

Transient 3-d Simulation of an Experimental Railgun using Finite Element Methods

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Abstract¹– Railguns have the capability to accelerate projectiles to velocities in excess of 2 km/s. Current railgun research is usually performed experimentally with support from simulations. The finite element method (FEM) is a wide spread tool in many fields of research and development. But the transient computation of a 3-d model of a railgun using FEM methods, taking into account the time evolution of the acceleration process and the coupling of the electromagnetic fields to the moving projectile, is a complex task. Such a simulation involves large gradients of the electromagnetic fields, large structures of the order of meters with areas of interest in the sub-millimeter range and a fast moving projectile causing a rapid change of the current flow through the volume in the next vicinity of the contact. Nevertheless, recent developments in FEM tools make it attractive to attempt such a simulation. At the French-German Research Institute of Saint-Louis the electromagnetic acceleration group uses the program COMSOL for a transient 3-d simulation of a small caliber railgun. This article presents the implementation of the railgun as COMSOL model and compares simulation results to experimental data.

I. INTRODUCTION

Since 1987 the ISL maintains an experimental railgun research program [1]. The main interest of this research is the use of railguns in the military domain, therefore concentrating on the acceleration of projectiles with weights of 0.1 kg to several kilograms up to velocities of 3 km/s [2].

Conceptually railguns are simple electrical devices, converting electrical energy into mechanical energy. For a given railgun, the value of the current and its time evolution determines the acceleration of the projectile. In the practical realization of a railgun difficulties are usually connected to the large currents that are required to achieve high velocities. The large currents together with a small contact area between the current carrying rails and the armature, lead to large local current densities. This results in a situation where the acceleration of the projectile is limited by the inability of the material of the armature and the rails to withstand the resulting heat developing at the sliding contact. Due to the rapid movement of the armature, it is difficult to actually measure the exact current distribution in the vicinity of the armature rail contact area. In

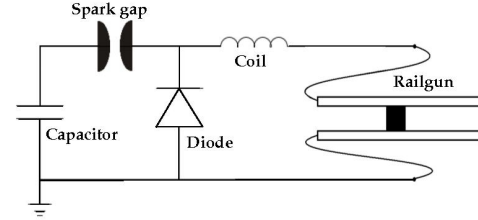


Fig. 1. Electrical circuit for a simple railgun setup.

[4] a measurement of the varying magnetic fields during the passage of a railgun projectile at velocities of 1000 m/s with a statically mounted sensor array is described. For a superior measurement a sensor array would need to be mounted inside the moving projectile to monitor the distribution of the current at the contact area as a function of the acceleration time. Due to the movement of the projectile, the transmission of the sensor data to the laboratory is difficult. A possibility would be the incooperation of a radio link to the projectile [5]. Using electromagnetic simulation codes, the electric currents and magnetic fields in a railgun can be simulated, giving the possibility to study the current distribution and for example the local heat development to optimize a certain railgun design. This paper describes an implementation of a COMSOL-FEM-simulation that uses a current pulse as input and propagates the armature as a function of time through the railgun. For a FEM tool the railgun simulation is difficult for two reasons: firstly, the effects that are to be studied require a spatial resolution on the millimeter scale, while the railgun has lateral dimensions of the order of meters. Thus on the one hand a fine meshing is needed, while on the other hand the solution time grows drastically when the number of mesh elements is becoming too large; secondly, the transient railgun simulation results in large and sudden changes of the simulated parameters. Examples are the magnetic field or the position of the armature with respect to a mesh element. Such sudden changes are inherently difficult to solve with FEM methods. In [6] it was shown that such an implementation is possible, while here the influence of the simulated volume around the railgun and the size of the individual elements distributed into this volume on the simulation results are studied. In addition to this, the mass of the accelerated body was varied. In this article the results of the different simulations are compared to the experiment.

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Fig. 2. The SR\3-60 railgun.

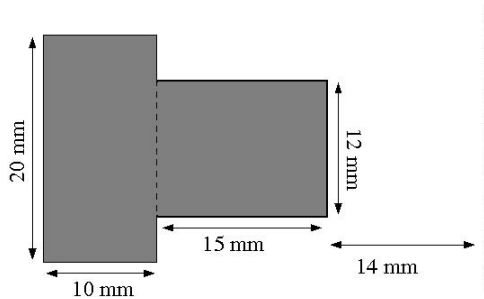
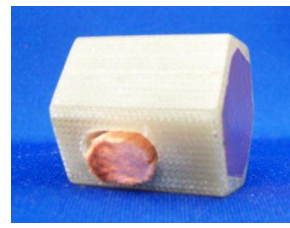


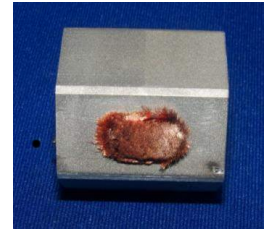
Fig. 3. Cross-sectional view of the rail for the SR\3-60. The dashed line on the right hand side is the center line of the railgun barrel.

II. EXPERIMENTAL SETUP

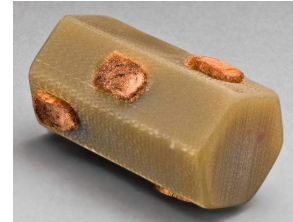
The electrical circuit of a simple railgun is shown in figure 1). The capacitor, the spark-gap, the diode and the coil compromise a so called capacitor bank. The capacitor bank is connected with coaxial cables to the railgun. After the capacitor is charged by an external circuit, not shown in the figure, the spark gap is triggered and current starts to flow through the coil and the armature of the railgun. Once the capacitor is discharged, the diode becomes conducting and decouples the capacitor from the circuit. In this investigation, the SR\3-60 railgun was used [7]. This railgun, shown in figure 2), has an overall length of about 2 m. The setup of this gun is flexible and allows the installation of up to three pairs of rails in the same barrel. Here the gun was used as a simple railgun, accelerating the projectile with only one pair of rails. Each of the rails is composed out of two copper bars, being mounted on top of each other, resulting in a T-shaped rail. A cross-sectional view of this arrangement, together with the rail dimensions is shown in figure 3). To investigate the stability of the simulation results versus variations in input parameters, the experiments were performed at different electrical energies and with different masses of the projectiles. Three different types of projectiles were used, weighing approx. 45 g, 60 g and 90 g. These projectiles are shown in figure 4). The 45 g and 90 g projectile are made out of glass-fiber reinforced plastic (GRP), while the 60 g projectile is fabricated out of aluminum. Figure 4(c)) shows that the 90 g projectile exhibits three brushes. Here the accelerator was used with three installed pair of rails, each serviced by one individual brush. The rail pairs are installed sequential along the length of the railgun [7]. For the purpose of this investigation only the data from



(a) 45 g projectile.



(b) 60 g projectile.



(c) 90 g projectile.

Fig. 4. Three different types of projectiles were used for the experimental test series.

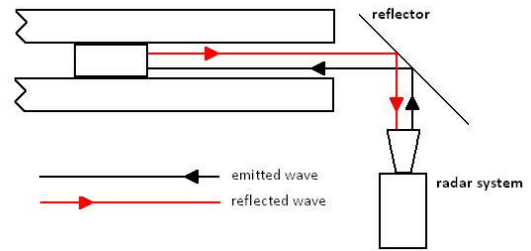


Fig. 5. The radar installation at the SR\3-60, as used to measure the projectile velocity.

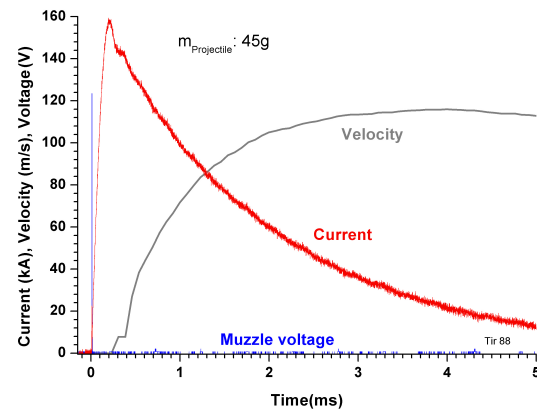


Fig. 6. Example for the measurement of current, muzzle voltage and velocity as taken for each shot.

the first pair of rails is being used. During the acceleration with the first pair of rails, the other two brushes are running freely in air, thus acting only as additional weight and do not contribute to friction. The velocity of the projectile can

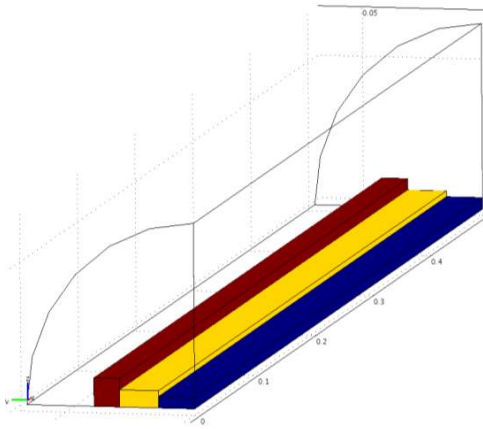


Fig. 7. Implementation of the railgun as a COMSOL model.

be measured by different means. A convenient method is the use of signals from B-dot probes being distributed along the barrel. The passage of the armature induces a voltage in the probes and from the signal of two such probes a velocity can be derived. The end-velocity can be controlled by using breaking wires or a laser light barrier. These methods do have the drawback that one either has only the end-velocity or a velocity profile being derived from a few measurements points (the number of probes), only. The usage of a Doppler radar allows a highly accurate measurement of the velocity during the whole acceleration length. Examples of the usage of a radar system at ISL are reported in [8]. The radar setup for the SR\3-60 can be seen in figure 5). The microwaves being emitted by a gunn diode are reflected by a mirror into the barrel of the railgun. The projectile moves toward the mirror and reflects the microwaves with its front end. Figure 6) shows the measurements from a typical shot within this test series. Traces of the injected current, the muzzle voltage and the resulting velocity are measured. In this shot a 45 g projectile was accelerated to a velocity of 115 m/s. Visible is the typical current profile, with a quick rise within 0.2 ms and a slow decay for several milliseconds. For each of the three masses, three shots were performed, resulting in the velocities as shown in table I). These velocities span from 25 m/s up to 534 m/s. As it can be seen from these values quite a wide range of the relevant parameter space can be compared to simulation results.

45 g	60 g	90 g
115 m/s, 424 m/s, 534 m/s	61 m/s, 70 m/s, 81 m/s	25 m/s, 52 m/s, 86 m/s

TABLE I

VELOCITIES FOR THE NINE EXPERIMENTAL SHOTS PERFORMED WITH THREE DIFFERENT PROJECTILE MASSES.

III. SIMULATION SETUP

The simulations were performed using the COMSOL Multiphysics[®] [9] program. COMSOL is a modern simulation framework, using the Finite Element Method to solve

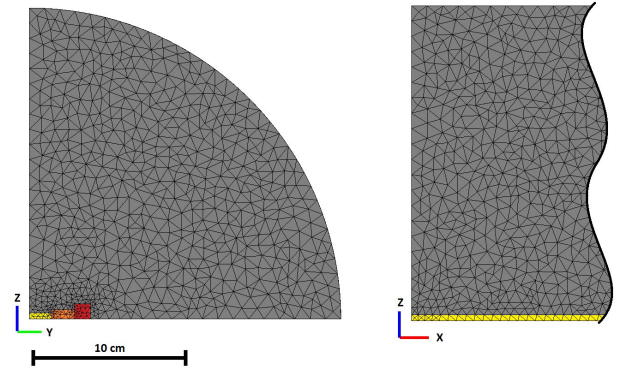


Fig. 8. Visualization of the meshing for the extremely fine setting. Cross-sectional view (left), side view (right).

problems in quite diverse areas. It is organized into so called modules, the selection of which depends on the problem one wants to solve. Relevant for the implementation of an electromagnetic model of a railgun is the AC/DC module. Over the time the COMSOL program was further developed and different versions of this tool do exist. In this investigation the version 3.5a is utilized. The railgun being described in the section II needed to be translated into an geometrical model. This model is shown in figure 7). Due to the symmetries for the electromagnetic fields in a simple railgun, only a quarter model needs to be simulated. The outer quarter cylinder is the volume surrounding the railgun, allowing the simulation of the external magnetic fields. The three bars seen in the lower part of the figure are (from left to right), the two copper bars of the rails (in the figure red and yellow) and in blue the volume in which the short circuit element (the brush) runs. To replicate the current profile as it was measured in the experiment, a voltage port was connected to the front end of the leftmost copper bar in figure 7), while the short circuit element was connected to ground. Using a global equation setting, this voltage is varied for each time step by COMSOL in a way that the current through the railgun matches a given current distribution. As the current pulse does look rather similar for the different shots, a current template was used in the simulation, being scaled to the experimentally measured maximum current. Meshing is done with three different granularities, normal, finer and extremely fine. These settings are pre-defined by the COMSOL user interface, with “extremely fine” resulting in the best mesh quality. Interesting for the simulation is the number of mesh elements in the simulated volume and the degrees of freedom (DoF) which the solver needs to solve for each time step. The number of mesh elements and the DoF do depend on the size of the simulated volume and on the granularity. As a guide, for a radius of the outer cylinder of 20 cm the selection of the normal mesh mode resulted in 11338 elements with 15598 DoF, the finer has 33286 elements and 44152 DoF and the extremely fine mesh mode has 311777 elements and 381432 DoF. The resolution of the meshing can be seen in figure 8) for the extremely fine mesh setting. On the left hand side of

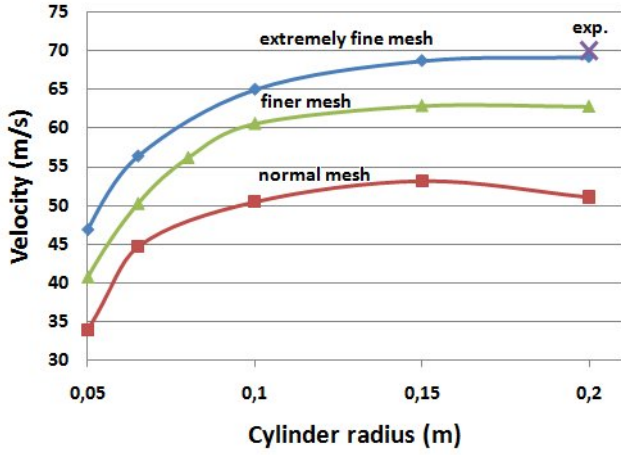


Fig. 9. Results from simulations with different radii of the outer cylinder.

this figure it is visible that for example the 14 mm length of (half of) the brush is resolved into not more than nine mesh elements. The right hand side shows that in this direction along the axis of the cylinder the meshing is even coarser than in the cross-sectional dimension. With a resolution of about 1 mm and above in the respective projections, this model is not yet capable to fully resolve details in the current and magnetic field distributions, but should give an indication as to what can be expected from the simulations. The rational behind the variation in the different meshing settings was, that the effect of the meshing on the simulation result was to be investigated. From the computational point of view, the meshing has a strong influence on the time required for a solution of the problem. For the simulation a 12 core 3.33 GHz Xenon[®] machine was used and the simulation times ranged from about 10 minutes for the normal meshing to several hours for the extremely fine meshing. Another important feature of this simulation is the treatment of the moving armature. Instead of actually moving the mesh elements associated with the armature, the conductivity of the volume representing the armature with 8 mm diameter is changed smoothly from 0 S/m to $5.99 \cdot 10^7$ S/m. In this way, a moving copper armature is simulated.

IV. RESULTS

Simulations were performed with the three different mesh settings and five to six different radii of the outer cylinder. For each of the simulations the end-velocity of the projectile is shown in figure 9) and compared to the corresponding experimental value (the marker "exp." in the upper right corner of the figure). There are two trends visible. The end-velocity of the projectile increases with a better spatial resolution of the meshing (finer meshing) and with the radius of the cylinder. Starting with a radius of 5 cm and the "normal" mesh the derived velocity is a factor of two smaller than the experimental value, but increasing the number of mesh elements increases the velocity. At a radius of about 15 cm a sort of plateau is reached and the velocity of the projectile does

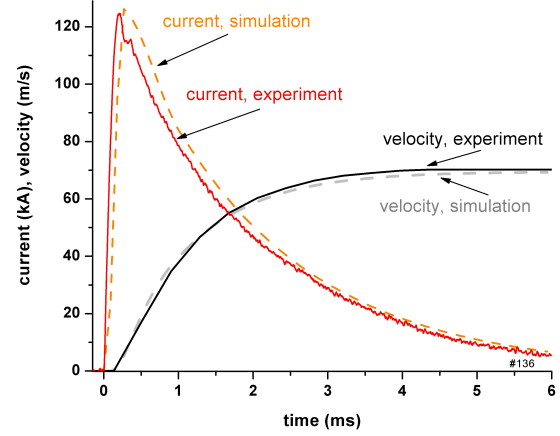


Fig. 10. Comparison of the simulated and experimental values for current and velocity for one shot with a projectile mass of 60 g.

not increase any more. For the extremely fine mesh setting the simulated velocity value approaches the experimental value of 70 m/s. From this series of simulations it can be concluded that the simulation radius should be at least 15 cm large and the extremely fine mesh mode should be used to be able to reproduce the experimental results. For the further discussion a radius of 20 cm was used in the simulations. As listed in section II for each of the three projectile types three shots with different end-velocities ranging from 25 m/s to 534 m/s were performed. Figure 10) shows the comparison of experiment and simulations for one shot with a 60 g projectile. The velocity profile shows good agreement between experiment and simulation. The slight disagreement in the current distribution between experiment and simulation does come from the fact that the simulation uses a current template being scaled to

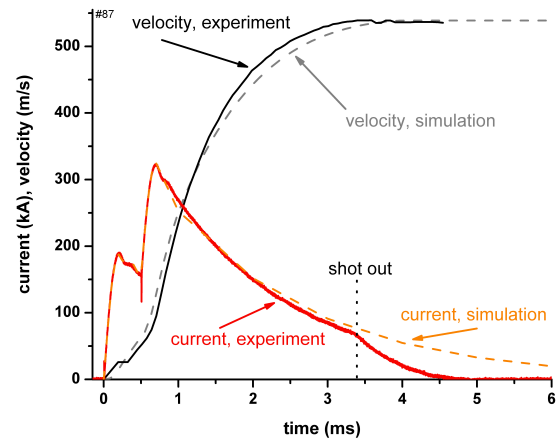


Fig. 11. Comparison of the simulated and experimental values for the shot with the largest current and velocity (projectile mass: 45 g).

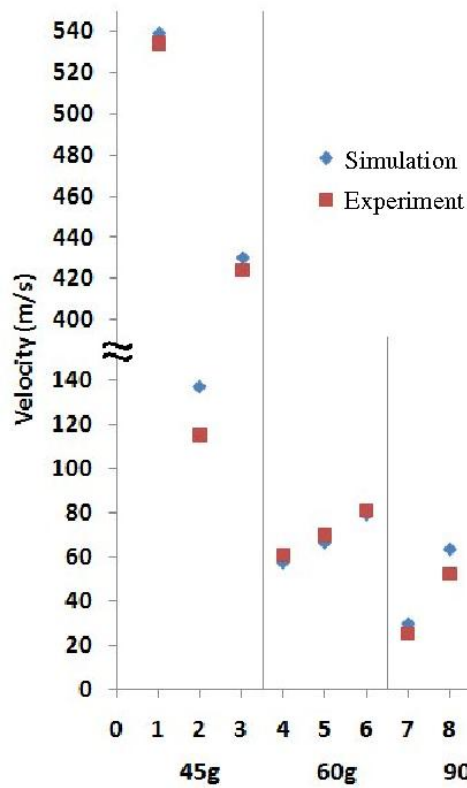


Fig. 12. Comparison of experimental and simulated end-velocities for three different projectile weights.

the maximum current amplitude taken from the experiment as input. In figure 11) the highest energy shot in this test series is shown. Two capacitor banks are injected into the railgun, resulting in a double peaked current profile, with a maximal value of 320 kA. The current input for the simulation follows closely the experimental current. At 3.4 ms a change of slope can be seen in the current trace of the experiment. This is the time, when the projectile has reached the end of the rails. Again, the agreement in the velocity between simulation and experiment is good. An end-velocity of about 535 m/s is reached at the shot out time. For all nine launches, the end-velocity from the simulation is compared to the experimental value in figure 12). The left three entries relate to the projectile weight of 45 g. The two shots with velocities above 420 m/s were performed with two capacitor banks, instead of one, connected to the railgun. The second bank was released with a small time delay with respect to the first bank. The next three shots used projectiles weighing 60 g and the rightmost three entries correspond to a projectile weight of 90 g. Overall the agreement between simulation and experiment has an deviation of below 20 %, with an average of 9 %. Within these limits the simulation reproduces the experiment.

V. SUMMARY

Using the COMSOL Multiphysics® software a transient 3-d simulation of a simple railgun was implemented and the results

of the simulation was compared to a series of experiments. To get a fair impression about the quality of the simulation, a wide range of different velocities and different masses of the projectile were simulated. In all cases the simulated values deviate less than 20 % from the experimental values, with an average deviation of 9 %. From these results it is clear that the simulation with COMSOL can be used to give guidance in designing new railguns and interpreting the measurements taken at existing installations. In the future it is desirable to investigate parameters that are more specific and sensitive to short term variations, as for example the magnetic field strength and current density in the rails and at the rail-armature interface. The transient simulation could help to interpret experiments as being described for example in [10].

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