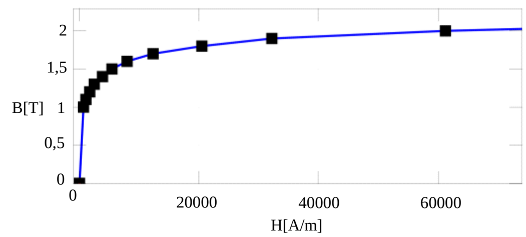

Figure 3. Nonlinear BH Curve

Material properties are separately defined outside the Magnetic Field interface. The magnetization curve can be implemented as a table or as a function.

By choosing HB curve for the constitutive relation inside Ampère’s Law Domain the deposited material data is used. This is applied to all steel domains. The remaining domains are adjusted to constant relative permeabilities. The valve plate is the only domain with nonzero conductivity. This allows eddy currents inside the plate.

The added permanent magnet is defined by choosing the option remanent flux density inside the Ampère’s Law feature. The remanent flux density is defined in z-direction.

Additionally the solenoid domains are defined by using the multi-turn Solenoid Domain and applying a current excitation.

Finally the valve plate is marked as a force calculation domain to apply the Maxwell Stress tensor. The tensor is used to calculate the magnetic force acting on the plate. This force is stored inside a variable which is used bye the Global ODEs and DAEs (ge) interface.

2.2 The Moving Mesh interface

The Moving Mesh interface allows the deformation of the mesh by user defined functions.

Figure 4 marks the defined boundary conditions for the Moving Mesh interface. As mentioned this boundaries are not part of the actuator. The exterior boundaries limit the deformation of the mesh. This is done by setting the motion to zero in the prescribed mesh displacement feature.

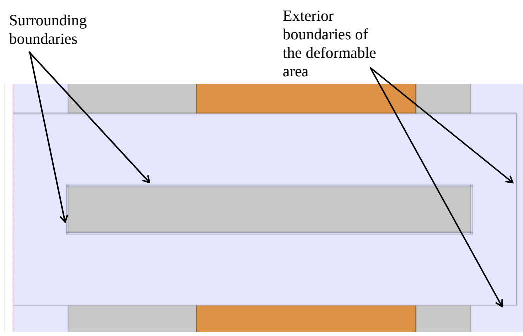

Figure 4. Boundary conditions of the Moving Mesh interface.

The interior boundaries are placed equidistant around the valve plate. By surrounding the plate with one layer of rectangular mesh elements the force calculation is improved very effectively. The force calculation using the Maxwell Stress Tensor is very sensible against irregular and asymmetric mesh distributions [3]. Therefore the boundaries of the valve plate and the additionally placed boundaries move together using the prescribed mesh displacement feature.

The motion is defined by another interface which is described next. The only domain condition is the free deformation feature for the area enclosed by the exterior boundaries in Fig. 4.

2.3 The Global ODEs and DAEs (ge) interface

The Global ODEs and DAEs (ge) interface is used to implement an ordinary differential equation (ODE) which uses Newton's Law to describe the acceleration of the valve plate. Therefore the Eq. 5 is used.

$$\ddot{x} = \frac{1}{m}(F_A - c \cdot x - d \cdot \dot{x}) \qquad \text{Eq. 5}$$

It depends on the force F_A resulting from the magnetic circuit which is calculated using the Maxwell Stress Tensor (Subsection 2.1). Additionally springs (parameter c) and viscous friction (parameter d) act on the valve plate (Fig. 5).

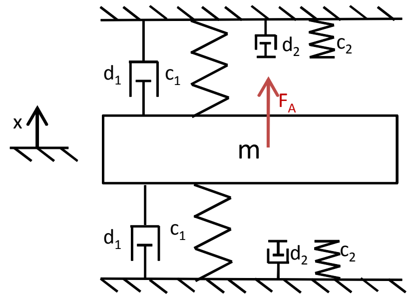

Figure 5. Mechanical model of the EMVD

To avoid that the valve plate domain penetrates the upper and lower solenoid and to simulate the elastic collision, additional elements are necessary (c_2 and d_2 in Fig. 5). Therefore the spring and damper characteristics are nonlinear and rise when the valve plate is getting closer to the upper or lower limit. This is done when the distance between the valve plate and solenoid is less than two times the distance between the valve plate and the surrounding boundaries (see Section 2.2). In this case at 0.2 mm.

2.4 Meshing the geometry

As already mentioned the calculation of forces is sensible against irregular meshes. Additionally this effect is amplified by the Moving Mesh which leads to deformed mesh elements of poor quality. Therefore the valve plate is surrounded by boundaries which make the meshing process very easy. The mesh size is forced to be equal to the distance between the boundaries using the same size for the minimum and maximum element size. This leads to a perfectly distributed mesh. The rest of the mesh is created by triangular elements (Fig. 6).

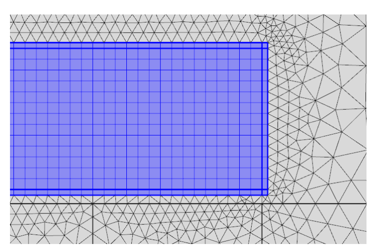

Figure 6. Right side of the valve plate with mapped mesh

2.5 The solver configuration

The study consists of two solvers. First of all the magnetic field is calculated without being influenced by the other interfaces. This is done using a Stationary Analysis feature. The result of this analysis is taken as initial result for the transient analysis.

A conservative configuration of the transient solver is important when dealing with moving meshes. That means that a very small and fixed step size should be chosen as the mesh quality is controlled every time step. When the mesh quality drops below a defined value the geometry is remeshed. This is done by the Adaptive Remeshing feature.

When the valve plate is approaching the upper or lower limit the velocity rises very fast due to the nonlinearity of the magnetic circle. This is expressed by the Eq. 6, which can be used to estimate the force acting on the valve plate. It shows the quadratic influence of the flux density.

$$F_A \approx -\frac{B^2}{2\mu_0} \cdot A \qquad \text{Eq. 6}$$

This causes the mesh to deform fast while the magnetic flux gets even stronger. The interaction of those effects is difficult to handle for the transient solver which often leads to aborted simulations.

Hence the maximum step size should be reduced until the simulation is passed with constant step size. This improves greatly the force calculation at the upper and lower limit.

Additionally the simulation has to be stopped before the valve plate and the surrounding boundaries reach the upper or lower limit. That is why the distance between valve plate and boundary should be chosen with care. A to small gap leads to very high number of elements and large calculation periods. However a too large gap distorts the static actuator force when reaching the upper or lower limit.

3. Simulation results

Different design studies were done including the variation of the geometrical and material properties. Two sequences were simulated which are presented by the Figures 7-9.

The first sequence starts at the lower position with the no solenoid being activated. At the time when the valve plate passes the point of equilibrium it should be attracted by the permanent magnet without the use of the upper solenoid.

Figure 7 shows an overshoot of the valve plate into the additional spring and damper elements. This is not obviously when looking at the plate position because of the small amplitude, but the amplification of the electromagnetic force near 0.003s is clearly notable. The force reaches 345N and returns to 315N. This is not the typical behavior regarding the Eq. 6.

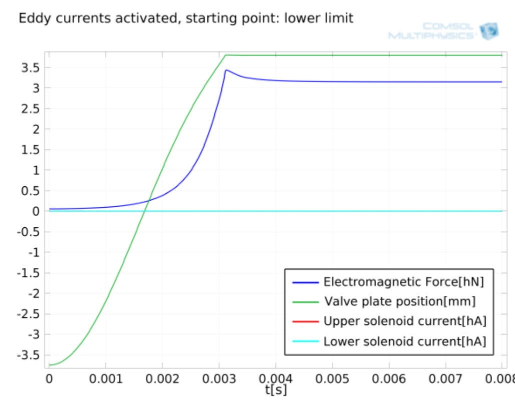

Figure 7. Testing the failsafe function with eddy currents

Figure 8 shows the same situation. This time the plot of the electromagnetic force has the typical parabolic characteristic. The different behavior in both plots is caused by eddy currents.

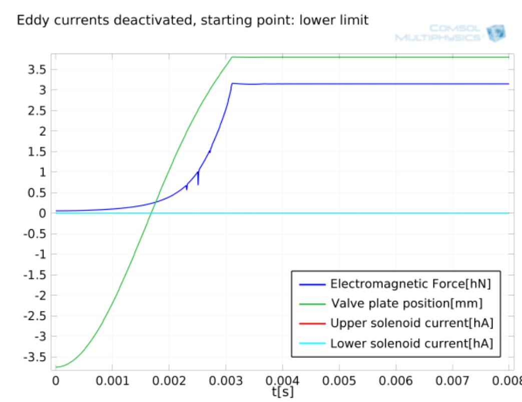

Figure 8. Testing the failsafe function without eddy currents

Both times the actuator compresses the spring element. When the velocity of the valve plate is returned due to the elastic collision, the eddy currents support the permanent magnet. As described by Lenz's law the eddy currents work against their cause which is the motion of the plate. Therefore the valve plate is attracted to the upper solenoid and stops to oscillate. Without eddy currents the valve plate hits various times the upper limit.

The effect of the eddy currents is not clearly noticeable before the valve plate reaches the upper limit (0 – 0.003s). That is because of the small flux density inside the magnetic circle. However the valve plate is faster without eddy currents. This can be noticed when looking at the spikes in Fig. 8 at 0.002s. Those result from a to large step size relating to the higher velocity (see section 2.5).

Despite of the eddy currents the same static force and the same static positions are reached. The permanent magnet is able to attract the valve plate with a remanent flux density of 1.3[T].

The second sequence begins with the valve plate being hold by the permanent magnet in the upper position. The upper solenoid is then activated. The generated magnetic field weakens the field of the permanent magnet and the valve plate starts to move. The springs push the valve plate over the point of equilibrium. Then the plate is cached by the lower solenoid (Fig. 9).

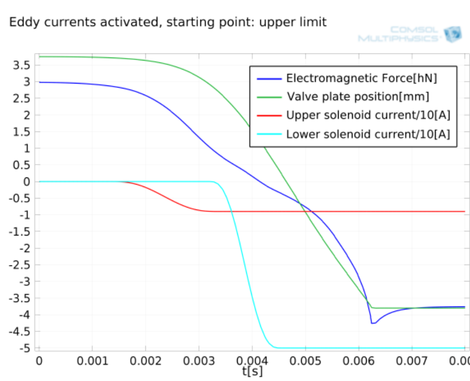

Figure 9. Testing the normal transition mode with eddy currents

Again the eddy currents prevent the plate from bouncing against the lower limit and let the magnetic force overshot at 0.006s. This effect does not exist, when eddy currents are deactivated (Fig. 10). Similar to the first analysis the step size should be reduced because of the faster valve plate.

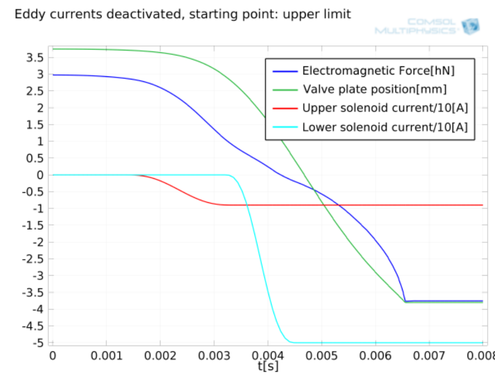

Figure 10. Testing the normal transition mode without eddy currents

4. Conclusion

It was shown that the permanent magnet is able to catch the valve plate. It was also shown that COMSOL Multiphysics is able to combine the calculations of the magnetic field, the deformation of the mesh and the ODE when the step size is tuned manually. Also the calculation of eddy currents leads to reasonable result. This model is now used to run several design studies, which will help to build first prototypes. Then the simulation results will be compared to test readings.

8. References

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