Reluctance Launcher Simulations and Experiment

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***Abstract*— Single stage reluctance launcher simulations and experiment reaching velocity of 54.3 m/s are presented. A comparison between the experimental and two type of simulations, a numeric simulation and a Quasi-analytic simulation was done. An average accuracy of ~4% were obtained for the numeric simulation and ~6% for the quasi-analytic simulation. The two complementary approaches of simulations can be used for effective optimization of many parameters of the launcher making it possible to improve the system.**

***Index Terms*— Electromagnetic Accelerator, Coil Gun, Launcher, Reluctance.**

I. INTRODUCTION

ACCELERATING a projectile using electrical power attracts scientific attention in view of several important advantages [1]. Widely investigated methods based on magnetic acceleration are the rail gun and coil gun. In a railgun [2], the projectile is placed on conducting rails and close an electric circuit of high current through the rails using sliding contact. The current induces strong magnetic field in the rail loop pushing the projectile out of the rail, reaching high velocities. However, due to the high current passing through the sliding contact a severe damage is given to the rail limiting the shuts number of the rail. Also, the railgun generates a loud noise and explosion. In coil gun there is no sliding high current contact which is an important advantage. A strong magnetic field is induced by a coil accelerating a projectile. The projectile is not in contact with the barrel and therefore there is low weariness of the system and long lifetime. Also there is no explosion and noise during the operation.

Two different coil-gun mechanisms are used: induction acceleration [3] or reluctance acceleration [4]. In induction acceleration a conductive hollow cylinder is used as a projectile. The coil induces current in the projectile and it is pushed out by the magnetic field of the coil. To obtain high velocity, high currents are induced on the projectile which is severely heated and even melted along the barrel [1, 5]. Therefore cooled projectiles are used [6].

In reluctance acceleration coil gun simpler projectile is used, made of ferromagnetic material such as iron [7]. When the coil is activated a strong magnetic field pulls the projectile into the coil, accelerating it due to the positive magnetic gradient in the coil entrance. There is no need to induce high currents on the projectile which simplifies it. Even small projectile can be launched. However, the current pulse must end before the projectile reaches the maximal magnetic field to avoid deceleration of the projectile in view of the negative magnetic gradient at the coil exit. As well-known, it is difficult to induce high current pulse in a coil for a short time. Shutting off the coil current takes time and this conflict limits the launch velocity. Nevertheless, since the projectile is simple and not heated up, several accelerating stages can be added to reach a higher velocity.

There have been many experiments in reluctance acceleration. In addition, many models can be found in the literature to describe the behavior of the system. Because of the dynamic nature of the system and co-dependence of the parameters, it is difficult to solve the equations that describe it analytically. In many cases, certain assumptions are made relieving the calculations, and therefore the theory and experiments are not sufficiently reconciled. In cases where there was a high correlation between the experiments and the theory, high velocities were not reached. Therefore the dynamic nature of the system was less significant. For higher velocities poor match was obtained.

Ref. [4] showed theoretical calculations based on the response surface method, analysis of the change of energy in the various elements. Maximum velocity of 36.7 m/s was demonstrated with a projectile of ~0.6 g in agreement with the theoretical calculation. In Ref. [8] a velocity of 23.01 m/s with a 32.46 g projectile was reached including a theoretical calculation but with a mismatch of 15% explained as system losses. Ref [9] reports a velocity of 18.9 m/s, including a theoretical calculation with an error of about 12%. In Ref. [10] a velocity of 19.93 m/s was reached including corresponding theoretical results. In Ref. [11] velocity of 52.1 m/s, relatively high, was obtained with a 8 g projectile in a system with 5 acceleration stages, but there is no compatible simulation.

In Ref. [12] a MATLAB simulation was carried out predicting a velocity of 69.8 m/s but the experiment result was 27.4 m/s. Ref. [13] showed a simulation of a reluctance launcher with 3 stages reaching a maximum velocity of 37.6 m/s, but there are no experimental results. In Ref. [7] 18.59-24.34 m/s velocity was reached using two types of projectiles, a smooth cylindrical projectile and a grooved cylinder to prevent Eddy currents. In the simulations of the

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grooved projectile, an excellent match was obtained (1-5%), whereas in the simulations without the groves the error was extended beyond 10%. The difference in accuracy level was explained as the elimination of the induced Eddy currents in this experiments, which are not taken into account in the theoretical model.

It seems that analytical models of reluctance launchers has limitations especially for high velocity predictions.

In this work, a reluctance launcher is modeled by two different approaches, numeric and quasi-analytic simulations. The numeric approach is accurate but consumes long run-time and therefore preforming optimization over many values is time consuming. To complete it, a quasi-analytic code was developed. This code runs fast and can support optimization calculations of many values in short time. Still it is not accurate as the numeric simulation. A comparison between the methods is presented and verified by experimental results.

II. Experimental setup

The experimental setup was based on single stage coil wrapped from a copper wire on an aluminum guider. The projectile was made of a ferromagnetic cylindrical steel. The initial position of the projectile was determined by a location ruler placed at the entrance of the coil, as shown in Fig. 1. The initial position was relative to the coil entrance which was determined as zero position (Z0_p=0 mm). The dimensions of the setup are detailed in Table 1.

The launcher was driven by a capacitor bank with total capacitance of 3 mF and a typical charge voltage of 1100-1250 V, generating a ~1.5 ms current pulse with amplitude of 3500-3800 A (Fig. 2). The current pulse was switched by a Silicon-Controlled Rectifier (SCR) and was measured by Fluke i6000s FLEX AC current probe (0.5 mV/A).

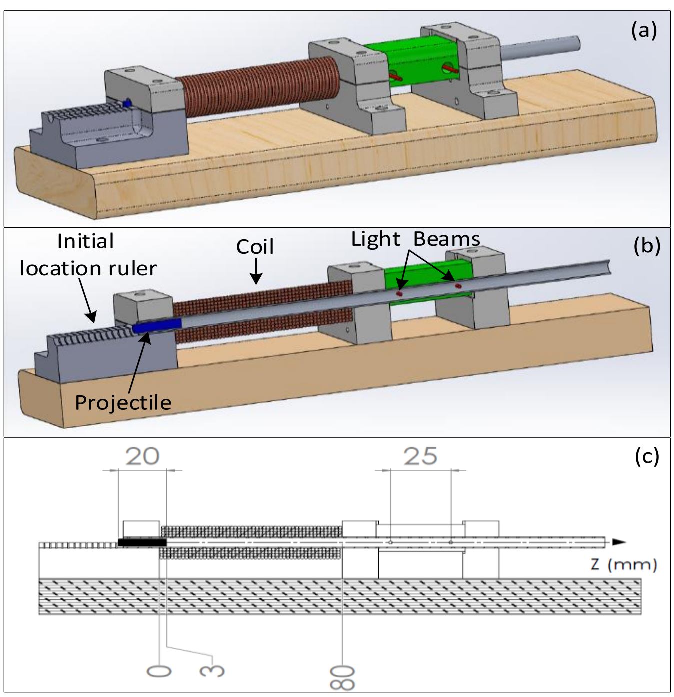

Fig. 1: Experimental setup general overview (a), device cross section (b), schematic and dimensions of the experimental setup (c).

TABLE 1
SETUP DIMENSIONS.

DIMENSION	VALUE
Coil length [mm]	**80**
Coil inner diameter [mm]	**6**
Guider inner diameter [mm]	**5**
Num. of layers	**4**
Wire width [mm]	**1.5**
Number of turns (approximated)	**200**
Projectile length [mm]	**20**
Projectile diameter [mm]	**4**

The projectile velocity was obtained by measuring the time interval of the projectile passing throw a pair of light beams, distant 25 mm apart, activating a pair of phototransistor sensors. A typical measurement of the sensors detection is shown in Fig. 2. In this measurement a pick current of 3700 A, and a velocity of 50 m/s are measured.

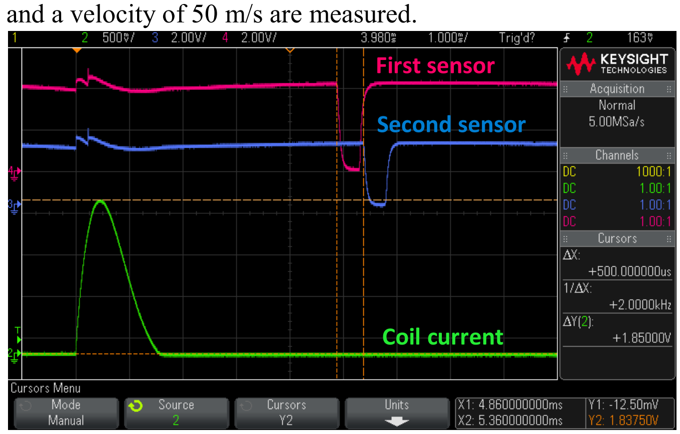

Fig. 2: A typical sensors detection and coil current measurement (probe factor 0.5 mV/ A). Time scale 1 ms/div.

The experimental setup parameters detailed above and the coil current measurements were used as input parameters for the simulations described hereinafter.

During the experiment different shots were done. In the various shots the initial position of the projectile was changed and the velocity was measured.

In order to properly evaluate the magnetic field profile a simulation and measurement of the magnetic field generated by the coil were made. The simulation was carried out by a COMSOL multi-physics code, and the measurement was done with A Gauss meter [14]. The magnetic field profile is seen in Fig. 3.

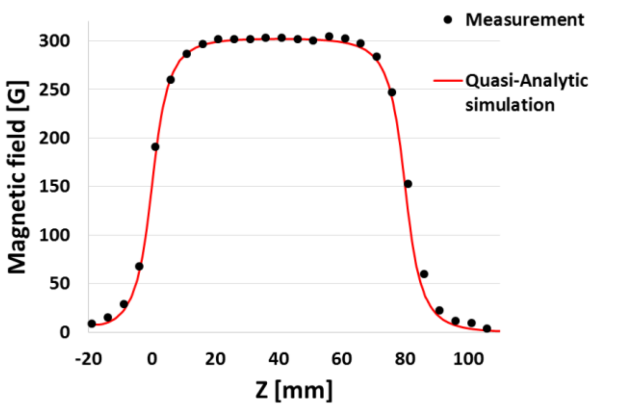

Fig. 3: Simulated and measured coil magnetic field profile at I=10A.

III. Numeric simulation

The physical problem of the reluctance launcher is complex due to the codependence of many variables, such as the nonlinear permeability of the projectile. In order to get a proper solution COMSOL Multi-Physics simulation program was used. A model of the problem was built and a code to numerically solve the problem was developed (Fig. 4). The model was simulated in a 'dynamic study' mode which takes into account time dependent effects such as induced Eddy current developing on the projectile, and codependence of all variables. The time steps of the model are determined by the current pulse measured in the experiment in order to achieve accurate results.

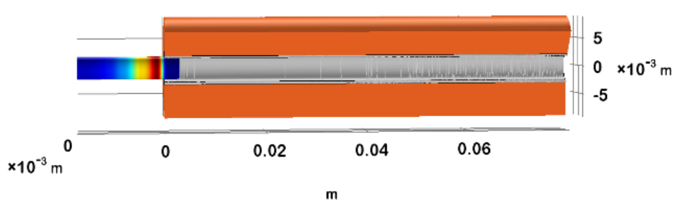

Fig. 4: 3D model of the numeric simulation setup. The projectile initial position (Z0_p) is 3 mm in this example.

An optimization of the system can be examined by cross sweeping of different parameters such as coil length, number of turns, projectile length, projectile initial position, coil current, etc. For example Fig. 5 shows the cross sweeping results of coil length and projectile initial position. For each possible combination between the two parameters a plot line of the projectile velocity as function of the displacement is obtained. In addition the code can calculate the magnetic force on the projectile, position, magnetic profile, and the magnetic flux density.

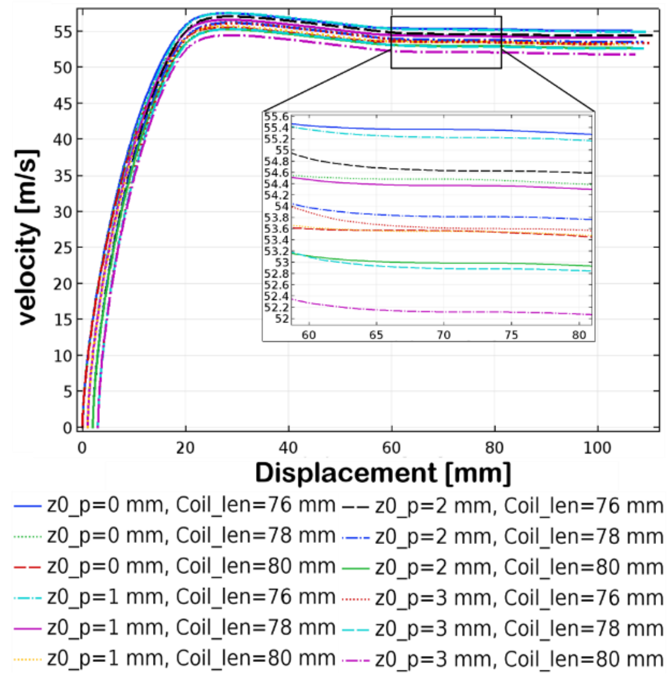

Fig. 5: Velocity as function of displacement for a cross sweeping of coil length (Coil_len) in values 76,78,80 mm, and initial position of the projectile (Z0_p) in values 0,1,2,3 mm.

For each parameters set that was changed a full run of the code, which takes about 30 minutes, is required. A cross sweeping of several parameters as shown in Fig. 5 can take up to several days. Therefore this simulation is good for general design of the system but it is not effective for optimization by sweeping parameters. The results of this simulation is detailed in the results section.

IV. Quasi-analytic simulation

In order to overcome the problem of long running time, an analytic MATLAB code was developed to analyze the physical problem in an analytical approach. The code calculate the velocity (v) and the position (z) of the projectile in small time steps (dt) using regression formulas:

(1) $$v_{i+1} = v_i + \frac{F_i}{m} \cdot dt$$

(2) $$z_{i+1} = z_i + v_i \cdot dt + \frac{1}{2} \cdot \frac{F_i}{m} \cdot dt^2$$

Whereas F is the magnetic force acting on the projectile and m is the mass of the projectile. Here also the time steps are determined from the coil current measurement in order to achieve accurate results.

The magnetic force was predominantly calculated in a stationary simulation using COMSOL multi-physics. A lookup table of the force on the projectile was calculated for a set of currents and for every position. The current through the coil was taken as a constant in these calculations. Therefore, this model neglects time dependent effects such as induced Eddy currents. First, the magnetic force was calculated for multiple positions of the projectile at the same current, repeating this process for multiple currents yields a lookup table with the magnetic force on the projectile for every positon and current.

The MATLAB code calculates the position and velocity of the projectile for every dt using interpolation of the magnetic force from the lookup table to the exact location and current. At $dt = 0$ the projectile is at rest and the initial position is known and determined from the experiment. A typical result of the velocity as function of displacement is shown in Fig. 6

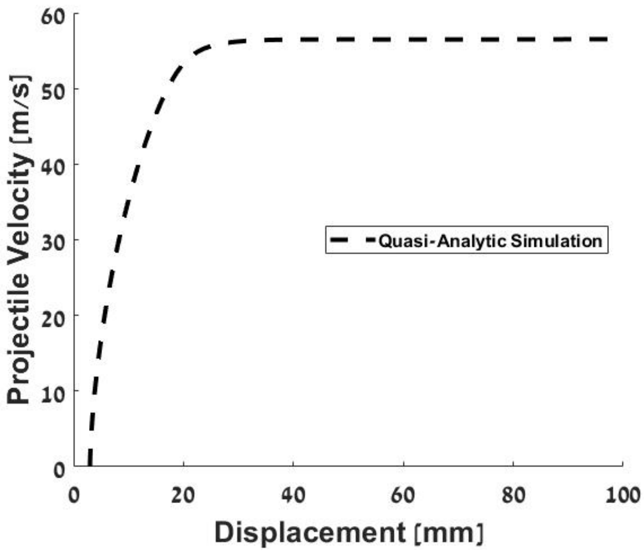

Fig. 6: Typical result of the projectile velocity from the quasi-analytic simulation.

In this method, the lookup table is valid for a chosen coil and projectile. If one would like to replace the coil or projectile, a different lookup table is to be calculated. However, optimization of the initial position (Fig. 7) of the projectile and the current pulse takes a few seconds instead of many hours as in the numeric simulation method. The results of this simulation are presented in the following results section.

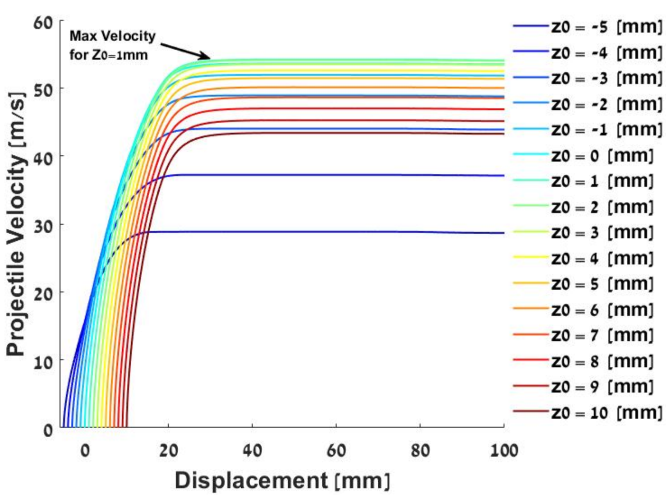

Fig. 7: The analytic projectile velocity results for sweep of the projectile initial position

V. Results

In this section the results of the experiment, numeric simulation and quasi-analytic simulation are presented. The velocity of the projectile is the out coming result that will be compared to determine the simulations accuracy. A comparison of all the results is presented in Table 2.

Each simulation was fed with the initial position and current pulse that were measured in the experiment. The velocity obtained from the quasi-analytic and numeric simulations for shot number 4 (Table 2) is shown in Fig. 8. As can be seen a velocity decreasing can be noticed only in the numeric simulation. This can be explained by time dependent affects such as induced Eddy current developing on the projectile, which are neglected in the analytic simulation.

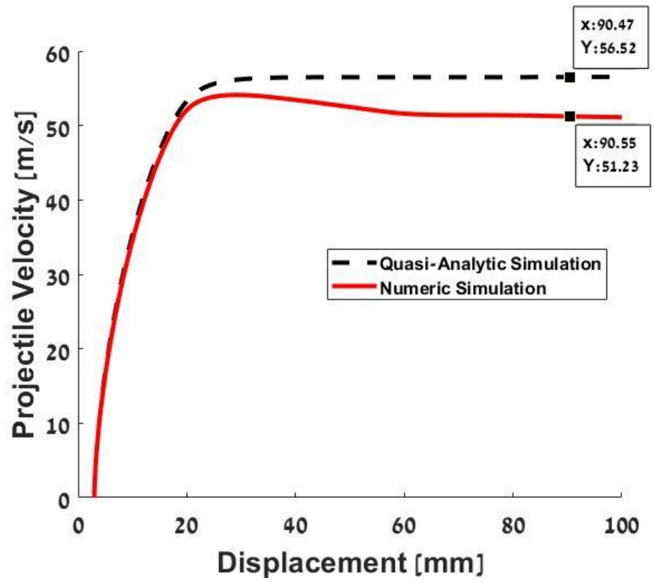

Fig. 8: Typical compression between the velocity as function of the projectile displacement obtained by quasi-analytic simulation and the numeric simulation.

Fig. 9 presents the output velocity of the projectile obtained from the experiment and both of the simulations. As expected, increasing the initial position lead to an output velocity upraise until a maximal output velocity is reached, beyond this position the output velocity is decreasing. It is seen that similar pattern is obtained for the experimental results and both simulations. Also, the maximal result is obtained for the same initial position.

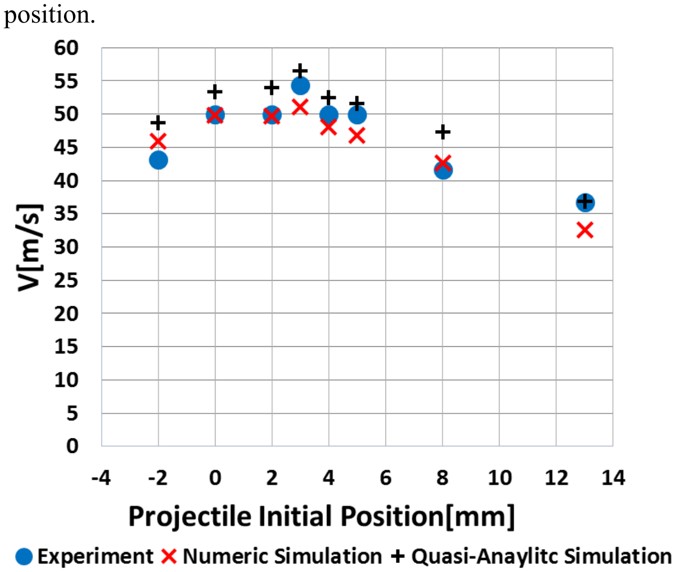

Fig. 9: Comparison graph of experimental and simulations output velocity results.

TABLE 2
RESULTS COMPARISON FOR EXPERIMENT AND SIMULATIONS

Shut Num.	Experiment Initial Position [mm]	Experiment Velocity [m/s]	Numeric Simulation Velocity [m/s]	Numeric Simulation Error [%]	Quasi-analytic Simulation Velocity [m/s]	Quasi-analytic Simulation Error [%]
1	-2	43.1	45.87	6.4	48.64	12.9
2	0	50.0	49.88	0.2	53.34	6.7
3	2	50.0	49.68	0.6	54.03	8.1
4	3	54.3	51.14	5.8	56.53	4.1
5	4	50.0	48.03	3.9	52.48	5.0
6	5	50.0	46.86	6.3	51.63	3.3
7	8	41.7	42.7	2.4	47.3	13.4
8	13	36.8	32.64	11.3	36.9	0.3

VI. CONCLUSIONS

This work shows two complementary approaches to simulate reluctance accelerator and compared the simulations results with experimental results. Relatively high velocity of 54.3 m/s was obtained using one accelerating stage.

The numeric approach was more accurate but takes a long run-time. On the other hand the quasi-analytic approach was less accurate because it neglects the time dependent effects such as Eddy currents, but has much shorter run-time. Nevertheless, it is shown that both of the simulations predict similar pattern as the experimental pattern. The maximal velocity is obtained for the same initial position with good agreement to the experiment.

Several aspects are indicated as possible factors limiting the accuracy of the simulations. Since the initial position ruler was printed, there is limited accuracy of the initial position evaluation in the experiment. Also, after the experiment, change in the coil length was noticed due to the force acting on the coil itself making it shorter in ~ 4 mm. Therefore the coil entrance was shifted away from the zero position. This effect added to the results mismatch. The difference in coil length also lead to a change in the current density which also lead to a change in the force and as a result change the velocity too. It would be wise in future design of the coil to take mechanical measures in order to solve the coil shortening.

Nevertheless, the velocity is predicted with good agreement to the measured velocity. Therefore, once the basic model parameters (coil length, projectile length etc.) is chosen, an optimization can be quickly performed with the quasi-analytic simulation to find the optimum configuration of the system. For more accurate simulation result the numeric simulation can be operated one more time for the optimal results of the quasi-analytic simulation. As a result, the real system can be built with high confidence in its expected performance.

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