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Strategies for 3D simulation of electromagnetic forming processes

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ABSTRACT

Although electromagnetic forming is a technology known for a few decades, renewed interest for its industrial application is currently taking place. Along with this interest an increasing demand for simulation tools can be found. Up to now, modeling approaches found for this process in the literature are restricted to the axisymmetric case or small deformation problems. However, for real industrial applications, the modeling of large deformation 3D forming operations becomes crucial for an effective process design. On the basis of previous modeling concepts in the work at hand we develop and investigate further approaches particularly suitable to reduce the enormous computational cost inherent to 3D simulations. These consist of a carefully chosen discretization, a data transfer method for both, the electromagnetic loads and the mechanical deformation to utilize an efficient solid shell formulation and a termination criterion for the electromagnetic part of the model. As a result the simulation time is reduced by about one order of magnitude. Finally, a 3D forming setup is modeled and detailed insights with respect to the development of eddy currents, magnetic field and deformation of the sheet metal are provided.

1. Introduction

Electromagnetic forming (EMF) is a dynamic, high strain-rate forming method in which strain-rates of $10^3\,\mathrm{s}^{-1}$ are achieved. In this process, deformation of the workpiece is driven by the interaction of a current generated in the workpiece with a magnetic field generated by a coil adjacent to it. In particular, this interaction results in a material body force, i.e., the Lorentz force and the electromotive power, representing an additional supply of momentum and energy to the material. On the other hand, the electromagnetic part of the system is sensitively influenced by the spatio-temporal evolution of the deformation of the mechanical structure. With increasing interest in this forming operation, in recent years considerable effort has been made to simulate such coupled processes. However, approaches tested so far were mainly restricted to axisymmetric geometries (Fenton and Daehn, 1998; Gourdin et al., 1989; Imbert et al., 2004; Oliveira et al., 2001; Takatsu et al., 1988) or to small deformation problems (Schinnerl et al., 2002). Yet, it is the 3D modeling capability in combination with the large inelastic deformations that is required to advance effectively in the design of industrial EMF processes. To meet these modeling requirements the sound derivation of a physical model of the relevant magneto-mechanical phenomena has been developed in Svendsen and Chanda (2005). Its algorithmic realization is given in Stiemer et al. (2006a,b).

For axisymmetric modeling, nowadays PC computational capacities are sufficient to model forming operations within

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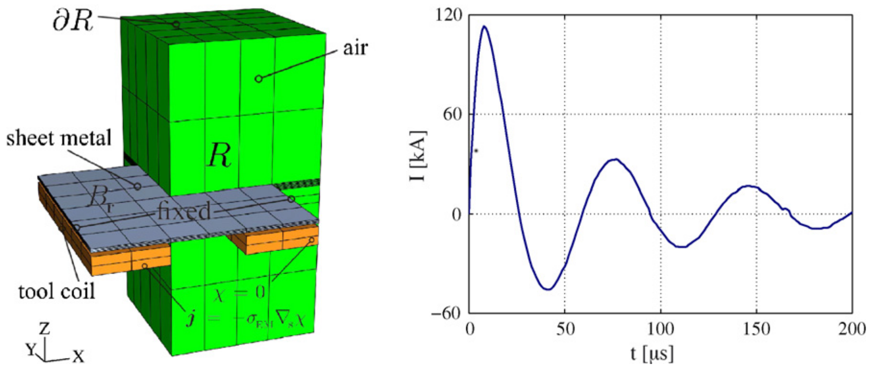

Fig. 1 – Illustration of forming setup including tool coil, sheet metal, air and annotation of the entire domain of the system R, its boundary ∂R and the mechanical domain B_r. At ∂R homogeneous Dirichlet boundary conditions are assumed. The experimentally measured input current is implemented as a Neumann boundary condition for χ, where $j = -\sigma_{\mathrm{EM}} \nabla_s \chi = (0, -I/A_{\mathrm{con}}, 0)$. Regarding the mechanical component of the model, the lateral edges of the sheet metal are fixed.

several hours. As it turns out, in the case of 3D process models the computational cost increases dramatically. While typical 2D models of EMF in general exhibit a model size of between about 3000 and 10,000 degrees of freedom similar 3D models usually require discretizations with an extent of a model which is one order of magnitude higher. It is the goal of the present work to elaborate and demonstrate approaches particularly suitable to reduce the computational cost for the 3D modeling of EMF processes in the aforementioned context. In detail these represent an extensive study of convergence, the proposal of a body force and deformation data transfer method which facilitates the use of solid shell elements (Reese, 2007) and the development and elaboration of a termination criterion for the electromagnetic part of the model. These measures are demonstrated by means of a relatively simple forming setup. Although this presented forming setup geometry is rather exceptional (see Figs. 1 and 2), dimensions and timescales are relevant for typical forming setups. As elaborated below, since the results are general in nature they can be transferred to other forming setups.

After a brief summary of the physical model and its algorithmic formulation (see Section 2) the study of convergence is discussed in Sections 3 and 5. Here, the study allows for the exploitation of potential for reduction of the computation time by selectively choosing a coarse discretization at locations where this is admissible according to the scope of the desired accuracy. Further, by studying the convergence of certain components of the EMF forming setup (*e.g.* tool coil, sheet metal, air gap, etc.) further physical insight is provided and the algorithmic model can be verified. In Section 4 the data transfer between the electromagnetic and the mechanical part of the model is discussed. In contrast to 2D modeling of EMF where the electromagnetic loads are transferred elementwise, here an independent discretization of the sheet metal is facilitated. Here, we exploit the fact that the electromagnetic loads are algorithmically independent of the mechanical deformation in the context of the staggered solution algorithm and can be integrated separately. In consequence, the use of a very efficient solid shell element formulation for the mechanical part of the model becomes feasible. In Section 6 a termination criterion particularly suitable for an efficient modeling of EMF processes is proposed and evaluated. In Section 8 a fully coupled forming operation where all the aforementioned approaches were implemented is performed and the results are discussed. The work is concluded in Section 9.

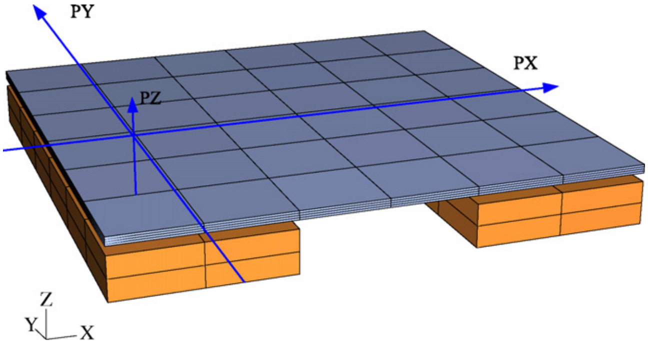

Fig. 2 – Forming setup with illustration of evaluation paths denoted by PX, PY and PZ. These proceed in horizontal and vertical direction. Horizontal paths are located in the midplane of the sheet metal.

2. Synopsis of model formulation and description of forming setup

The coupled multifield model for electromagnetic forming of interest represents a special case of the general continuum thermodynamic formulation for inelastic non-polarizable and non-magnetizable materials given in Svendsen and Chanda (2005), where a full elaboration of this model can be found. In summary, this special case is based on the quasi-static approximation to Maxwell's equations, in which the wave character of the electromagnetic (EM) fields is neglected. In this case, the unknown fields of interest are the motion field $\boldsymbol{\xi}$, the scalar potential χ and the vector potential $\boldsymbol{a}$ determining in particular the magnetic field in the usual fashion (Jackson, 1975). Assum-