



3D MODELING AND SIMULATION OF A RELUCTANCE COIL GUN

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1. INTRODUCTION

Today, chemical explosives are used to launch projectiles, rockets and spacecraft. There are some limitations in increasing the speed of these systems. Chemical fuels cannot be reused, so their costs are high. Storage of chemical fuels is dangerous and the chemical reaction is difficult to control. Electromagnetic launchers have been discovered as an alternative to chemical launcher systems (Fair, 1982). The importance of electromagnetic launchers has increased recently due to their many advantages such as high speed, reusability, flexibility and durability. Numerous industries, including the military, nuclear physics, space exploration, and medicine, use electromagnetic launchers..

1.1. Types of Electromagnetic Launchers

There are many types of launchers. Some of these are electromagnetic (EM), chemical, hydrostatic, elastic and gravity. Electromagnetic launchers (EML) can be classified as induction, direct, electro-thermal-chemical (ETC), magnetic, electrostatic and hybrid. This classification is shown in Figure 1.

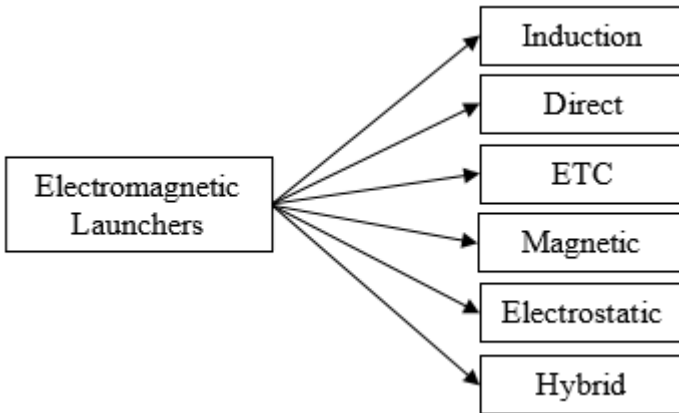


Figure 1. *Classification of Electromagnetic Launchers.*

Rail launchers (RAL) and reluctance launchers (REL) are the most studied EML. RAL are the constant specific force type of the direct class. REL are the variable specific force type of the direct class (Engel, 2017).

1.1.1. Rail Launchers (Rail Gun)

There are typically three different types of RAL based on rail structure: conventional RAL, augmented RAL, and barrel-fed RAL (Yu and Fan, 2010). The most commonly used conventional RAL have two rails and a movable conductive armature that short-circuits these rails. When voltage

is applied to the rails, the conductive armature short-circuits the rails and a current flows through the rails. This current produces a magnetic field. The armature moves with the Lorentz force that occurs as a result of the magnetic field and throws the object to be thrown (Keshtkar et al., 2008).

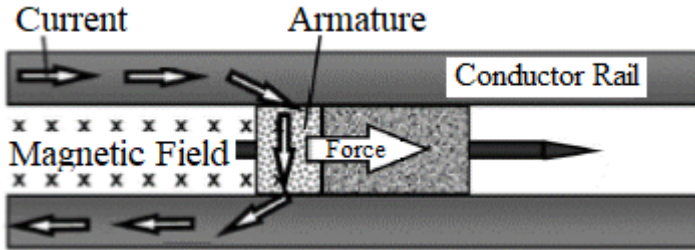


Figure 2. Rail gun.

RAL can reach high speeds (higher than 2000 m/s) and their efficiency can exceed 30% (Lehmann et al., 2006). RAL are large in size. For this reason, it is not portable and must be mounted on a fixed place or vehicle. RAL are mostly suitable for use in land and sea vehicles. The representation of the RAL, also known as the rail gun (Tzeng and Schmidt, 2010), is shown in Figure 2, and the equivalent circuit of the RAL (Zhang et al., 2010) is shown in Figure 3.

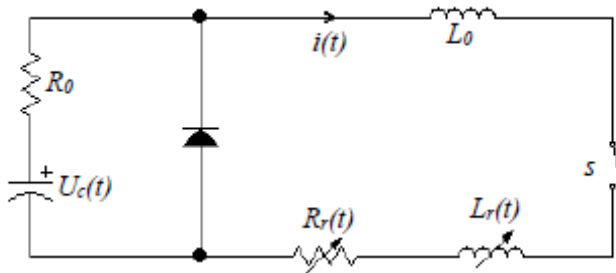


Figure 3. Equivalent circuit of rail gun.

1.1.2. Coil Launchers (Coil Gun)

Another name for coil launchers (CL) is coil gun (CG). In CG, coils are used to launch the object to be thrown. CG may have one coil or multiple coils (Marder, 1993). CG consist of two main parts; mechanical part and electronic part. The mechanical section consists of three subsections.

1. Winding
2. Barrel (the pipe through which the object to be thrown will move)
3. Projectile (The object to be thrown)

In the electronic part, there are power supply and control circuits. When a current flows through the winding, a magnetic field is created around the winding. The object to be thrown is thrown with the effect of this magnetic field. CG can be generally divided into induction coil guns (ICG) and reluctance coil guns (RCG) (Daldaban and Sari, 2016). There are also electromagnetic launchers where induction and REL are used together (Jing et al., 2017).

1.1.2.1. Induction Coil Gun

The projectile launched in ICG is not ferromagnetic, but paramagnetic or diamagnetic. The projectile is not pulled, it is pushed. Therefore, the projectile must stay outside the part of the coil that is intended to be launched. The operation of ICG is related to eddy currents (Slade, 2005). Figure 4 shows the ICG, and Figure 5 shows the equivalent circuit of the ICG.

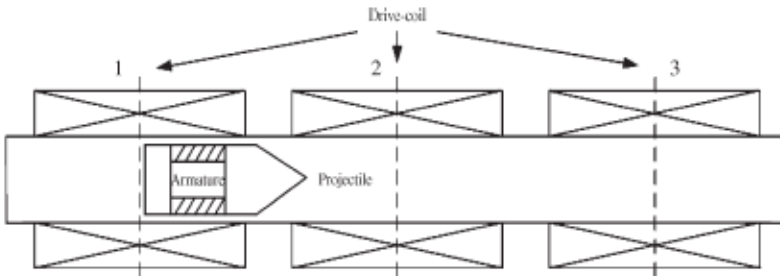


Figure 4. Induction coil gun (Liu et al., 2010).

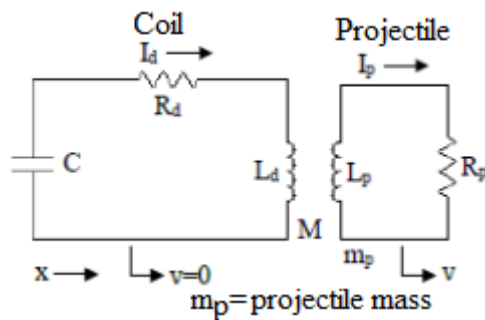


Figure 5. Equivalent circuit of induction coil gun (McKinney and Mongeau, 1984).

1.1.2.2. Reluctance Coil Gun

The operation principle of RCG is similar to reluctance motors (ChaoWei et al., 2008). The projectile to be launched in RCG must be made of ferromagnetic material. The projectile is moved toward middle of the coil by RCG. The projectile cannot be pushed. (Mosallanejad and Shoulaie, 2012). When current flows through the coil, a magnetic field is created. This magnetic field wants to use the projectile as a bridge (due to the magnetic permeability of the ferromagnetic projectile being much higher than air) and therefore pulls the projectile towards the center of the coil. The coil's energy should be cut off and the coil's energy should be absorbed when projectile reaches the middle of the coil. Otherwise, the projectile cannot be thrown or it will be thrown slowly because the projectile will be pulled in the opposite direction and again to the center of the coil. This is the most important point in the design of RCG. The efficiency of the RCG is very dependent on this timing. In multi-stage RCG, energy must be given to the relevant coil according to the position of the projectile, and when the projectile reaches the center of that coil, the energy of that coil must be cut off and the energy in that coil must be absorbed. Sensors can be used to energize and disconnect the coils. These sensors are shown in Figure 6 (Daldaban and Sari, 2014). After the coil is de-energized, a parallel diode can be connected to absorb the energy in the coil. This parallel diode is shown in Figure 7 (Bresie and Andrews, 1991).

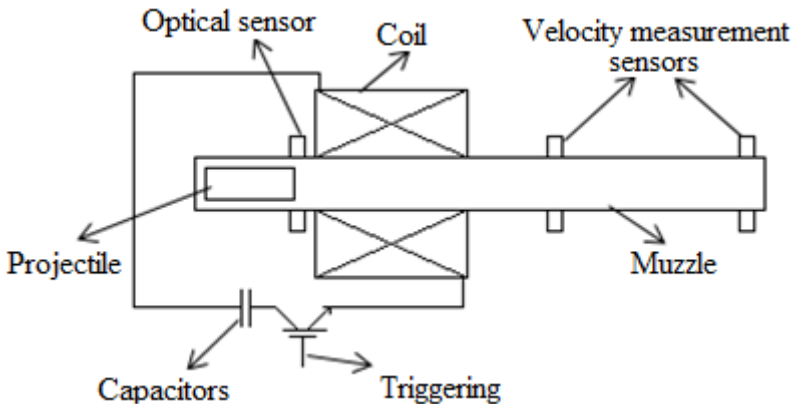


Figure 6. Reluctance coil gun.

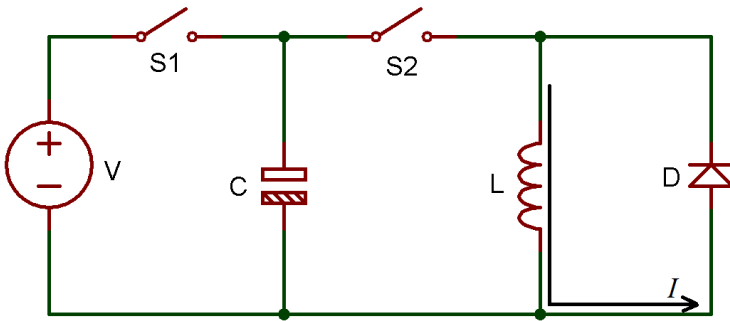


Figure 7. *Equivalent circuit of the reluctance coil gun.*

Figure 7 shows the equivalent circuit of the RCG. While switch S_2 is open, switch S_1 is closed and the capacitors are charged. Subsequently, the energy within the capacitor is transferred to the coil when switch S_1 is opened and switch S_2 is closed. In order to switch the energy given to the coil, semiconductor circuit elements such as thyristors, transistors, MOSFETs and IGBT, which can operate at high voltages, should be used as switching elements. While the trigger circuits of these semiconductor circuit elements operate at relatively low voltage, the voltage applied to the coil is high. Therefore, these circuit elements must be used with a driver. In addition, a damping circuit should be used to protect against damage that may occur from on and off states. The damping circuit may consist of diode, capacitor and resistor.

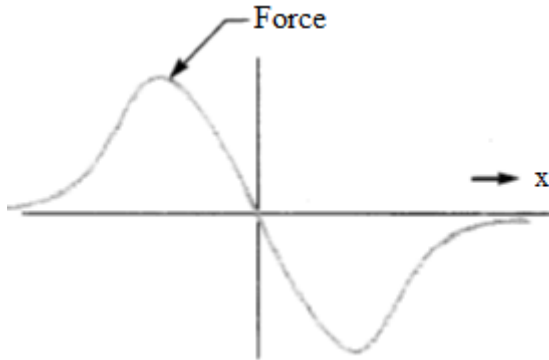


Figure 8. *Force applied to the projectile vs distance.*

Figure 8 shows the change of the force exerted on the projectile in the REL depending on the distance. Here the zero point is the middle point of the coil. When the projectile passes the midpoint of the coil, the force applied to the projectile is in the opposite direction, that is, the projectile is pulled back to the center of the coil (Bresie and Andrews, 1991).

$$a = \frac{x\mu_0(NI)^2}{2\rho l a I^2} \quad (1)$$

$$x = \mu / \mu_0 - 1 \quad (2)$$

In REL, the acceleration of the projectile can be found with Equation 1 (Chaowei et al., 2008). Here

l = projectile length,

ρ = material density of the projectile

NI = magnetomotive force

l = coil length

Given that the RCG's projectile is ferromagnetic and the B-H curve of the ferromagnetic material is nonlinear, it is difficult to determine the performance of REL. For this purpose, the finite element method (FEM) is used. FEM is an analysis method used to analyze problems that cannot be solved or are difficult to solve with known methods (Daldaban and Sari, 2015). In many previous studies, FEM was used to analyze REL (Daldaban and Sari, 2014; Daldaban and Sari, 2016; Sari and Daldaban, 2019; Chaowei et al., 2008; Yadong et al., 2010; Hou et al., 2012). There are many computer programs that can perform solutions with FEM. The most popular of these is the ANSYS Maxwell program. ANSYS Maxwell may be used to create a three-dimensional model of the REL. and the desired data can be obtained by solving it with FEM.

1.1.3. Hybrid Electromagnetic Launchers

Hybrid launchers are the combination of RAL and CL. Therefore, they have the characteristics of both RAL and CL (Shiyong et al., 2004).

2. VELOCITY MEASUREMENT SYSTEMS

Measuring the velocity of the launched projectile is an important issue regarding EML. As examples of velocity measurement systems; Ultrasonic velocity measurement systems, laser velocity measurement systems and velocity measurement systems using optical sensors can be given. The most used and most sensitive velocity measurement system is the velocity measurement system using optical sensors. In this velocity measurement system, two pairs of optical sensors are placed consecutively on the path of the projectile. If the time the projectile passes through these sensors is measured and the distance between the sensors is divided by this time, the velocity of the projectile can be found (Daldaban and Sari, 2016).

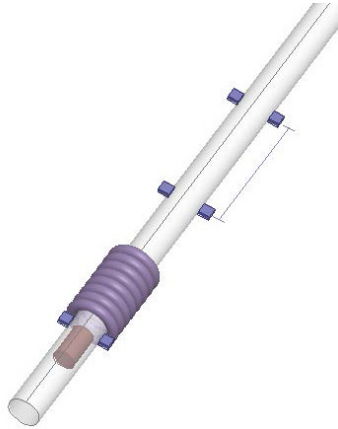


Figure 9. Measurement of projectile velocity with optical sensors.

3. GENERATING A 3D MODEL OF A RCG

Before realizing REL, the FEM model of the REL must be generated and analyzed. This is an important step to solve problems encountered in practice and optimize the system. Before generating the launcher model, the physical dimensions of the launcher (projectile thickness, projectile length, barrel inner and outer diameter, coil length and coil height) must be determined. The diameter and number of turns of the wire used in the coil must be determined, and the dimensions of the coil when it is wound must be determined. Figure 10 provides the launcher's dimensions. Here, the outer diameter of the barrel is 10 mm, the inner diameter of the barrel is 8 mm, the projectile length is 25 mm, the projectile diameter is 7 mm, the coil length is 50 mm, the coil diameter is 28.6 mm and the barrel length is 200 mm.

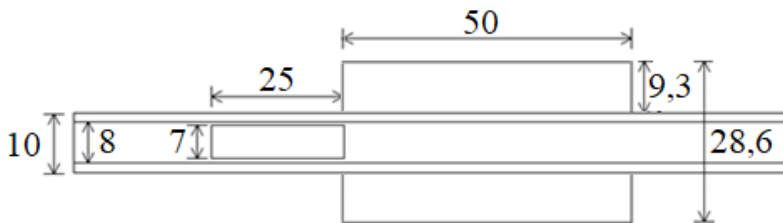


Figure 10. Dimensions of the launcher.

A 3D model of a RCG can be generated using the ANSYS Maxwell program, which can solve with FEM. Initially, after opening the program, click on the “Insert Maxwell 3D Design” section from the “Project” tab or click on the “Insert Maxwell 3D Design” icon. The name “Project1” in the

“Project Manager” section can be changed. A desired name is given instead of “Project1”. In this study, it was named “3D_RF”. To select the solution type, click “Solution Type” from the “Maxwell 3D” tab. Select “Transient” from the window that opens on the screen.

To generate the inside of the barrel, click “Regular Polyhedron” from the “Draw” tab or click the “Draw Regular Polyhedron” box. The starting coordinate, inner radius coordinate, and barrel length coordinate are entered in the coordinate boxes in the lower right corner of the program screen. The Enter key is pressed each time. Segment number is entered. Then click on “RegularPolyhedron1” in the “Model” section, its name can be changed in the “Properties” section, in this study it is entered as “InsideBarrel”. Material is changed in the “Properties” section, “vacuum” is selected by default. Select “air” from the “Edit” section.

To generate the barrel, click “Regular Polyhedron” from the “Draw” tab or click the “Draw Regular Polyhedron” box. The starting coordinate, outer radius coordinate, and barrel length coordinate are entered in the coordinate boxes in the lower right corner of the program screen. The Enter key is pressed each time. Segment number is entered. Then, click on “RegularPolyhedron1” in the “Model” section, its name can be changed in the “Properties” section, in this study it is entered as “Barrel”. Material is changed in the “Properties” section, “vacuum” is selected by default. Select “PVC plastic” from the “Edit” section. If desired, the color of the barrel can be changed by selecting a desired color from the “Color” section in the “Properties” section.

To obtain a hollow tubular barrel, the “InsideBarrel” must be removed from the generated “Barrel”. To do this, “Barrel” and “ InsideBarrel “ in the “Model” section are selected together by holding down the Ctrl key. Then click on the “Subtract” command from the “Boolean” section of the “Models” tab. In this box, there should be “ Barrel” on the left and “ InsideBarrel “ on the right.

In order to model the current flowing through the coil, a rectangle should be generated in the coil cross section on the “YZ” axis and excitation should be given from this rectangle. For this purpose, “YZ” is selected from the “Grid Plane” section in the “Models” tab. From this moment on, the drawings will be relative to the “YZ” axis. From the “Draw” tab, click the “Rectangle” command. Coordinates are entered in the coordinate section in the lower right corner. The Enter key is pressed each time. The model obtained with what has been done so far is shown in Figure 11.

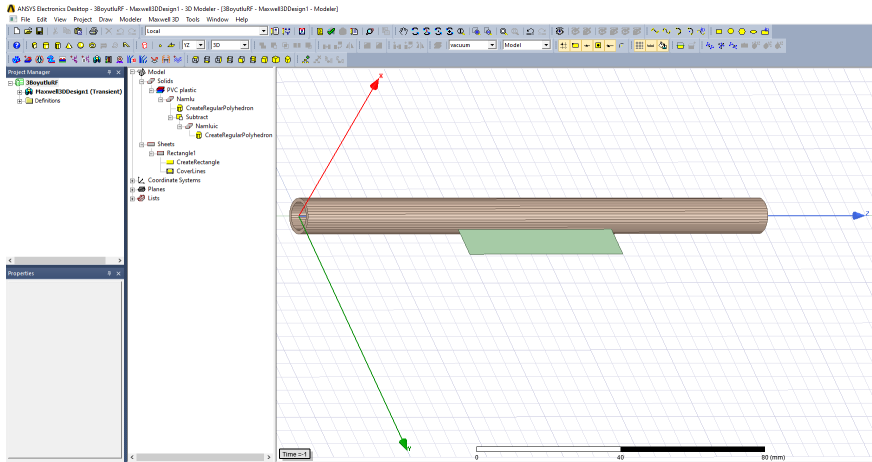


Figure 11. Steps to generate the model.

While “Rectangle1” is selected in the “Model” section, “Copy” and then “Paste” commands are clicked and “Rectangle2” is generated. While “Rectangle2” is selected, click “Around Axis” in the “Sweep” section of the “Draw” tab. Click on the “Z” axis in the opened box. Here, “Angle of sweep” should be 360 degrees. Thus, the coil is generated. Click “Rectangle2” in the “Model” section and its name can be changed in the “Properties” section. Here it has been changed to “Coil”. In the “Properties” section, click on “vacuum” in the “Material” section and select “Copper”. The model obtained with what has been done so far is shown in Figure 12.

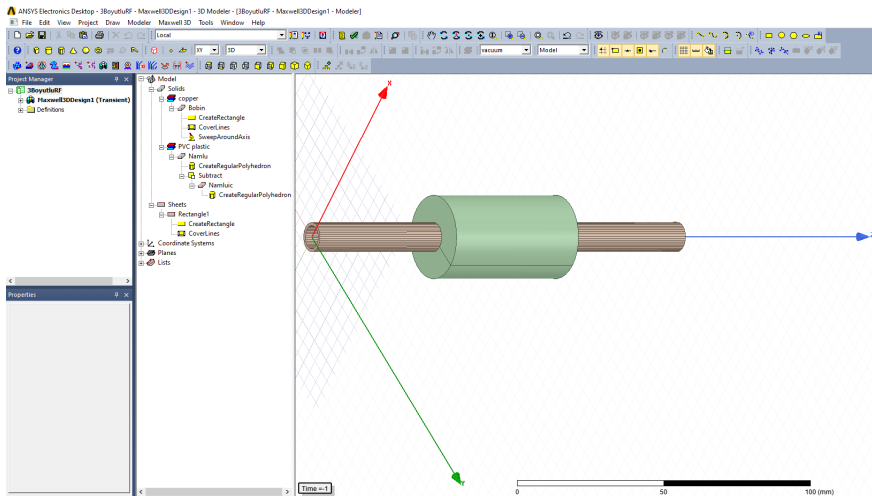


Figure 12. Steps to generate the model.

To generate the projectile, select “XY” from the “Grid Plane” section of the “Models” tab. From now on, plots will be relative to the “XY” axis. From the “Draw” tab, click “Regular Polyhedron” or click the “Draw

Regular Polyhedron” box. The starting coordinate is entered in the coordinate boxes in the lower right corner of the program screen, the radius coordinate of the projectile is entered, and the projectile length coordinate is entered. The Enter key is pressed each time. Segment number is entered. Click on “RegularPolyhedron1” in the “Model” section, change its name in the “Properties” section, and in this study it is entered as “Projectile”. Material is changed in the “Properties” section, “vacuum” is selected by default. A desired ferromagnetic material is selected from the “Edit” section, “steel_1010” is selected here. If desired, the color of the projectile can be changed by selecting a desired color from the “Color” section in the “Properties” section.

To excite the coil, select “Rectangle1” in the “Model” section we generated previously. Then click on “Excitations” from the “Maxwell 3D” tab, then click on “Coil Terminal” from the “Assign” section. The number of coil windings is entered in the “Number of Conductors” section in the window that opens. Right-click on “Excitations” among the project items in the “Project Manager” section and click on “Add Winding” from the menu that opens. In the sections in the window that opens, how the coil will be excited (Voltage, Current), starting current, the value of the voltage to be applied, the resistance and inductance values of the coil are entered. Right-click “Winding1” in the “Project Manager” section and click “Add Terminals” from the menu that opens. Select “Coil Terminal” in the opened box. Thus, the excitation of the coil is completed.

To generate the section where the projectile will move inside the barrel, click “Regular Polyhedron” from the “Draw” tab or click the “Draw Regular Polyhedron” box. The starting coordinate is entered in the coordinate boxes in the lower right corner of the program screen, the movement section radius coordinate is entered, and the movement section length coordinate is entered. The Enter key is pressed each time. Segment number is entered. Click on “RegularPolyhedron1” in the “Model” section, change its name in the “Properties” section, and in this study it is entered as “Band”. Material is changed in the “Properties” section, “vacuum” is selected by default. “air” is selected in the “Edit” section because the projectile will move in the air in the pipe. If desired, the color of the projectile can be changed by selecting a desired color from the “Color” section in the “Properties” section. The model obtained with what has been done so far is shown in Figure 13.

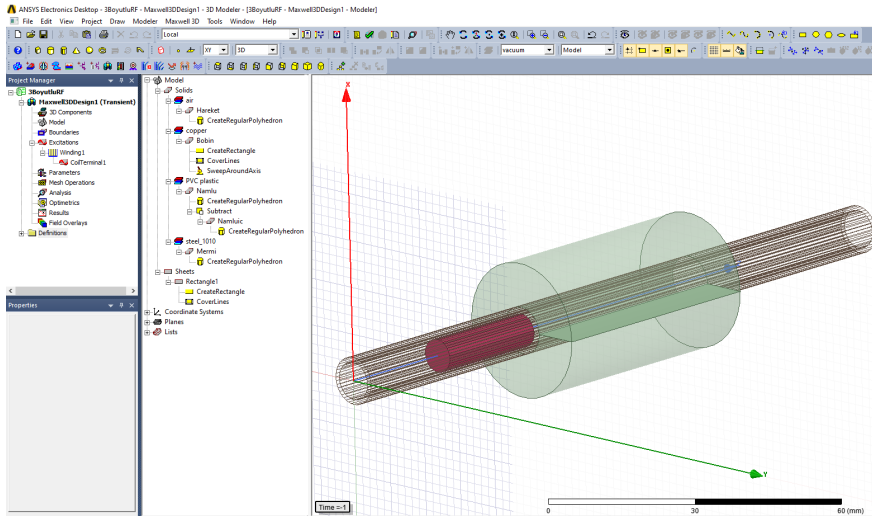


Figure 13. Steps to generate the model.

While “Band” is selected in the “Model” section, right-click on “Model” in the “Project Manager” section, click “Motion Setup” from the menu that opens, then click “Assign Band”. In the “Positive” section of the “Data” tab of the window that opens, the length that the projectile will travel in the barrel is entered. Click “Consider Mechanical Transient” in the “Mechanical” tab, enter the weight of the projectile in the “Mass” section. The program can calculate the weight of the projectile. If desired, the weight of the projectile can be calculated by clicking “Calculate”.

“Coil” is selected from the “Model” section, then “Mesh Operations”, “Assign, Inside Selection” and “Length Based” are clicked on the “Maxwell 3D” tab. In the window that opens, uncheck “Set maximum element length” and tick “Maximum number of additional elements” and write the desired value in front of it.

Select “Projectile” from the “Model” section, then click on “Mesh Operations”, “Assign, Inside Selection” and “Length Based” from the “Maxwell 3D” tab. In the window that opens, uncheck “Set maximum element length” and tick “Maximum number of additional elements” and write the desired value in front of it.

To define the area to be analyzed, click “Box” on the “Draw” tab and enter the analysis boundaries in the coordinate section at the bottom right.

From the “Maxwell 3D” tab, click “Analysis Setup” and then “Add Solution Setup”. The simulation time is entered in the “Stop time” section in the “General” tab of the opened window, and the simulation step time is entered in the “Time step” section. After entering the simulation time in

the “Stop” section of the “Save Fields” tab and the simulation step time in the “Step Size” section, click the “Add to List” button.

To add eddy current loss to the model, click “Excitations” and then “Set Eddy Effects” from the “Maxwell 3D” tab. “Coil” and “Projectile” are ticked in the window that opens. Thus, the eddy current loss in the coil and projectile is added to the model.

From the “Maxwell 3D” tab, click “Validation Check”. All those listed on the right should have a green check mark at the beginning. There are errors in the parts without green markings and these should be corrected. From the “Maxwell 3D” tab, click “Analyze All”. The program simulation runs. Figure 14 shows the final view of the model.

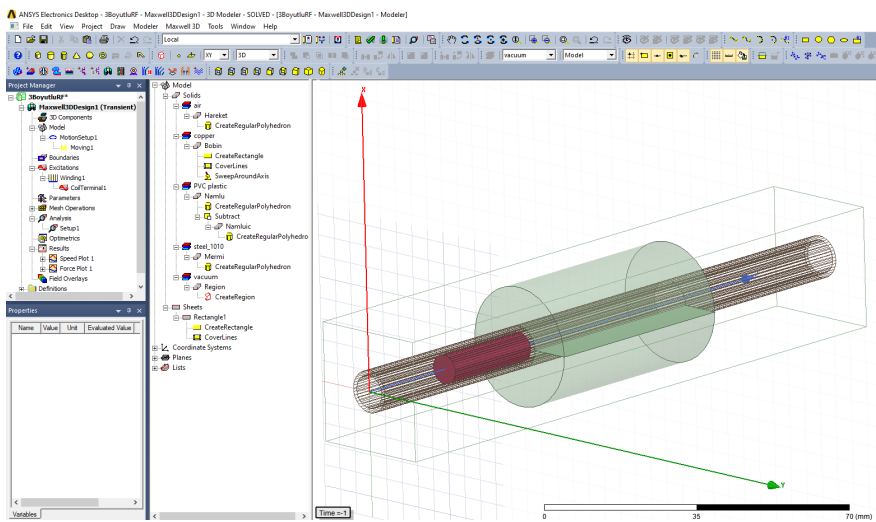


Figure 14. Final version of the model.

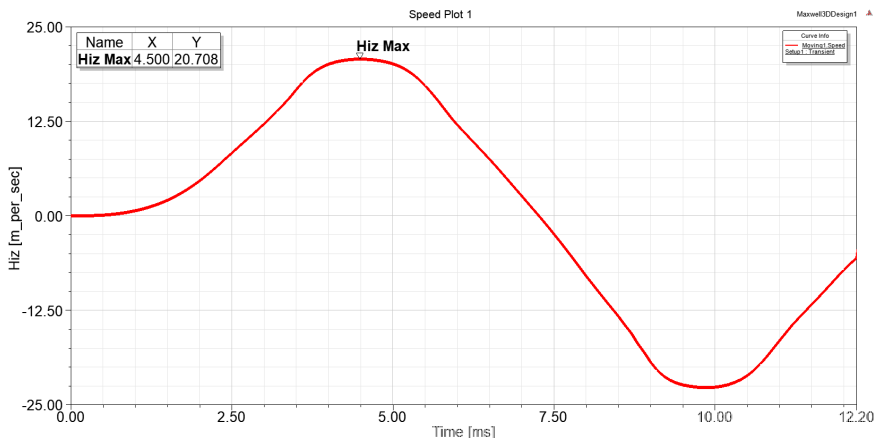


Figure 15. *Projectile velocity change.*

From the “Maxwell 3D” tab, click “Results”, “Create Transient Report”, “Rectangular Plot”. A graph can be drawn by selecting the parameter whose graph you want to draw in the window that opens. For example, for projectile velocity, “Speed” is selected in the “Category” section, and if “New Report” is clicked, the projectile velocity graph screen over time opens. If you want to draw a graph of the force applied to the projectile, click “Results”, “Create Transient Report”, “Rectangular Plot” from the “Maxwell 3D” tab. If “Force” is selected from the “Category” section in the opened window, “Moving1.Force_z” is selected from the “Quantity” section and “New Report” is clicked, a graph of the force applied to the projectile on the Z axis is drawn according to time.

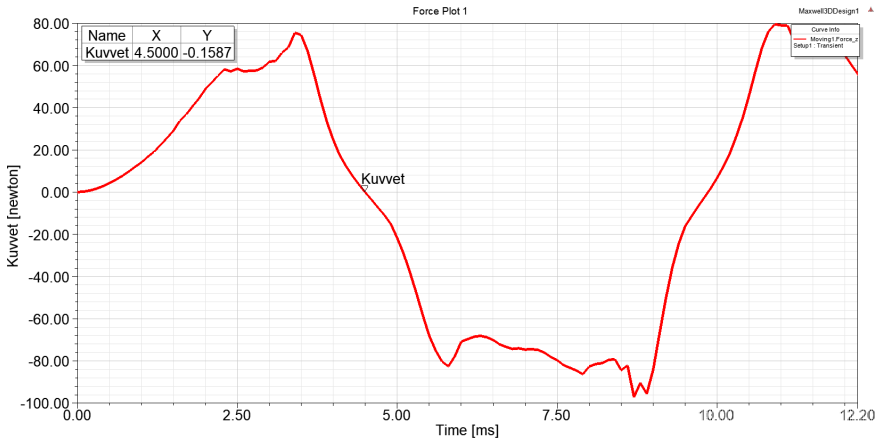


Figure 16. *Change of force applied to the projectile.*

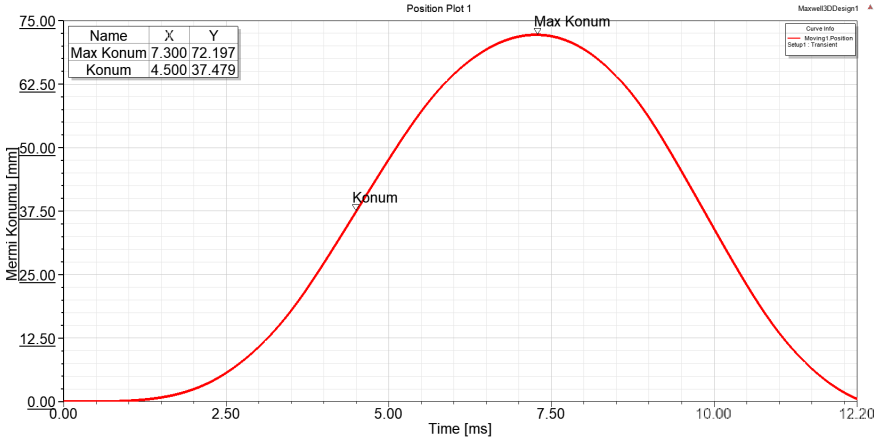


Figure 17. *Change of the projectile position.*

Figure 15 shows the projectile velocity change graph, Figure 16 shows the change graph of the force applied to the projectile, and Figure 17 shows the change graph of the projectile position. When these graphics are examined, the projectile velocity reached its highest value in the 4.5th millisecond with 20.708 m/sec. At this moment, the force applied to the coil is close to zero and the position of the projectile is very close to the middle of the coil, at 37.479 mm (37.5 mm is in the middle of the coil). At the 4.5th millisecond, the energy applied to the coil must be cut off and the energy in the coil must be absorbed, otherwise the projectile 's muzzle velocity will decrease as the projectile will be pulled back to the middle of the coil. As shown in Figure 16, if the energy applied to the coil is not cut off within 4.5 milliseconds, a force acts in the opposite direction on the projectile and the projectile velocity decreases or even becomes negative, as shown in Figure 15. In other words, the projectile is drawn back into the middle of the coil. As shown in Figure 17, the projectile reaches its furthest position at 72.197 mm in 7.3 milliseconds, and from this point onwards its position decreases, that is, it is drawn back into the coil.

The Maxwell program solves the problem by dividing the system into small pieces according to finite element analysis. To see the launcher divided into small pieces, select the relevant part of the launcher, right-click on "Fields Overlays" in the "Project Manager" section, and click on "Plot Mesh" from the menu that opens. Figure 18 and Figure 19 show the launcher divided into small parts.

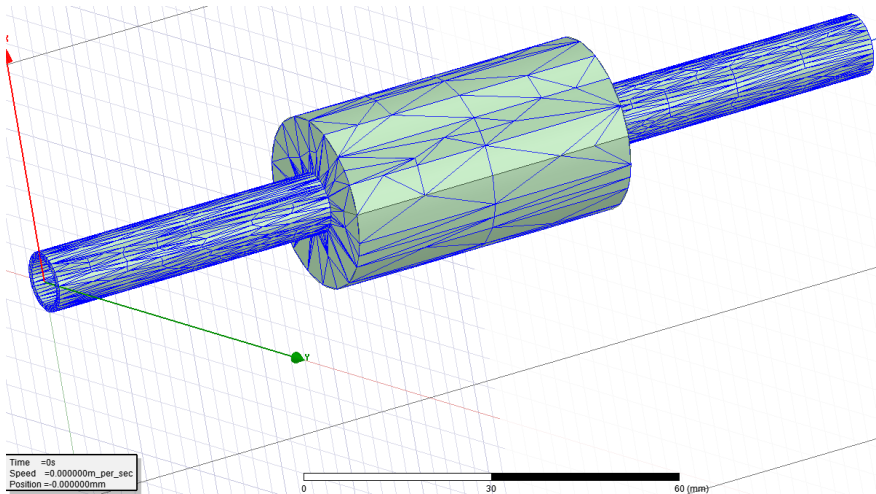


Figure 18. Division of the barrel and coil into small areas according to the finite element method.

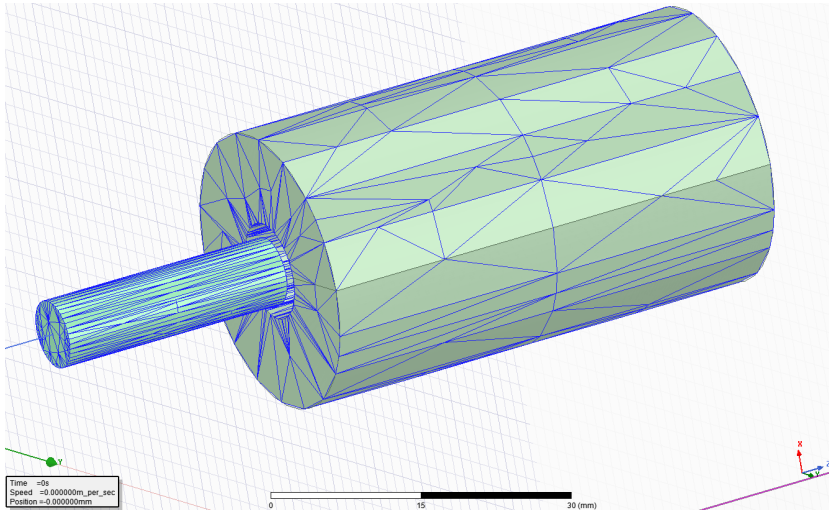


Figure 19. Division of the projectile and coil into small areas according to the finite element method.

The magnetic field examination of the launcher can also be done with the Maxwell program. To do this, right-click on “Field Overlays” in the “Project Manager” section while the part of the launcher that you want to examine is selected or all its components are selected. From the menu that opens, click “Fields”, “B”, “Mag_B”. The time to be examined in the simulation is selected. Figure 20 shows the magnetic field at 1 msec. With the colored scaling on the top left, you can see how much magnetic field is in which part of the launcher. As shown in Figure 20, the magnetic field in the coil is around 0.5 T - 1 T. Figure 21 shows the magnetic field at 4.5 ms. Here the projectile is in the middle of the coil.

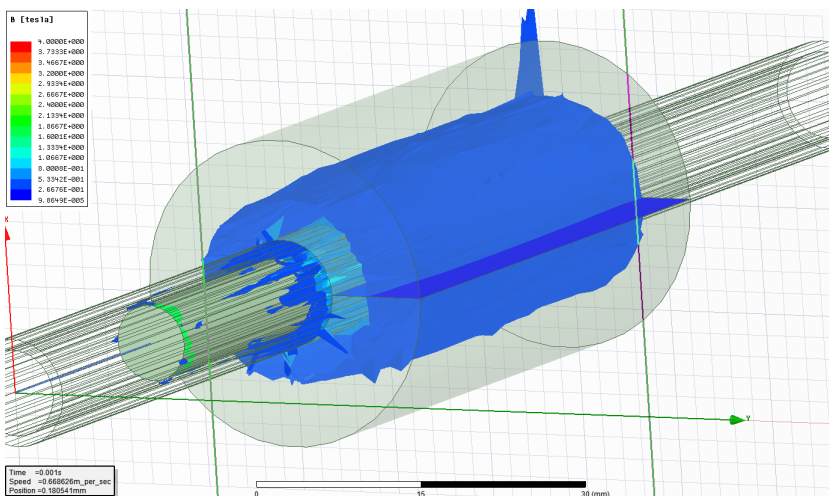


Figure 20. Magnetic field of the launcher at 1 ms.

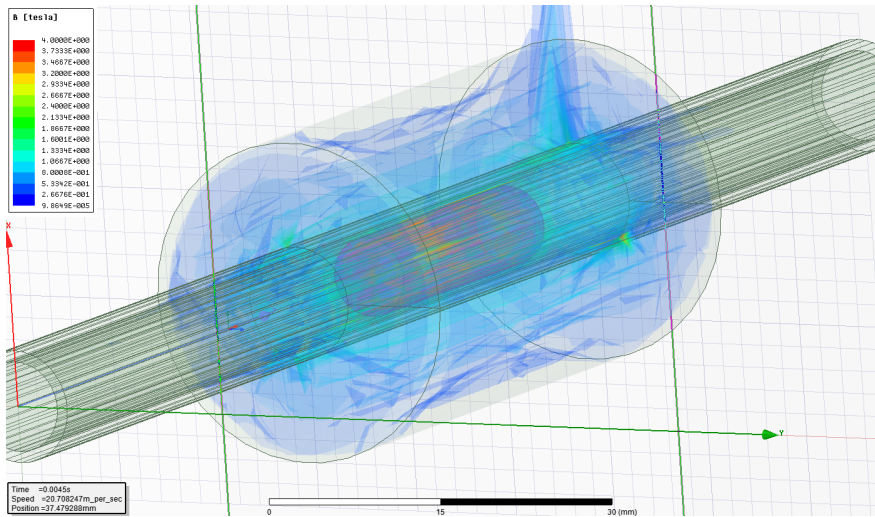


Figure 21. *Magnetic field of the launcher at 4.5 ms.*

4. CONCLUSION

In this study, a 3D model of a REL was generated and the effect of launcher parameters on projectile velocity was examined. At the end of the investigations, it was seen that a launcher with a higher velocity could be obtained by changing the launcher parameters. Choosing the correct parameters of EML is important in terms of projectile velocity and efficiency of the system. If chosen incorrectly, the muzzle velocity of the launcher and the efficiency of the system will decrease.

Optimization studies can be carried out by changing the launcher parameters to increase the launcher's projectile velocity. In previous studies (Daldaban and Sari, 2014) (Daldaban and Sari, 2015) (Sari and Daldaban, 2019), it was examined how projectile material and shape affect projectile speed. It is possible to increase the projectile velocity by changing other parameters. These parameters; It may be the inner and outer diameter of the barrel, the length of the coil, the number of windings, the thickness of the coil wire, and the diameter of the coil. By changing these parameters, optimization can be made without building the launcher, thus saving time and cost can be achieved by determining the parameters of the launcher with the highest velocity.

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