# A NOVEL RAILGUN SIMULATION MODEL BASED ON A QUASISTATIC

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This paper presents a novel railgun simulation model based on a quasistatic study in COMSOL. Traditional analytical models are inaccurate as they use the coenergy principle to calculate the force on the armature, yielding the total force in the displacement axis. By using a numerical magnetic solution, a parametric analysis evaluates the flux linkage, armature force, and system resistance at various positions and currents. After characterizing the railgun, the transient problem is solved by coupling the parametric study results with the system's equivalent circuit. Finally, the results are compared with those from the analytical approach.

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## I Introduction

Simulating the electromagnetic behaviour of a railgun is crucial for predicting the performance and optimizing the design. Railguns can be modelled analytically or via a Finite Element Method (FEM) software. Analytical models, like those in [1] and [2], use the coenergy principle to calculate the force acting over the armature, however, this approach actually yields the total force acting on the longitudinal axis of the rails and armature. FEM models, such as the one in [3], require the railgun's current profile as input, necessitating experimental setups and they do not allow for geometric optimization. This paper outlines a methodology for integrating both approaches and discusses the results obtained.

## II Methodology

To calculate the armature position (*y(t)*), speed ($\dot{y}(t)$), and acceleration ($\ddot{y}(t)$) the following equations must be solved.

$$F(t) = m_a \cdot \ddot{y}(t) \tag{1}$$

$$\dot{y}(t) = \int_{t_0}^{t_1} \ddot{y}(t) \cdot dt + \dot{y}_0 \tag{2}$$

$$y(t) = \int_{t_0}^{t_1} \dot{y}(t) \cdot dt + y_0 \tag{3}$$

*F(t)* corresponds to the force exerted on the armature, and $m_a$ is the mass of the armature. It is important to highlight that *F(t)* actually depends on the armature position and electrical current.

Figure 1 shows the drive and railgun equivalent circuit.

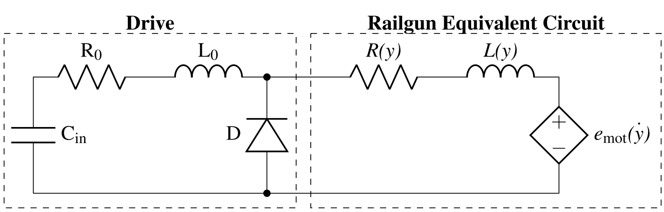


**Figure 1: Railgun equivalent circuit.**

$C_{in}$ represents the capacitor bank capacitance. $R_0$ is the sum of the equivalent series resistance (ESR) of the capacitor bank, the connections resistance, and the PCB tracks resistance. Since the ESR is dominant in this case, $R_0$ is effectively set equal to the ESR. Similarly, $L_0$ is the total of the equivalent series inductance (ESL) of the capacitor bank and the PCB stray inductance. Again, only the ESL is considered for the $L_0$ calculation due to its dominance. The antiparallel diode D is placed across the capacitor bank to prevent reverse voltages. $R(y)$, $L(y)$ and $e_{mot}(\dot{y})$ denote the railgun's resistance, inductance and the back electromotive force (BEMF), respectively. The $e_{mot}(\dot{y})$ depends on the flux linkage ($\lambda(y,i)$) and armature speed:

$$e_{\mathrm{mot}}(t) = \left.\frac{\partial\lambda(y,i)}{\partial y}\right|_{i=ct} \cdot \dot{y}(t) \tag{4}$$

To solve the problem in the time domain, the kinematic equations are coupled with the equivalent circuit. Prior to this, it is necessary to determine $F(y,i)$, $\lambda(y,i)$, and $R(y,i)$. These data are obtained through a parametric sweep performed in COMSOL. The results are then integrated into the kinematic equations and in the equivalent circuit, the problem can be effectively solved in the time domain by means of numerical integration based on backward differentiation formulas.

## III Results

Figures 2 – 4 show the results of the parametric sweep. Figure 2 illustrates that the force is transmitted to the armature more efficiently when it is near to the origin. In Fig. 3, it can be seen that, as there is no magnetic material, the flux linkage increases linearly with the current. In Fig. 4, it is important to highlight that no thermal effects are considered, so the railgun's resistance does not depend on the current. Additionally, the parametric sweep is based on stationary studies, so the skin effect is not considered.

Figures 5 – 7 compare the final results with those from analytical model [1], implemented in Simulink. Figure 6 shows both approaches yield similar results. Figures 7 indicates the analytical model yields a peak force 10 % higher than the COMSOL model, leading to the mismatch shown in Fig. 6.

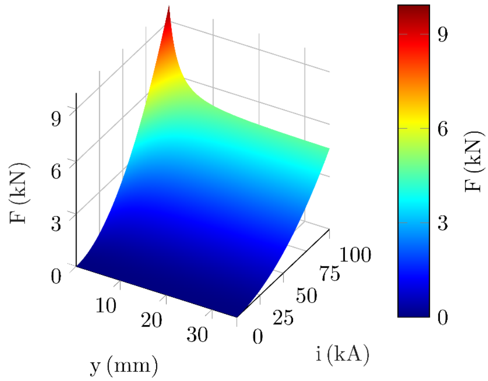


**Figure 2: Force as function of the armature position and the current.**

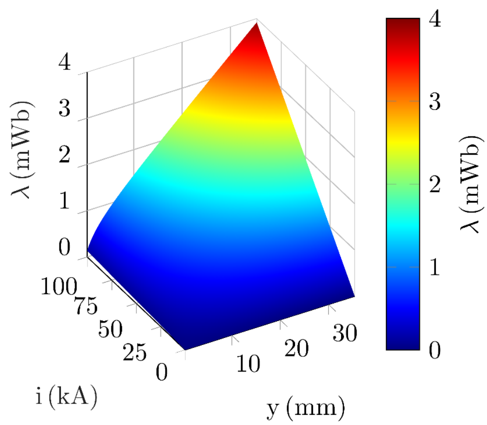


**Figure 3: Flux linkage as a function of the armature position and the current.**

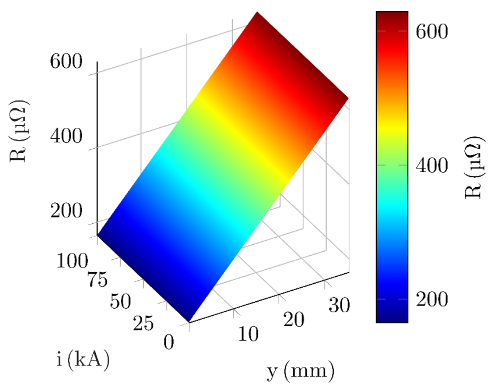


**Figure 4: Resistance as a function of the armature position and the current.**

## IV Conclusions and future work

A novel hybrid FEM-analytical model has been proposed to address the limitations of analytical models in terms of force calculation. Future work will focus on incorporating thermal effects and the skin effect into the model to enhance its accuracy.

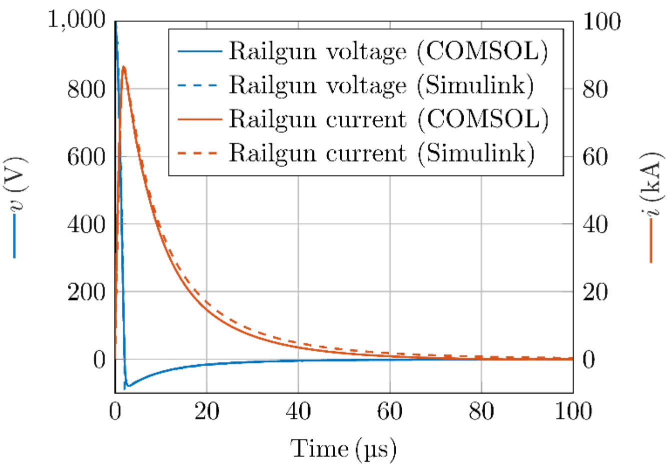


**Figure 5: Force as function of the armature position and the current.**

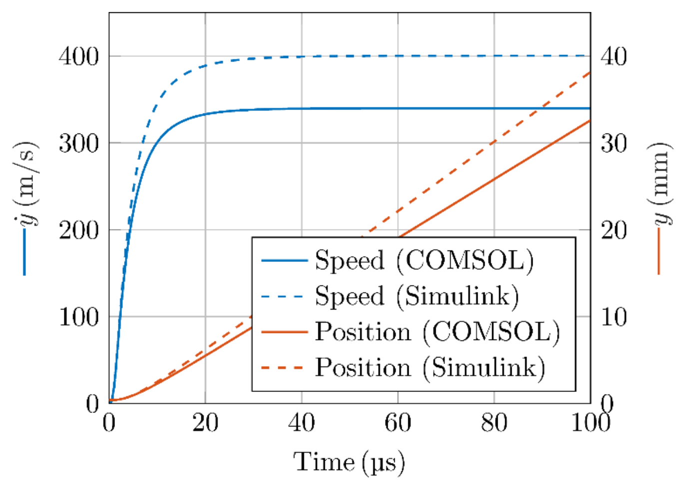


**Figure 6: Flux linkage as a function of the armature position and the current.**

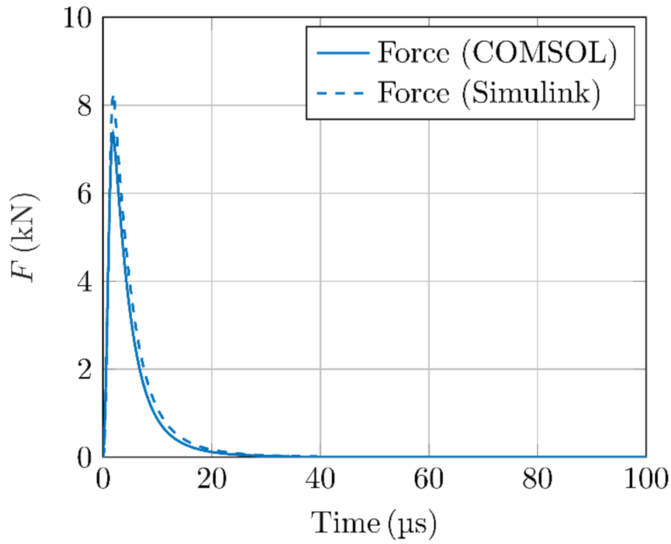


**Figure 7: Resistance as a function of the armature position and the current.**

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