Simulation of mechanical relays under coupled electromagnetic physics and structural dynamics

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ABSTRACT
The function of mechanical relays depends largely on the mechanics and electromagnetics. Both can be calculated separately using finite element analysis (FEA). In this specific application, the electromagnetic field, which is induced by a coil in the relay, generates forces in the component that lead to deformations in the geometry, which, in turn, influences the electromagnetic forces in the relay. The aim of this simulation is to couple both physics so that the mechanics and electromagnetics can be calculated in a combined model. For this purpose, the properties for mechanical deformations and magnetic fields are simulated with the software Comsol Multiphysics. The electromagnetic forces are calculated in the electromagnetic model and coupled into the structure in the mechanical model using Maxwell's surface tension tensor. The relay is operated by a voltage fed into the coil and is reset via a spring at the upper end of the relay. In this way, a work cycle of the relay can be simulated. The calculation can be used to determine the electromagnetic forces necessary to trigger the relay. Structural dynamic calculations in the electromagnetic field are possible, and the magnetic flux density in the corresponding areas can be optimised. Furthermore, interfering stray fields in the course of deformation can be determined, and the properties of the coil and the iron core can be optimised. This way, the function of a mechanical relay can be significantly improved.

1. INTRODUCTION

In the last few years, a number of different approaches have been published to simulate electromechanical relays. In a relay, many different effects of mechanics and electromagnetics appear together and interact. The goal is to combine the relevant physical effects in a fully coupled model. A well-known phenomenon of a relay is contact bouncing, which has already been the subject of various theoretical studies [1] [2]. Other approaches on the motion and electromagnetics of a relay are based on magnetic equivalent circuits (MECs) [3] [4], which show good results and display good performance in terms of computational time. Also, some FEA-based approaches [5] [6] [7] are well suited to simulate mechanical and electromagnetic effects in a relay but often are relatively time-consuming to solve. Moreover, many publications are limited to one or more effects within a relay to be investigated. In this publication, a comprehensive nonlinear model that can easily be extended is presented. This relates to the mechanical dynamics, including contact bouncing, and the electromagnetic dynamics as well as the shape of the air gap.

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2. COUPLED MODELLING

The commercial FEA software code Comsol Multiphysics has been applied for this study. The analysed geometry of the relay is shown in Figure 1.

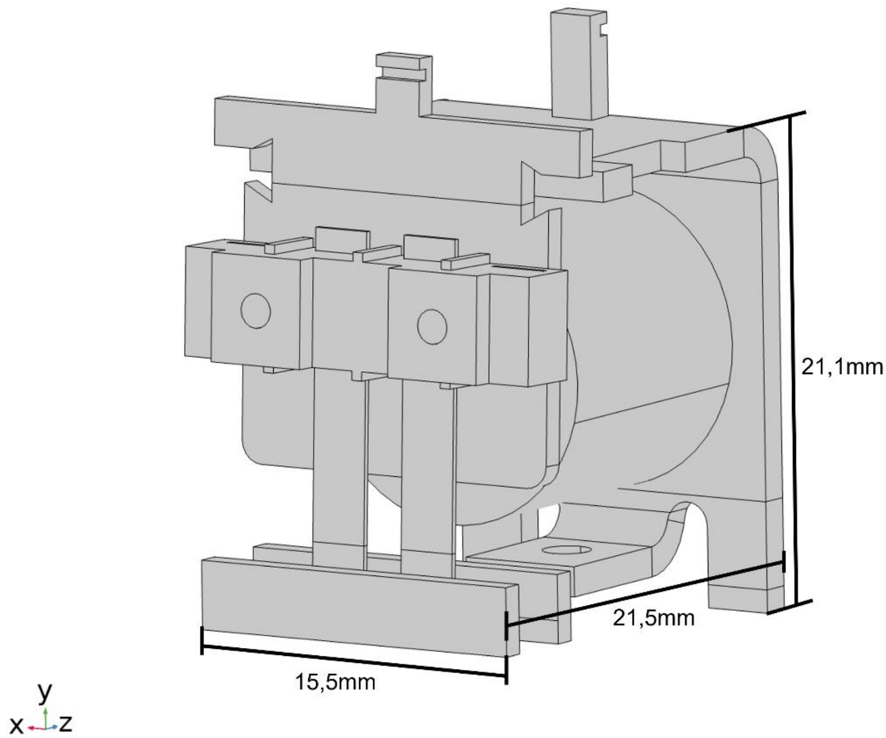


Figure 1: CAD model of the relay.

It consists of a coil inside the relay which excites an iron core and creates a magnetic circuit with the pole plate and the anchor plate. The anchor plate is rotatably mounted so that when the coil is activated, the armature is magnetically pulled by the iron core. In the relay's unpowered state, an elastic spring moves to the anchor plate in one position defined by one relay contact. In its powered state, the contact lugs contact a second relay contact.

2.1. Mechanical model

To simulate the mechanical properties of the relay, the physics interface 'solid mechanics' is used in Comsol. Two types of mechanical areas are modelled, one rigid and the other deformable. The rigid bodies can only move relative to the spatial frame, while the deformable ones can also contain stresses and linear elastic displacements within the component. Figure 2 shows the main components of the relay.

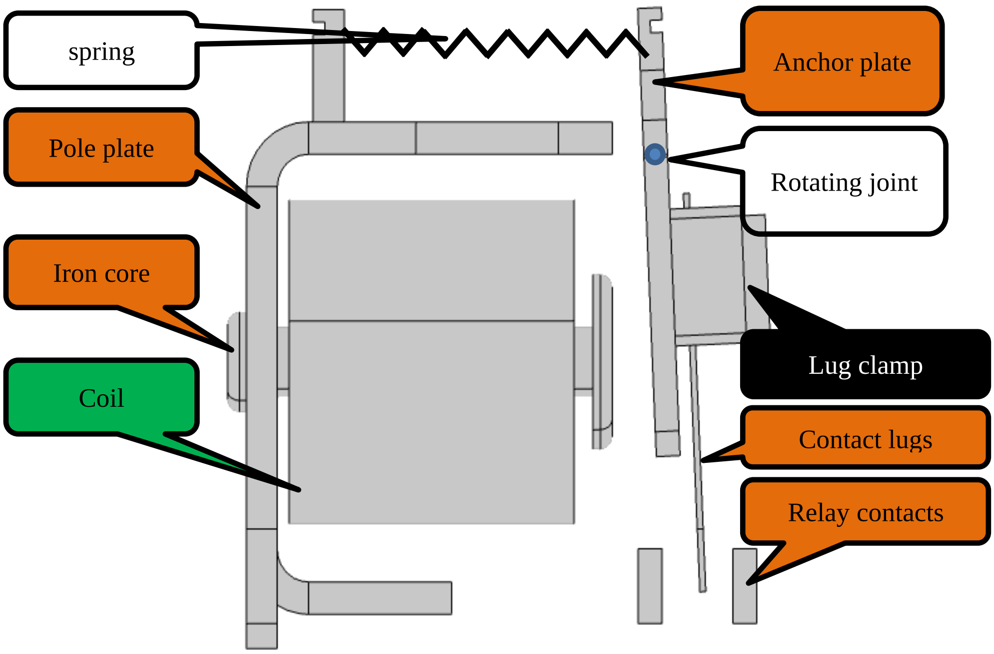


Figure 2: Mechanical components of the relay (black: polyethylene; orange: iron; green: copper).

The coil with its iron core is attached to the pole plate, which is connected to the ground. These areas and the relay contacts are assumed to be rigid. The deformable regions are the anchor plate, the lug clamp, and two contact lugs. The anchor plate is provided with a hinge joint near the pole plate to allow rotation. The lug clamp connects the contact lugs with the anchor plate. All the other electrical components of the relay are not considered in this model. In this model, two switching positions are discussed. Figure 3 shows the positions (state 0 and state 1) and the point where the velocity of the anchor plate is measured. Furthermore, the applied coordinate system is introduced.

From this view, the x-direction points outward from the plane. In state 0, the anchor plate is held in position by a spring with a stiffness of $c = 50\frac{N}{m}$. The spring has no pre-tension and is only tensioned by the movement in state 1. Because of computational costs, the spring attached to the top of the anchor plate is defined as a boundary condition. To simulate damping, the spring is modelled with a loss factor of $\eta_s = 0.3$. With that, the moving anchor plate can dissipate some energy, and the dynamics are stabilised and generate realistic movement. These measures help to make the model more realistic.

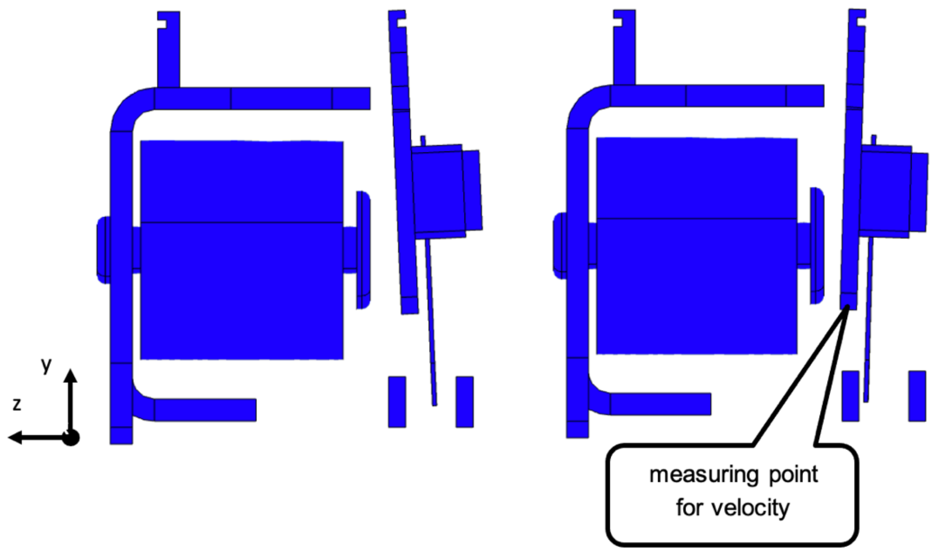


Figure 3: Mechanical displacement (left: state 0; right: state 1).

2.2. Electromagnetic model

To calculate the electromagnetic dynamics, the ‘magnetic fields’ interface of Comsol is used. In this interface, the areas that become relevant for electromagnetics are defined. These include the coil, the iron core, the pole plate, the contact lugs, and the anchor plate.

Once an electromagnetic field is calculated, the individual components must be surrounded by a medium. In this case, the medium is air and is simulated by a large cuboid in which the model of the relay is placed. In this paper, the air around the relay is called the domain. For visibility reasons, the air domain has been made transparent for the figures in this paper. Since the domain has no impact on the mechanical behaviour, it is not considered in the mechanical model. Fluid dynamics that could occur because of the displacement of the anchor plate are not considered in this model. The windings of the coil are simulated in the model as homogenised multiple windings as this means significantly lower computational costs. The number of windings and the wire diameter must be specified as parameters. The relay is designed to create a magnetic circuit that should lead to magnetic attraction forces in the anchor plate. Figure 4 shows the aimed magnetic circuit in the model.

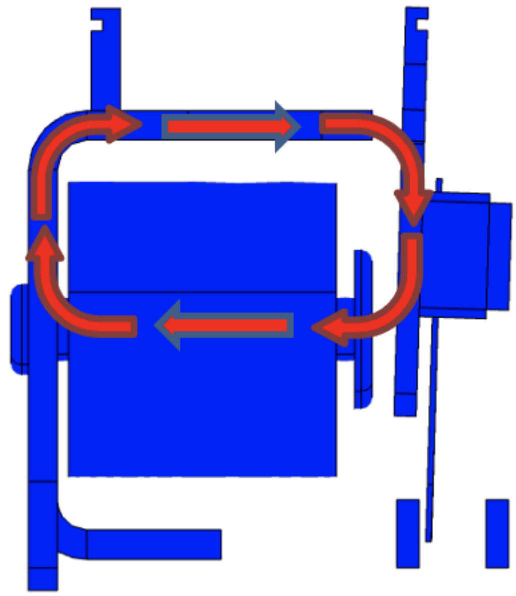


Figure 4: Dominating magnetic circuit.

The electromagnetic interface calculates a magnetic vector potential by means of the relative permeability of the different materials. The relative permeability feature leads to a linear B-H-curve of the materials. Any nonlinear effects of magnetic materials (e.g., soft magnetic behaviour of the iron) are not part of the simulation. The 'force calculation' feature can be used to calculate the electromagnetic forces in the corresponding area using the magnetic vector potential.

There is a small cylindrical gap of 0.1 mm radius difference between the iron core and the coil. This has a strong influence on the electromagnetic behaviour of the entire system and must therefore be simulated. Therefore, the boundary condition 'thin low permeability gap' was used to avoid extremely small finite elements. The coil has the parameters shown in Table 1.

Table 1: Coil parameters

Voltage [V], DC	**Windings [−]**	**Wire diameter [mm]**	**Resistance (DC) [Ω]**
12	700	0.2	9.1

2.3. Coupling of the mechanics and the magnetic model

To calculate the mechanics and electromagnetics in a model, the electromagnetic forces that occur must be transferred to the mechanics module. In addition, the mechanical deformations affecting the magnetic flux density must be transferred to the electromagnetics. If both are included together with the spatial frame, the fully coupled approach is fulfilled. Figure 5 shows the modelling scheme.

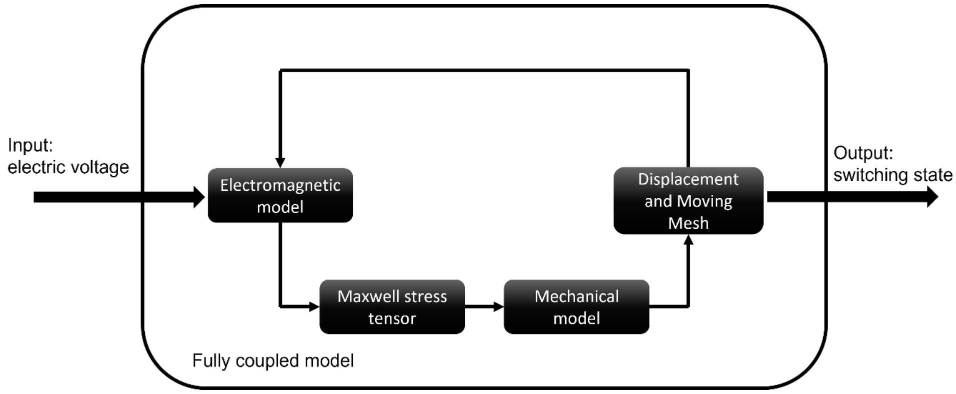


Figure 5: Modelling scheme.

As described in Section 2.2, the electromagnetic forces are calculated by the force calculation feature of Comsol. The Maxwell surface tension tensor makes it possible to generate mechanical stresses from these electromagnetic forces. In the mechanical model, this tensor is used in the respective area to generate the mechanical surface stresses

$$\sigma_{ij} = \epsilon_0 E_i E_j + \frac{1}{\mu_0} B_i B_j - \frac{1}{2}\left(\epsilon_0 E^2 + \frac{1}{\mu_0} B^2\right) \delta_{ij} \tag{1}$$

where ϵ_0 is the electric constant, μ_0 the vacuum permeability, E the electric field, B the magnetic field, and δ Kronecker's delta. The area in which the tensor acts must be identical to the area in which the force calculation feature calculates the force.

The deformations, which are calculated by the mechanics module, lead to a strong distortion of the mesh. Especially in the angular air gap, large deformations occur in the mesh, which mostly leads to a non-converging solution. Since the mesh in the air gap does not belong to solid mechanics and therefore no displacement variables are calculated, a moving mesh feature must be implemented. This ensures that the magnetic field variables are updated, and the mesh can be deformed in the areas where the relay instances move during the simulation. To do so, a prescribed displacement of the mesh is formulated. When the anchor plate, lug clamp, and contact lugs move in the simulation model, the displacement variables are transferred to the connected areas of the air domain mesh. Thus, the mesh moves with the moving instances of the relay. Without this formulation, smaller displacements can be calculated since the mesh is not strongly deformed, but larger deformations for switching from state 0 to state 1 do not converge.

2.4. Mesh

The mesh used is shown in Figure 6.

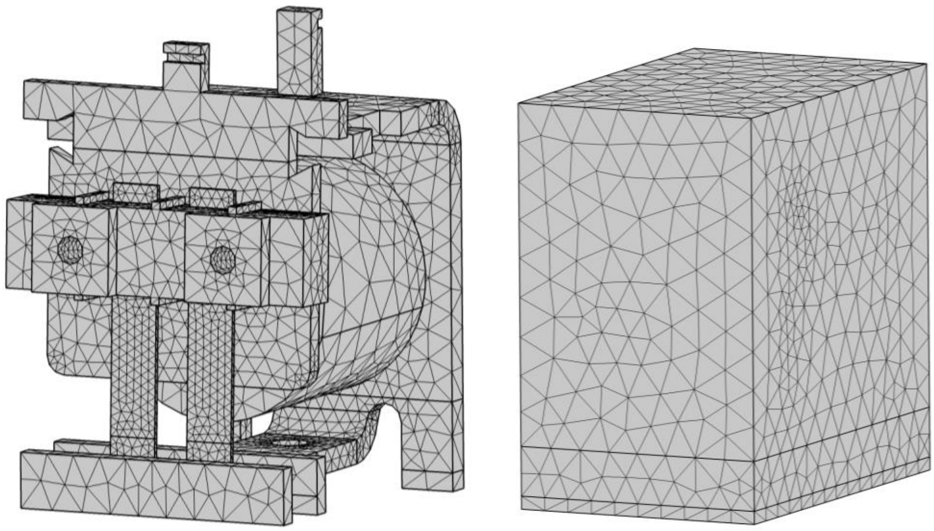


Figure 6: Mesh [left: relay (air domain invisible); right: air domain].

It contains 70,530 tetrahedral, linear elements. The element length lies between $l_e = 0{,}6mm$ and $l_e = 3{,}1mm$.

2.5. Materials

The materials used in the simulation are shown in Table 2.

Table 2: Materials

Material	**Young's modulus [MPa]**	**Poisson's ratio [−]**	**Density [kg/m³]**	**Rel. permeability [−]**
Polyethylene	1000	0.47	930	1
Iron	210,000	0.29	7,870	4,000
Copper	110,000	0.35	8,960	1
Air	-	-	1.2041	1

3. SIMULATION AND RESULTS

3.1. Transient solution of the model

The solution of the model is a fully coupled simulation where the solver used is the PARDISO solver from Comsol, a direct, implicit solver. For nonlinear equations, the Newton method is used. The system is simulated for a period of 0.08 s, which is sufficient to describe switching from state 0 to state 1. In the time between t = 0.002 s and t = 0.02 s, a direct voltage of 12V is applied to the coil. The voltage supply is not applied abruptly but with a ramp. Figure 7 shows the curve of voltage and the resulting current of the coil.

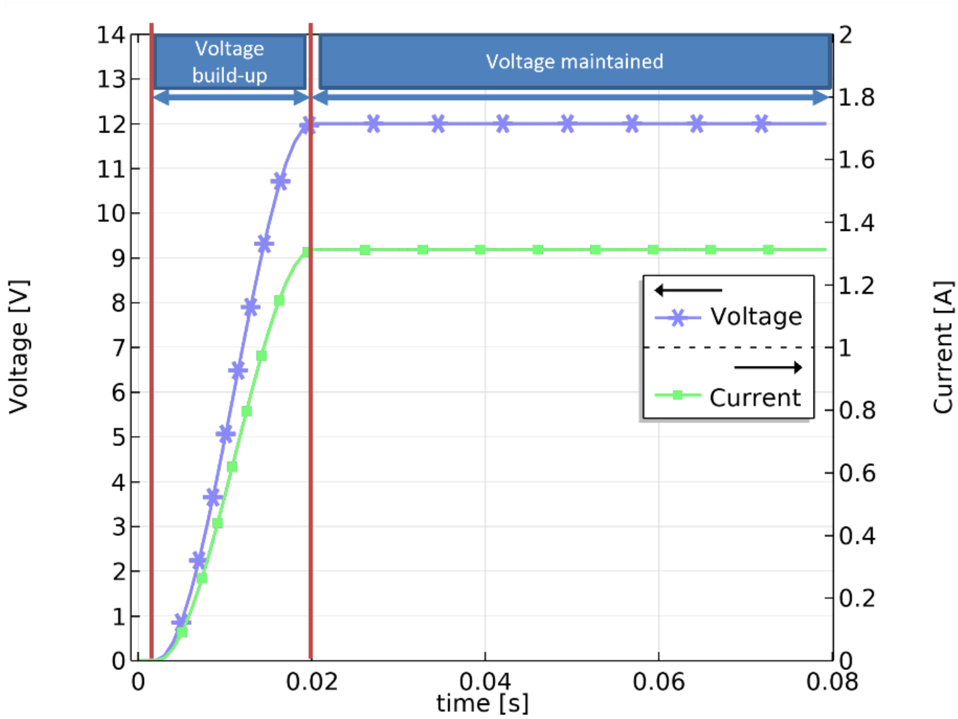
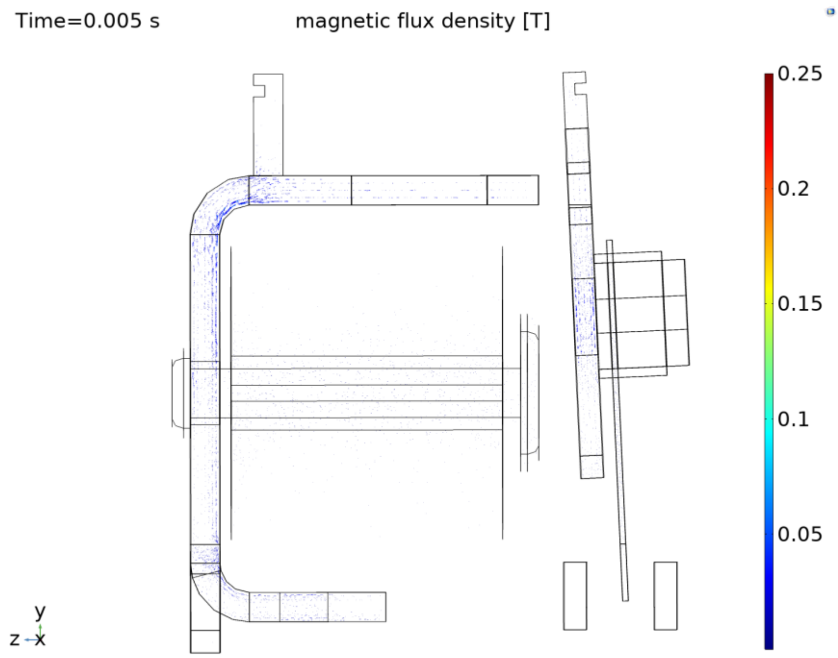


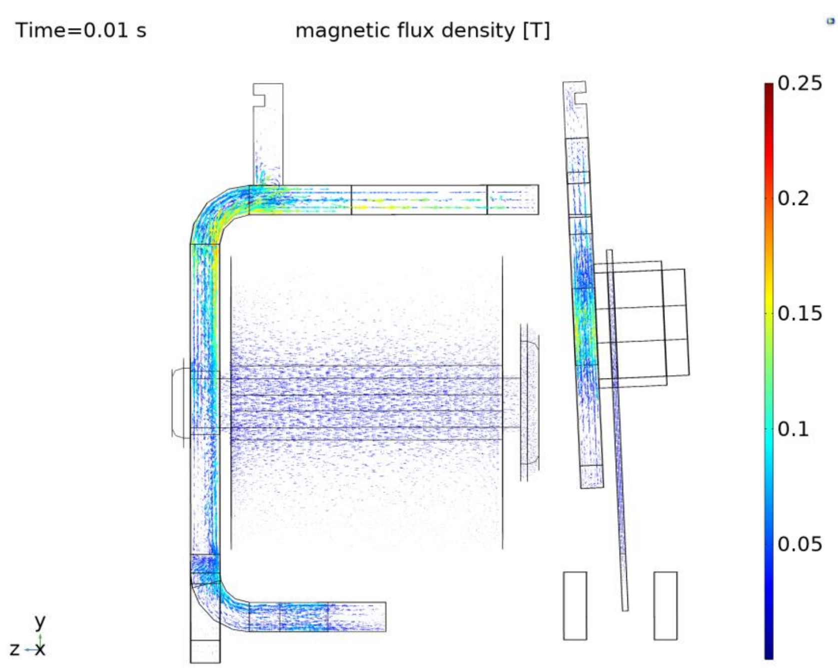
Figure 7: Voltage and current of the coil.

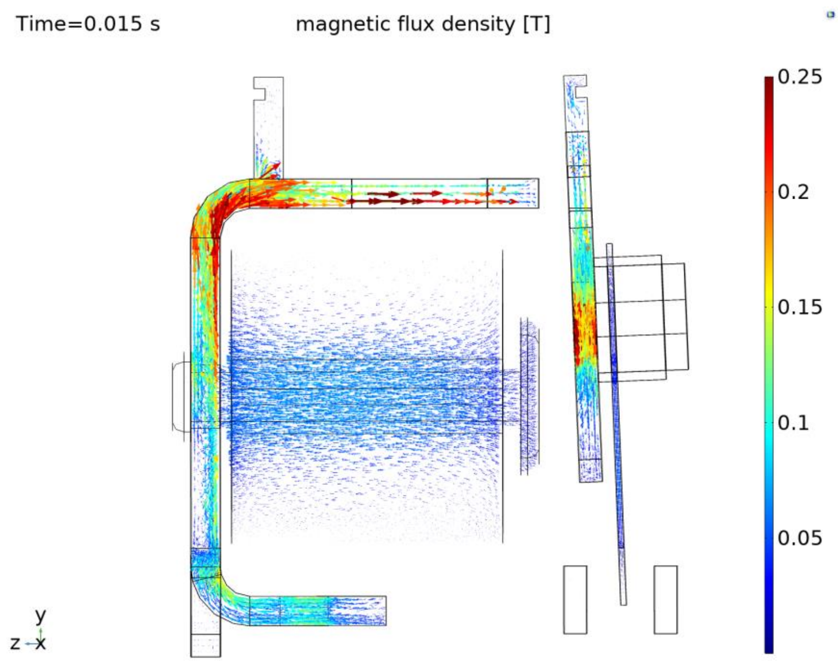
After the voltage has reached 12V at t = 0.02 s, the voltage is held constant till the end of the simulation. For this to occur, the current increases to a maximum of I = 1.32A. While the coil is being energised, a magnetic flux density occurs in the model. Figure 8 shows the distribution of the magnetic flux density at t = 0.005/0.01/0.015/0.02/0.025/0.027 seconds.

The anchor plate switches to state 1 as a result of the occurring forces. In some areas such as the coil or the iron core, the magnetic flux density is relatively low. Thinner areas inside the magnetic circuit such as the pole plate or the anchor plate lead to a significantly higher flux density, whereas the thinner areas outside the magnetic circuit show a low magnetic flux density. Figure 9 shows the magnitude of the magnetic flux density during the simulation for different nodes in the model.

It is shown that the magnetic flux density increases while the coil is fed with the voltage for all the areas. At t = 0.02 s, the voltage reaches 12V, and the magnetic flux density behaves differently for different areas. The magnetic flux density at points 52, 91, and 110 reach their peak before the coil is fully fed at t = 0.02 s. This can be explained by the inertia of the anchor plate so that the curves of voltage and velocity of the plate are shifted against each other. At point 52, the magnetic flux density has an overshoot just before t = 0.02 s and then decreases to 0.03 s to the level of the magnetic flux density of point 133, the iron core. The flux density of the iron core follows the profile of the voltage in the coil. The magnetic flux density of the contact lugs reaches the maximum just before the coil is fed with 12VD and then drops again close to zero. After the switch, the magnetic flux density is not constant but varies a little. This is because the mechanical system is not yet fully at rest.


Time=0.005 s
magnetic flux density [T]
0.25
0.2
0.15
0.1
0.05
y
z
x


Time=0.01 s
magnetic flux density [T]
0.25
0.2
0.15
0.1
0.05
y
z
x


Time=0.015 s
magnetic flux density [T]
0.25
0.2
0.15
0.1
0.05
y
z
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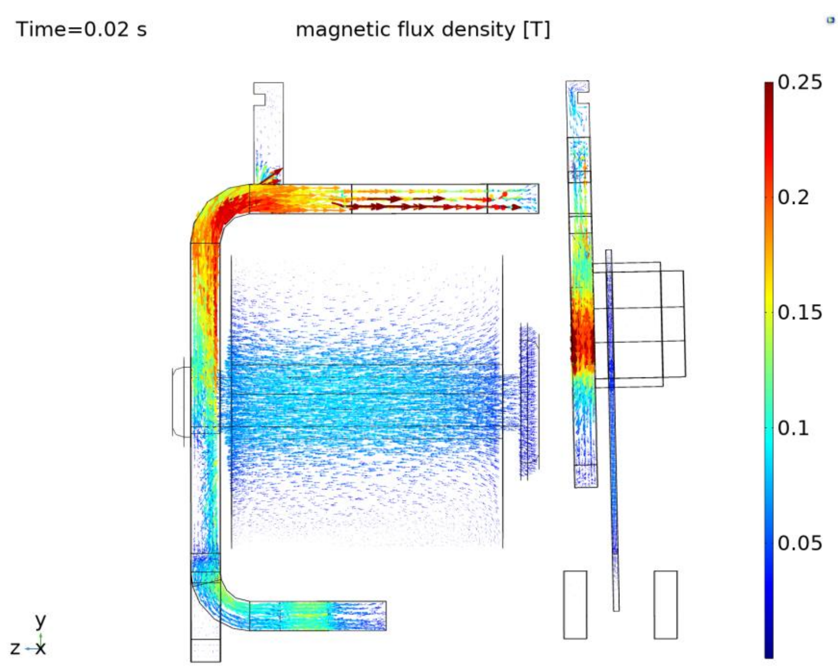

Time=0.02 s
magnetic flux density [T]
0.25
0.2
0.15
0.1
0.05
y
z
x

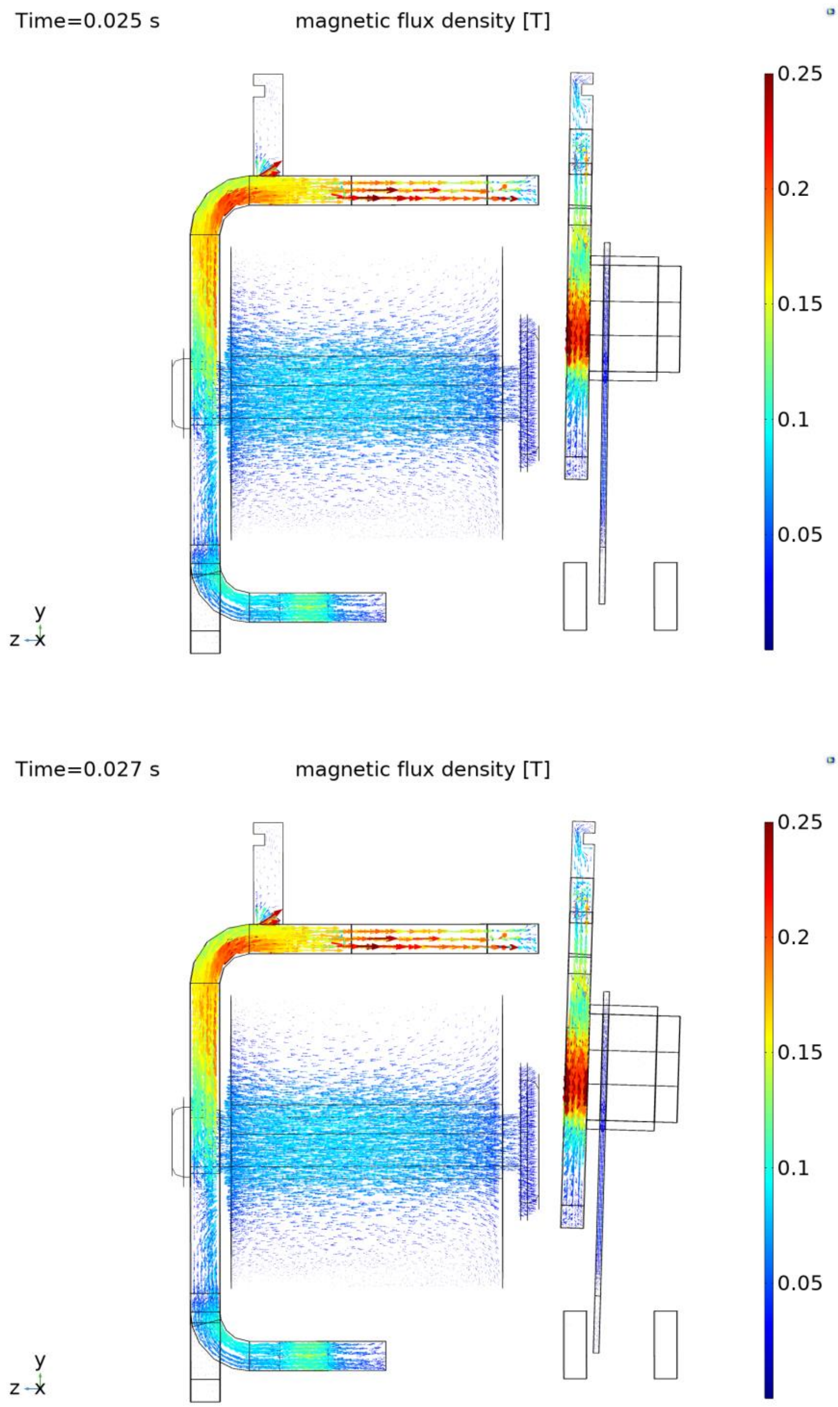
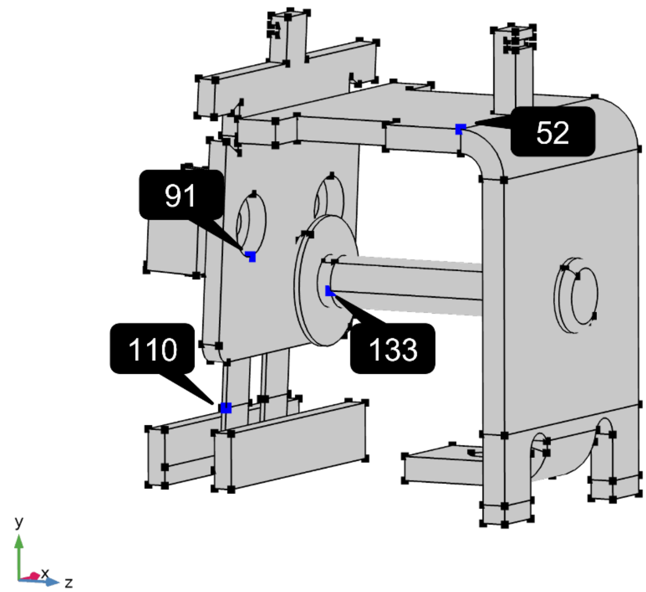


Figure 8: Magnetic flux density in the model



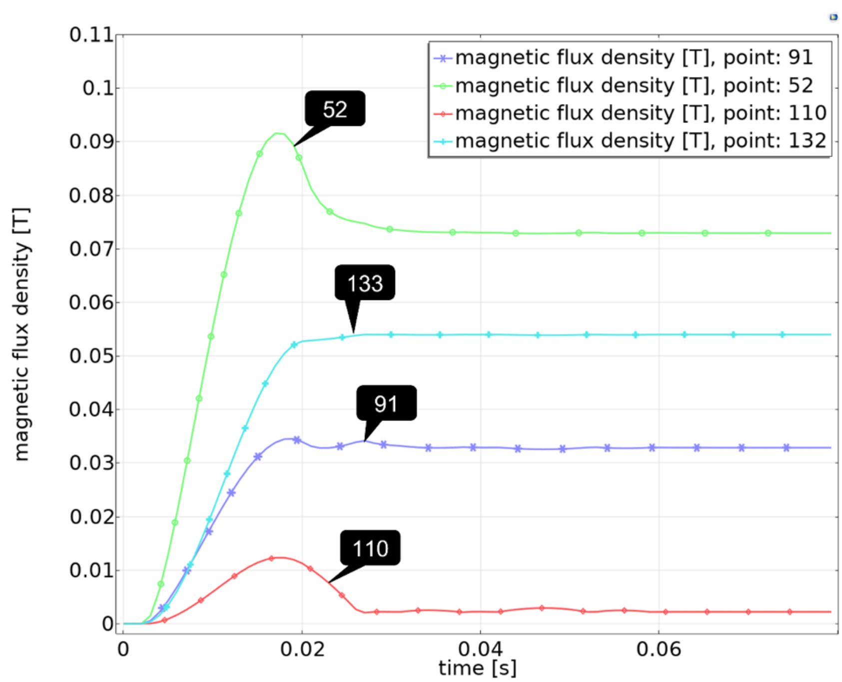


Figure 9: Magnetic flux density vs. time and absolute value.

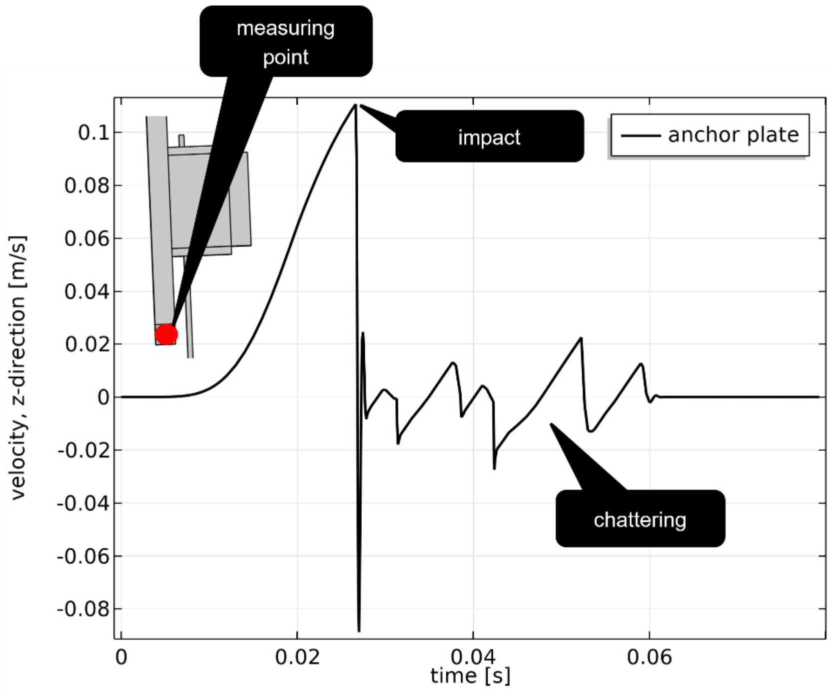


Figure 10: Velocity vs. time.

The magnetic field causes the anchor plate to move towards the coil. Figure 10 shows the velocity curve of the anchor plate over time. The curve is measured at the bottom of the anchor plate shown in Figure 3.

It is shown that the velocity of the anchor plate increases before it impacts the relay contact for the first time. The movement of the anchor plate is delayed regarding the magnetic flux density because the anchor is subjected to inertial forces. After the first impact, the plate bounces back but is pulled back towards the coil. This happens a few times until the anchor plate no longer shows movement. These bounces occur because there is only a little damping in the model and the pulse of the impact goes straight back into the contact lugs.

4. CONCLUSION AND OUTLOOK

In this paper, the mechanical and electromagnetic models of a relay were modelled. Both models were coupled using Maxwell's stress tensor and Comsol's moving mesh feature. The biggest challenge was that the mesh deformed strongly when the relay was switched, which affected the numerical stability of the calculation. The large deformations in the angular air gap could be fixed with the help of the moving mesh and the prescribed mesh displacement features. The model shows a plausible electromagnetic and mechanical response to the energisation of the coil with the current.

At the time of the highest current in the coil, the magnetic flux density in some areas of the relay is not at its maximum. This can be explained by the fact that the anchor plate moves from position 0 to 1 in the progress of the simulation, so the peak of the magnetic flux density appears in some areas before the coil experiences the maximum current. With the help of the proposed model and a good visualisation of the magnetic flux density, stray fields can be made clearly visible.

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