Numerical Analysis of the Response of Thick Wires to Extreme Dynamic Electro-Mechanical Loads

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Abstract

Research at Fraunhofer EMI addresses the response of materials in extreme dynamic loads. Besides mechanical or thermal loads, intense electric pulse currents also represent an extreme dynamic load. Experimentally, metallic samples, mainly thick wires, were electro-mechanically loaded with currents up to 400 kA. For this purpose, a test rig containing a high-voltage pulsed power supply and high-performance switches was built. Experiments comparing the response of copper, aluminum and tungsten wires are described in [1].

In this post, we present an approach for the modelling of the response of thick (metallic) wires to extreme electro-mechanical loads. For this purpose, the essential electrodynamics, thermodynamic and mechanical aspects are being extracted and a way to couple the interrelated phenomena is suggested, allowing for the use of FEM simulation to determine the material response.

Simulations are able to describe the time-dependent process of the multi-physics response for thick wires. The focus here is on the structural mechanical behavior including bending or buckling before the onset of the wire explosion. The new simulation approach is able to capture the basic experimental observations.

This problem is a highly multi-physics problem where multiple physical topics, such as electrodynamics, thermodynamics and structural mechanics are coupled.

The electrical circuit of the test rig mainly consists of the capacitor bank, the supply line and the wire itself. Consequently, we have a time-dependent RLC circuit which is modeled with the electrical circuit interface.

To describe the current through the wire sample, we assume current conservation equation based on Ohm's law using the scalar electric potential V as the dependent variable. The Ohmic heating of the wire affects the electrical conductivity which is taken by Tucker and Toth [2].

Following the time-dependent distribution of the current density, magnetic fields are induced. These magnetic fields produce Lorentz forces in combination with the electrical current. These forces are taken as the input data for the structural mechanics part. With the structural mechanics

part the displacement of the wire is calculated. In analogy to the electrical conductivity also the Young modulus is dependent of the local temperature. The decrease as function of the temperature is taken from [3].

The driving input is the electrical current. The agreement between simulation and experiment is very good for the whole duration and also promises high confidence for the dependent variables. FEM simulations allow the calculation of physical quantities which are difficult to access by measurement such as the Lorentz force. Figure 1 shows the Lorentz force with a resolution of 5 mm long wire segments. Figure 2 compares the simulated displacement (left hand-side) with the observed displacement (right hand-side).

The presented modeling approach shows good agreement with the experiment with comparable displacement values and structures. However, especially in the simulation of the structural behavior, differences remain.

The fragmentation of the material was not considered in this approach and therefore the model does not reproduce the large deformation at the end of the wires directly at the clamps, as can be observed in Figure 2.
The presented modeling approach now allows the coupled simulation of the complete process for components under extreme electro-mechanical loads. While the main focus in previous publications focuses on specific aspects of the wire explosion process, we here intend to describe the structural mechanical behavior of components which are charged with a dynamic electrical load over a wide range of both geometry as well as electrical load with an emphasis on the structural mechanical response.

Reference

1. Richard Cunrath, Jürgen Kuder, Dr. Siegfried Nau, Dr. Matthias Wickert, Interaction of extreme electric currents with metals. In: 27th International Symposium on Ballistics, S. 1877–1884, (2013)
2. Tucker, T.J. and R.P. Toth, A computer code for the prediction of the behaviour of electrical circuits containing exploding wire elements
3. Dodge, H. L. Young's Modulus of Drawn Tungsten and its Variation with Change of Temperature, Including a Determination of the Coefficient of Expansion, Physical Review, Vol. 11 (4), p311-315 (1918)

Figures used in the abstract

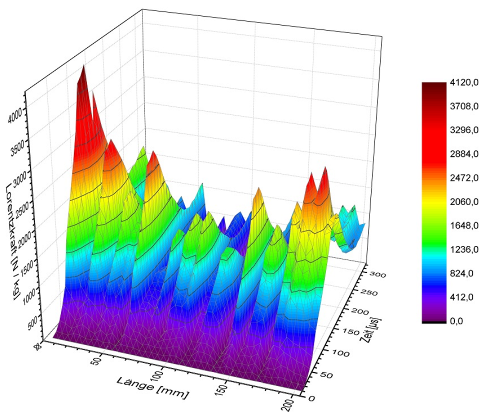

Figure 1: The time-dependent Lorentz force acting on the wire is plotted over its length with a resolution of 5 mm long wire segments.

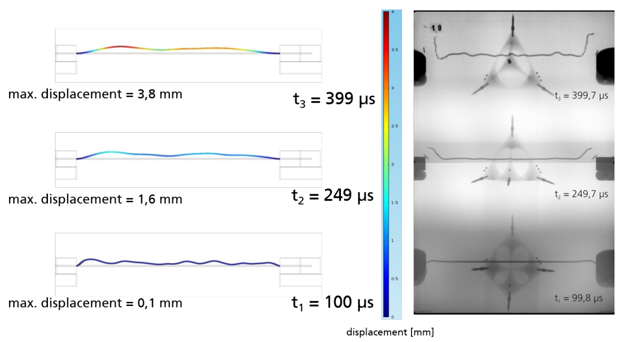

Figure 2: The calculated mechanical behavior of the wire (simulation on the left hand-side) is compared to the experimental observation (x-ray image on the right hand-side).