Numerical Simulation of Magnetic Pulse Welding: Insights and Useful Simplifications

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Abstract

The increasing demand for the use of lightweight materials and part designs, especially in the automotive industry, is a driving factor for the development of new joining techniques. One of the main challenges is joining of dissimilar materials. Magnetic pulse welding (MPW), a high-velocity, cold forming technique is a possible solution, as it is known for its ability to join dissimilar metals. To determine the potential of this technology for a certain application, simulation techniques have become a major part of the research process.

This paper shows some ways how to use simulation tools effectively to analyse the coil and the field shaper-geometry as well as to study their effect on the workpiece. The predictability of current distributions, resulting magnetic pressures and general process efficiency are discussed. Furthermore it is described which simplifications may be applied in order to reduce the simulation time for transient calculations. Especially aspects of the transient force evolution during a pulse are discussed and comparisons to simplified time-harmonic results are given.

Keywords

Simulation, Modelling, Finite Element Method (FEM)

1 Introduction

Electromagnetic pulse forming is a high-velocity, cold-forming technique with great potential for joining dissimilar materials. The use of tailored materials, e.g. to save weight, optimize strength or increase conductivity, is an ongoing trend in the industry. E.g. in the automotive industry this technology becomes more and more important. To determine its potential for a certain application, simulation techniques have become a major part of the research process.

Since in most cases an accurate model produces high computational costs, both time and capacity, it is essential to optimize the simulation process. Usually the models are simplified to a 2D-description, calculated as time-harmonic processes or in case of a symmetric structure only a part of it is evaluated.

With advanced computer technology it is possible to simulate 3D-models with a high level of details to gain insights into the realistic behaviour of a system.

The aim of this work is to examine some aspects of transient and time-harmonic calculations for MPW in detail. This is expected to lead to a better understanding of the usually applied simplifications. Details of the effects on a workpiece such as current distributions and magnetic pressure evaluation are discussed as well as the influence of meshing.

2 Transient Evaluation Regarding the Magnetic Pressure

The applicable magnetic pressure is an important parameter of an MPW system and it depends on the current distribution of the system. Therefore a transient (time dependent) calculation was carried out to determine the current distribution in the forming coil as well as the magnetic pressure distribution on the workpiece. The finite element (FEM) simulation tool Comsol Multiphysics was used to obtain those results. Comsol Multiphysics is a powerful simulation tool for solving electromagnetic problems. It is useful to calculate electromagnetic (current distributions, impedance and admittance matrices, magnetic field etc.) as well as mechanical aspects (deformation, strain) with good accuracy in different ways [1].

2.1 The Model

The model consists of a forming coil, field shaper and workpiece (Figure 1) which is a common arrangement for magnetic pulse welding (MPW). Usually the coil consists of more than one turn but here a relatively simple geometry is chosen to reduce the simulation time. This simplification is valid since it only influences the absolute values.

The field shaper which is needed to concentrate the magnetic flux for maximum deformation of the workpiece features a simple symmetric geometry. The tubular workpiece is placed in the middle. Furthermore a cubic element with small conductivity is created around the configuration to set a finite volume for the calculation and to reach convergence in the equations.

In addition boundary conditions have to be set. The forming coil is driven by a capacitor bank, forming an oscillating circuit. The best way would be to use a coupled circuit-simulation plus FEM simulation as this would also model the feedback of the process into the generator correctly. According to IWS experience, such a complex simulation can be avoided for lower frequencies and simpler setups. Instead a time-varying potential is applied directly as an input to the coil and losses along the cables and in all parts of the system are taken into account. Therefore the maximum value of the potential and damping factors are adapted accordingly.

The frequency is chosen from a MPW suitable range, usually between 5 kHz and 25 kHz. The potential follows a cosine function to create the situation of a capacitor switched on at some point which will immediately lead to high voltage at the coil's port.

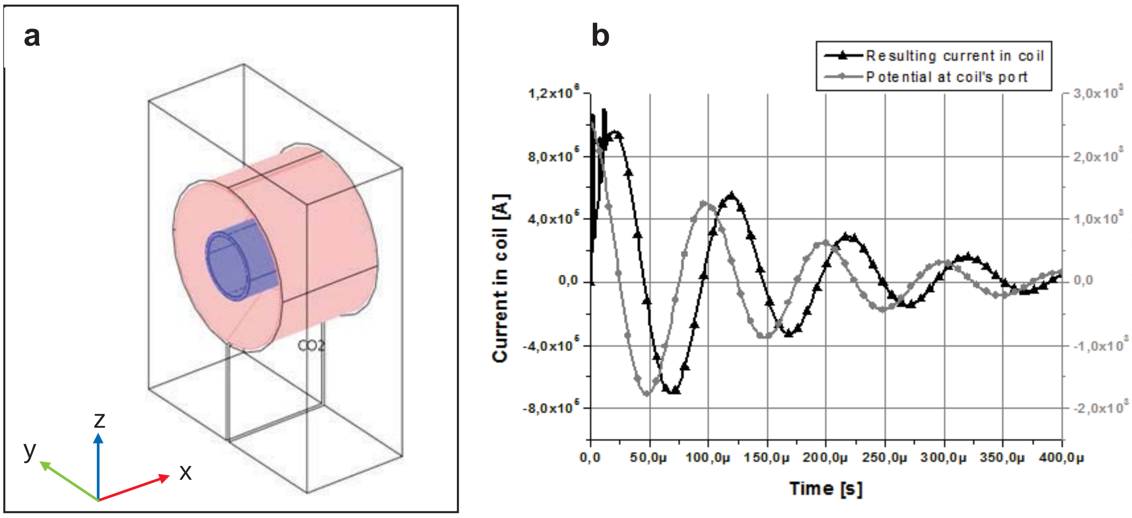

Figure 1: *Configuration for the simulation consisting of a forming coil, field shaper and workpiece (a). Resulting current and electric potential for the forming coil (b)*

2.2 The Result

A transient calculation should include the first one or two periods of the current distribution. It is generally agreed that the deformation of the workpiece occurs only within this time range. After one or two periods of the oscillation the energy in the system is decreased to a value where no deformation of the workpiece can be achieved.

The resulting current in the coil is a first quantity to determine if the simulation is correct, as the current can be relatively easily measured in reality, e.g. with Rogowski coils. Due to magnetic features, a phase shift of roughly 90 degrees between applied voltage and current should be visible. Furthermore the current is decreased not only by the inherent damping because of the voltage function but also because of eddy currents that occur in all parts of the model. Figure 1b shows the resulting current in the coil and the applied voltage.

In addition the current distribution is inhomogeneous over the coil's cross section as the skin effect leads to a current displacement inside the coil and therefore the current is almost completely flowing on the surface.

Forces on the workpiece can be calculated using two ways: applying the volumetric Lorentz force or calculating the magnetic pressure p_{mag}. Note that it is not sufficient to take only the pressure on the coil-side (outside) of the workpiece into account. Due to the field propagation, a pressure on the inside is possible as well. Therefore the magnetic pressure on both sides is discussed here. It can be derived directly from the magnetic flux density as shown in equation (1). For further information regarding the original derivation from Maxwell's equations see e.g. the work by Lee et al. [2].

$$p_{mag} = \frac{1}{2 \cdot \mu_0} \cdot (B(t))^2 \qquad (1)$$

Since the magnetic flux density is squared in equation (1) the frequency of the magnetic pressure is twice the frequency of the flux density and the current. The quantity which deforms the workpiece is not the magnetic pressure itself, but its difference inside and outside of the workpiece. Depending on the material of the tube and the wall thickness this difference can vary heavily in the amplitude evolution over time. Figure 2 shows the magnetic pressure on the inside and the outside of a steel workpiece separately and the resulting pressure.

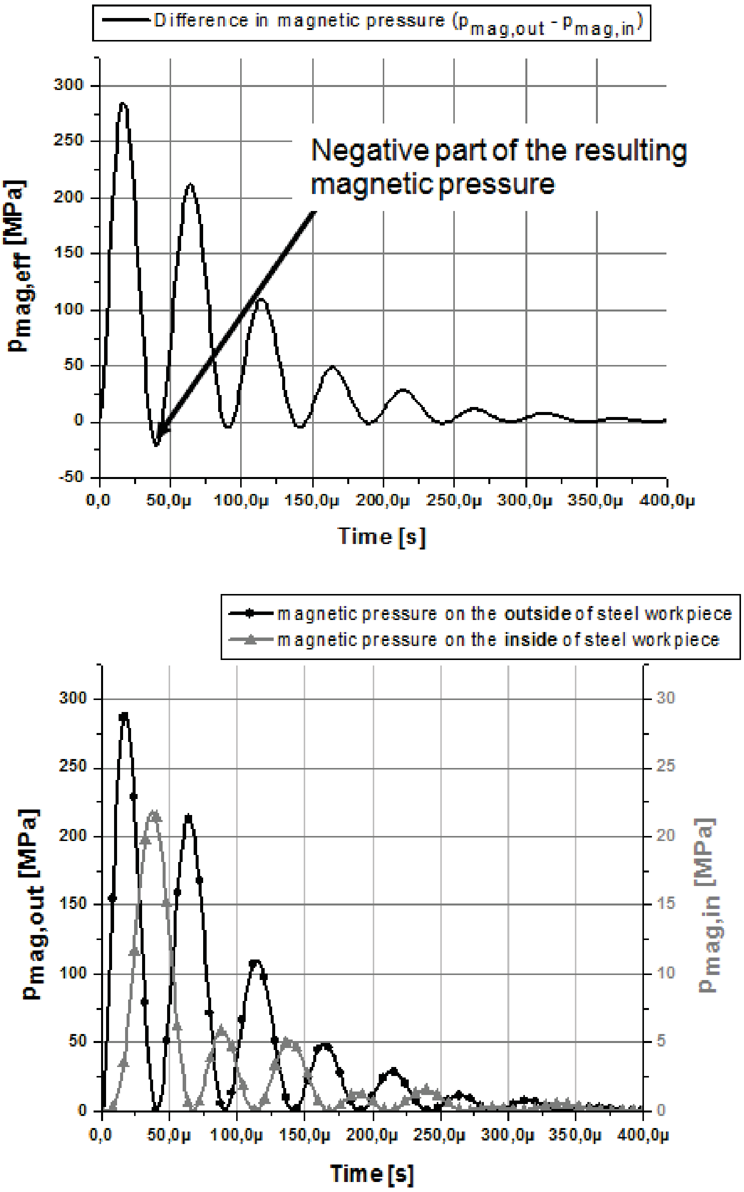

Figure 2: Magnetic pressure evaluation for the workpiece (simulated)Top: Resulting magnetic pressure as difference between inside and outside. Bottom: Magnetic pressure inside and outside of a steel workpiece.

Although the magnetic pressure is always positive (see equation (1)) the resulting pressure can be negative as shown in Figure 3. Its magnitude depends on the material and is a consequence of the phase shift between pressure evolutions on outside and inside respectively. This leads to a repelling force which is normally undesired in electromagnetic pulse forming. In a correct setup it does not influence the workpiece as it is much smaller than the yield strength. However, in some cases, e.g. with critical material properties and low frequencies, its influence can be significant.

The dependence of the absolute maximum value of the negative magnetic pressure on the wall thickness of the workpiece is shown in Figure 4. Note that the scale for the magnetic pressure is interrupted for clarity. It can be found that the maximum negative pressure decreases almost linear with the wall thickness of the workpiece. Thus, if the workpiece is thin-walled and has not been fully compressed onto the counterpart during the first pulse, its collapsing movement would be hindered by the repelling force. An expansion is unlikely but nevertheless possible for low strength materials.

Efforts to minimize the negative part could include an adapted current distribution e.g. two coils switched on in succession to compensate the negative magnetic pressure. This would reduce the peak pressure but could lead to a prolonged deformation of the workpiece. Since it requires a high effort for the driving circuit and the switches such a system would be more difficult to realize. Still, there are few examples, e.g. Deng et al. [3] show how the repelling force can be maximized by controlling the change rate of the current and therefore lead to a tube expansion. Another possibility is to use the negative resulting pressure to simplify driver removal as proposed in [4].

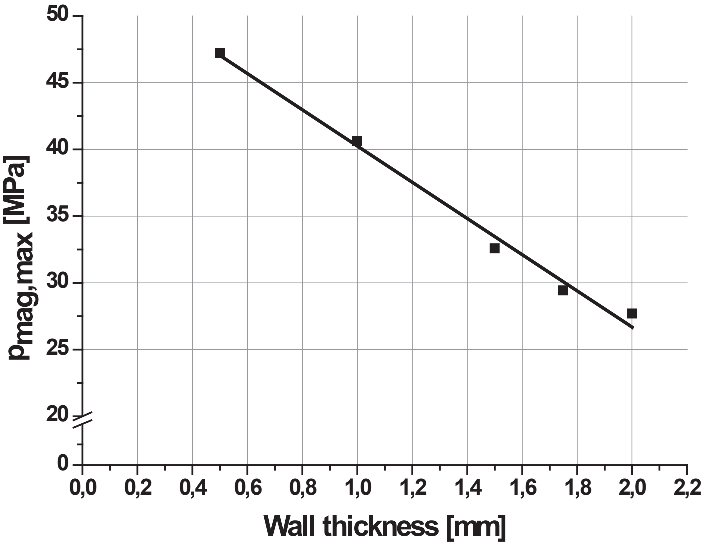

Figure 4: *Absolute value of the negative magnetic pressure for different wall thickness of the workpiece of the example model, part diameter: 36mm, f=10 kHz*

3 Time-harmonic vs. Transient Calculations

Transient and time-harmonic calculations are two approaches to simulate current and field distributions in MPW setups. While in a transient model all differential equations have to be solved for each predefined time step, only one solution is needed in the time-harmonic case. This reduces the calculation time tremendously.

In time-harmonic systems the amplitude of the applied parameter (e.g. the potential) and the frequency are defined and a model is solved that approximates the pulse as a continuous sine wave. In a transient system an arbitrary function can be applied.

Furthermore, the initial conditions are much different: the transient calculation can start with a system where all variables are zero, i.e. no currents or fields exist. In contrast the time-harmonic assumes a continuous process, therefore no real “start time” exists (steady-state system). The considered pulse is than approximated by using the evolution during one period, starting at the point where the potential is at maximum (=capacitor was fully charged).

One might think that therefore a time-harmonic system disregards important aspects of reality, e.g. the correct initial slope. So a time-harmonic and a transient calculation are compared using the simulation tool Comsol Multiphysics. The model geometry is the same as shown in Figure 1. Although real pulses are always damped, here for the transient case an undamped cosine function was used for the potential applied to the coil for a direct comparison. For simplicity no deformations were taken into account. Important MPW process parameters like the current distribution in coil and workpiece and the magnetic pressure are evaluated.

The results for the transient and the time-harmonic evaluation are surprisingly consistent. Figure 5a and 5b show the current distribution in coil and workpiece for both approaches obtained by integration over a predefined cross section. For the coil there is only a slight difference in the first half-wave because the current is starting from zero as explained above.

For the workpiece both calculation results are also in good agreement except for the first half-wave where a significant difference in amplitude is visible. This is an effect of the coupling and therefore also dependent on the material of the workpiece.

Figure 5c shows the magnetic field outside of the workpiece and Figure 5d the magnetic pressure at the same position, both compared for transient and time-harmonic analysis. Again the results are primarily different in absolute amplitude of the first pulse.

From those examples it can be seen that time-harmonic calculations are sufficient to determine some important parameters of MPW processes although MPW pulses are highly transient in nature. The time-harmonic system provides fairly accurate results for coil amplitude and field distribution but disregards initial effects. Furthermore it is clear that it cannot represent highly damped systems, as only undamped (continuous) pulsing can be simulated.

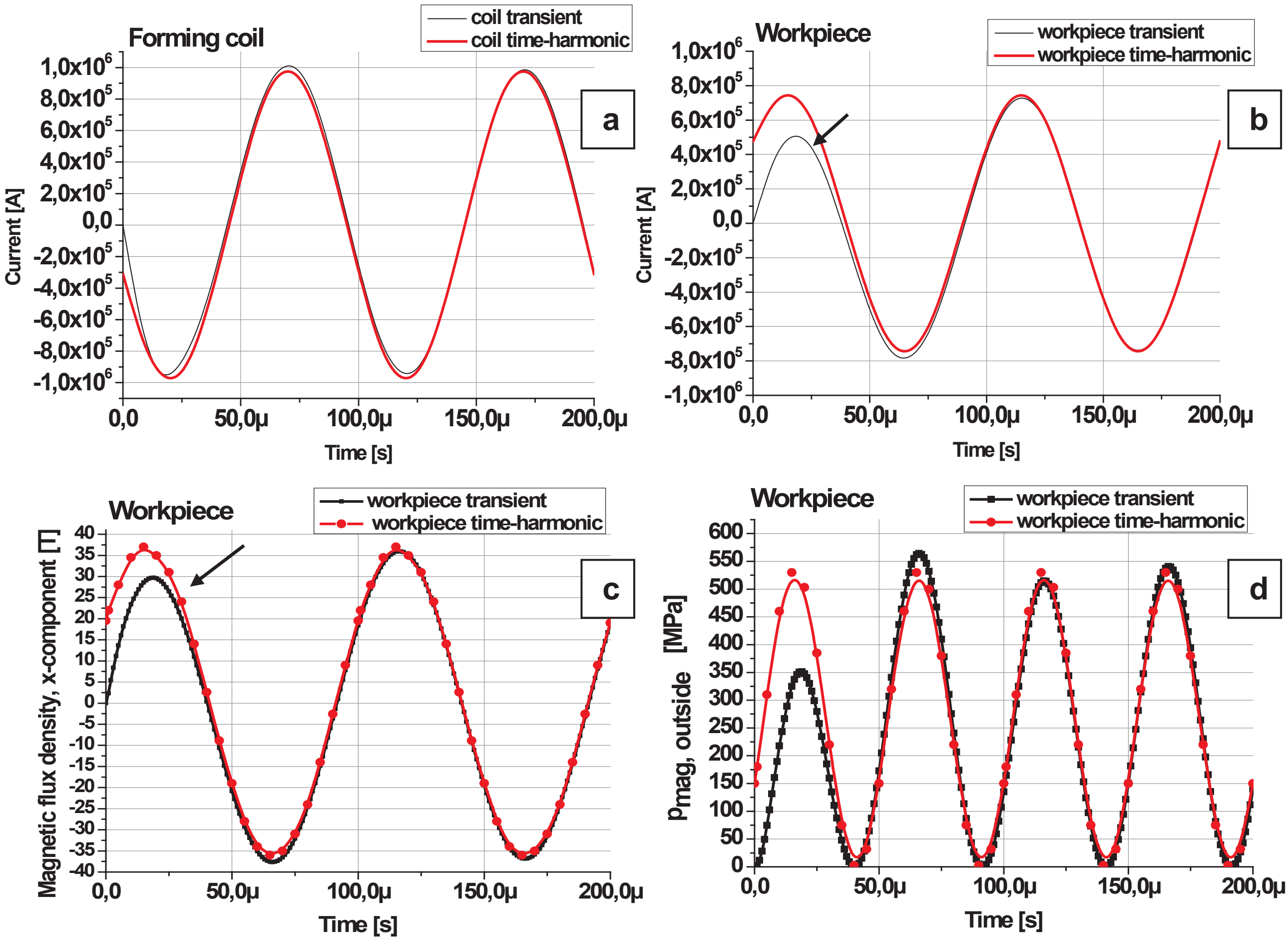

Figure 5: Overview on currents in coil (a) and workpiece (b), magnetic flux (c) and magnetic pressure (d) on the outside of the workpiece for time-harmonic and transient simulation. Arrows: lower first peak caused by initial conditions

Since a MPW configuration is generally a system which produces harmonic functions it can fairly well be described by such a time-harmonic system using a predefined frequency. A complete self-consistent model requires introducing capacitance, inductance and resistance of the pulse-generator. This would also reproduce the correct frequency and damping. But for that an (enhanced) transient model is necessary.

4 The Influence of Meshing

Meshing is an important part of a simulation since it has significant influence on the calculation time. It is often necessary to find a compromise between accuracy of the results and computational effort.

To demonstrate this influence a simple geometry only consisting of a coil with one turn is considered (Figure 6). The boundary conditions and simulation parameters are the same as described in section 2.1.

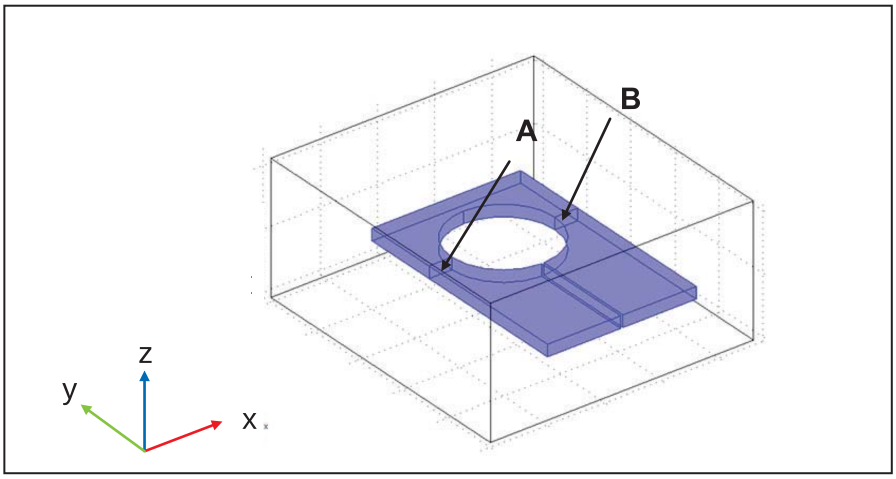

***Figure 6**: Model for the analysis of meshing with indication of the considered planes. Plane A is meshed with four elements per skin depth. The number of mesh elements per skin depth is varied for plane B.*

Two planes are defined where an integration over the current density is carried out to determine the total current through the planes. They are situated symmetrically on each side of the coil as indicated in Figure 6. The one on the left (plane A) is always meshed with four elements per skin depth. The other plane (B) is meshed identical with the rest of the coil.

The element size is changed for each calculation and the total currents through both planes A and B are evaluated in respect to each other and a reference. The cubic element around the coil is meshed relatively coarse since it is not relevant for the evaluation and only necessary to provide a finite and closed volume so that the equations converge.

Two results can be obtained from this simulation:

- Relation between time consumption and number of mesh elements
- Necessary number of mesh elements per skin depth to gain a satisfactory accuracy of the current value for the given model

Elements per skin depth	0,12	0,125	0,13	0,14	0,2	0,5	0,625	1,1	1,5	1,75
Percentage related to value of 4 elements per skin depth (plane A)	3	3,13	3,25	3,5	5	12,5	15,63	27,5	37,5	43,75

***Table 1:** Absolute and relative value of the number of elements per skin depth for different mesh sizes*

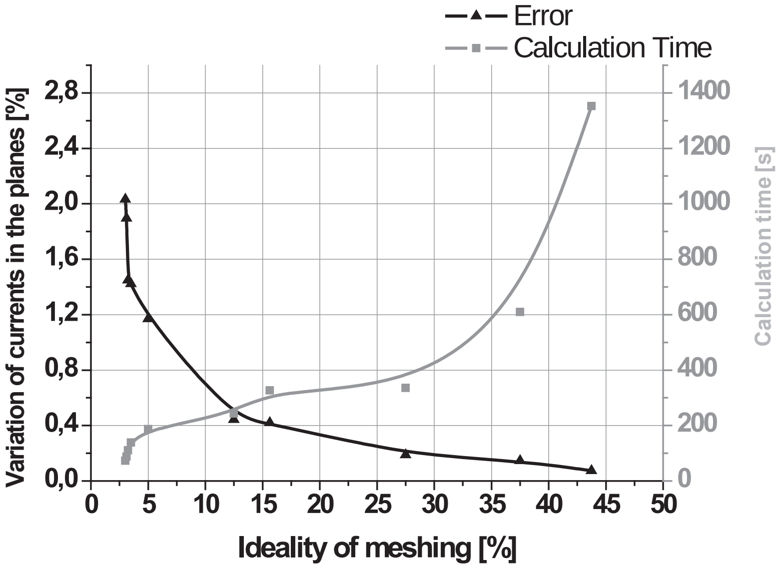

***Figure 7**: Discrepancy of currents in the two planes and calculation time for different mesh sizes (f = 10 kHz)*

It is commonly considered that three to five elements per skin depth are required for a good accuracy of the results [5] [6]. Due to that fact the current through plane A with four (second order) elements per skin depth is taken as reference for the evaluation.

The mesh of plane A is kept constant with four elements per skin depth while the mesh for the other parts of the geometry is refined after each calculation. Table 1 shows the increase of the number of second order mesh elements per skin depth in absolute value and with reference to plane A. However, the increase is not linear as predefined mesh sizes of the simulation program are used.

After each simulation for the different meshes the total currents in plane A and B are calculated by integration over the cross section of each plane. The current through plane A is constant while the current through plane B varies and converges to the value of plane A.

The variation of the currents in the predefined planes is calculated with equation (2) so that the difference is expressed by a percentage value.

$$V_I = \frac{\left| I_{\text{Plane A}} - I_{\text{Plane B}} \right|}{I_{\text{Plane A}}} \cdot 100 \qquad (2)$$

Figure 7 shows that the difference in the currents decreases with an increasing number of elements per skin depth which is not surprising. The interesting fact is that already with one (2nd order) element per skin depth one gets a fairly good accuracy of the current calculation for this type of model. In addition Figure 7 shows the necessary calculation time. It can be found that the simulation time for one element per skin depth is only about a third of the time needed for a calculation with two elements. But the error in the calculated value is smaller than 0.5%.

The variations of the current distributions in the planes in the left half of Figure 7 should also be considered. They show that a small number of elements per skin depth, although they only lead to a small percentage difference from the current value obtained with four elements per skin depth, have a significant uncertainty.

That leads to the following conclusion: For the given model it is sufficient to choose a relatively coarse mesh with only one to one point five elements per skin depth to be able to analyse the currents. The increase in accuracy which could be achieved with a finer mesh is very small compared to the increase in calculation time. Note that a special geometry and only current distribution are discussed here. The results might be different when regarding other parameters and geometries. But as currents and their distribution are a vital part of coil simulation, this is an important aspect.

5 Conclusions

This work describes effects occurring during an electromagnetic pulse forming process with special regard to the repelling force as a consequence of the evolution of the magnetic pressure during a pulse. This knowledge is useful to either improve the usage of driver materials or to create a compensation to prevent energy loss. Furthermore it is explained in which cases time-harmonic calculations are sufficient since they take much less time even for complex 3D-structures.

Another important part of a simulation is the meshing. It is shown that for typical 3D-coil models for MPW fine meshes strongly increase the simulation time but only attain a small increase in accuracy. Therefore the correlation between simulation time and accuracy is shown on the basis of current densities and hints are given how to find the fitting trade-off between those quantities.

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