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Research Article

Numerical Analysis of an Electromagnetic Plunger

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Abstract

A linear electromagnetic plunger device generates linear force in the direction of the motion of the plunger. One of the essential components of the system is the core. The core is winded by conductor wires and the wires are energized by a power source. In this way the core windings produce magnetic flux by the help of the currents carried through the conductor wires. The generated magnetic flux navigates through the core component to the pertinent direction. By this way the directed magnetic flux generates motion on the plunger. This mechanism has wide application fields in automotive industry and machinery especially for areas commonly requiring a controlled actuator motion. There is limited range of opportunities to illustrate physical phenomena related to electromagnetics. Particularly in electromagnetics, it is so useful to use computational methods for illustrating phenomena about electromechanical conversion calculations of force in a magnetic circuit. For this purpose, it is practical to make use of a software such as EMWorks. Via EMWorks software, force in a magnetic circuit and current density distribution can be calculated and the results of numerical results can be presented in an automated manner. The mechanism of the plunger system involves electric energy conversion into magnetic force energy. The overall workflow is nothing but an electromagnetic energy conversion. One of the essential advantages of an electromagnetic plunger is that it can easily be controlled by an electric control and the response time of the plunger system is quite applicable for industrial applications. In this study, the main goal is to obtain magnetic flux density distribution yielding a generated force. Using the force generation calculation, the decision of the magnitude of current required can be obtained. Which amount of elecrtic current will result in how much force generation on the plunger, is the aim of this study. The EMWorks simulation software is used in this study to perform the electromagnetic simulations.

Key Words: C-Shaped Core, Electromagnetic Force, Plunger.

Elektromanyetik Bir İticinin Sayısal Analizi

Öz

Doğrusal bir elektromanyetik itici cihazı, pistonun hareket yönünde doğrusal bir kuvvet üretir. Sistemin temel bileşenlerinden biri nüvedir. Nüve, iletken tellerle sarılır ve tellere bir güç kaynağı tarafından enerji verilir. Bu şekilde nüvedeki sargılar, iletken teller aracılığıyla taşınan akımlar yardımıyla manyetik akı üretir. Üretilen manyetik akı, nüve bileşeni boyunca ilgili yöne doğru ilerler. Bu şekilde yönlendirilmiş manyetik akı, piston üzerinde hareket üretir. Bu mekanizma, otomotiv endüstrisinde ve özellikle kontrollü bir tahrik hareketi gerektiren alanlar için makinelerde geniş uygulama alanlarına sahiptir. Elektromanyetik ile ilgili fiziksel olayları açıklamak için sınırlı sayıda fırsat vardır. Özellikle elektromanyetikte, manyetik bir devrede elektromekanik dönüşüm hesaplamaları hakkındaki olguyu açıklamak için hesaplama yöntemlerini kullanmak çok faydalıdır. Bu amaçla EMWorks gibi yazılımlardan yararlanmak pratiktir. EMWorks yazılımı aracılığıyla, bir manyetik devredeki kuvvet ve akım yoğunluğu dağılımı hesaplanabilir ve sayısal sonuçların sonuçları otomatik bir şekilde sunulabilir. Pistonlu sistemin mekanizması, elektrik enerjisinin manyetik kuvvet enerjisine dönüştürülmesini içerir. Genel iş akışı, basitçe bir elektromanyetik enerji dönüşümüdür. Elektromanyetik bir pistonun temel avantajlarından biri, bir elektrik kontrolüyle kolayca kontrol edilebilmesi ve piston sisteminin tepki süresinin endüstriyel uygulamalar için oldukça uygulanabilir olmasıdır. Bu çalışmada, temel amaç, istenen kuvveti üretebilen manyetik akı yoğunluğu dağılımını elde etmektir. Kuvvet üretimi hesaplamaları kullanılarak, gerekli akımın büyüklüğüne karar verilebilir. Bu çalışmanın amacı, piston üzerinde istenen kuvvet oluşumuna neden olacak elektrik akımının hesaplamaktır. EMWorks simülasyon yazılımı yardımıyla bu çalışmada elektromanyetik simülasyonları gerçekleştirilmiştir.

Key Words: C-tipi Nüve, Elekromanyetik Kuvvet, Elekromanyetik İtici.

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1. Introduction

An electromagnetic plunger system consists of a core segment with wire winding, electrical power source and a plunger (Song & Lee, 2015). The system is a type of linear actuators, in fact generally called linear solenoid actuators. These actuator types are so widely used and mostly known since this century (Boldea & Nasar, 1999). Among the elecromagnetic appliances, development of the electromagnetic linear actuators gave rise to its research and development field, which resulted in a product with more fast response (Theobald et al, 1994). The need to control the motion linearly required more and more electronical control technologies, and after 1960, this need was met by the development of power electronics, the historical evolving of the linear electromagnetic devices is provided in the literature. The linear actuators are namely used in; automatic kitchen appliances, door locks, electrical switching, energy harvesting applications using back and forth motion and etc. The superior features of these versatile devices are because they do no cost much, consume little energy, bring ease at tracking the position (Boldea et al, 2017; Guckel et al, 1996). A generic layout view of these devices is shown on figure 1.

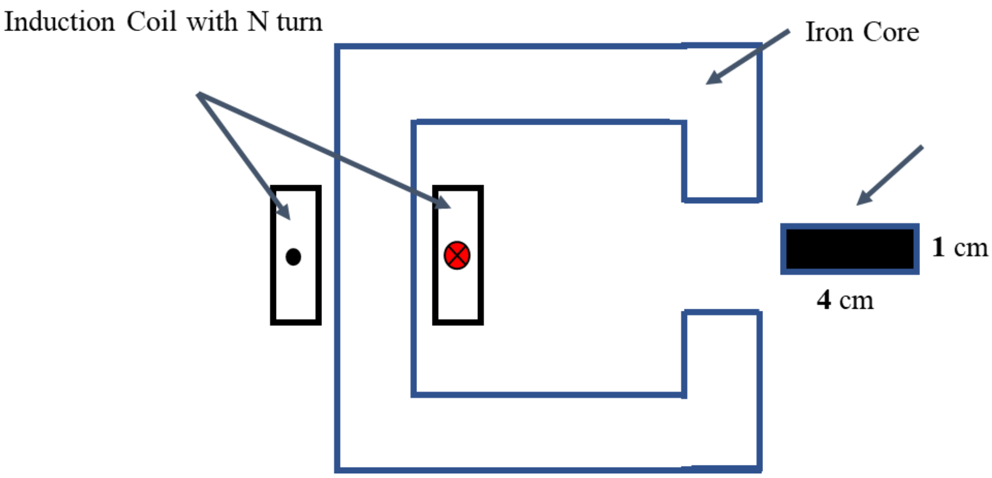


Figure 1. A generic type of linear actuator

While the actuator system throws off the plunger an abrupt back attracting move follows. This back move is damped by an absorber system, which provides a stable performance for the plunging action. This complex series of motions are numerically very complicated to solve, due to the sequential moves of actuator and plunger system resulting in magnetic energy storage (Nogueira, Analysis of magnetic force production in slider actuators combining analytical and finite element methods, 2011). The net force attracting the plunger stems from the leakage magnetic field. The effective action takes place in horizontal direction initailly, because the vertical components of the magnetic forces cancels each other.

For the system to perform efficiently the wires have to be highly conductive for electrical losses reasons, however this results in joule heating on the conductors. This brings an optimization problem due to the waste heat.

In this study, the purpose is to model a electromagnetic plunger system with a C-Shaped core and determine the coil current to generate force on the plunger using 2-D elecrtromagnetic simulation. Since the electromagnetic simulation was 2-D, the geometric model generated in two dimensions, and geometric modelling is done in SOLİDWORKS CAD (computer aided design) environment. The simulation software is is add-in type and compatible with SOLİDWORKS. The force calculation was done by using virtual work method. The flux density, force and work calculation were done by changing the relative posion of the plunger by incrementing the displacement in the CAD software environment.

2. Material and Method

In this section, the parameters, the physics and model used in the simulation is given. The finite element model and mesh settings is illustrated.

2.1. Physics and Model

The geometry was meshed with tetradhedral elements within the range varying from 1.1 mm to 7.55 mm. The regions where the flux is changing rapidly, relatively finer meshes were preffered. This was due to make the calculation to capture the rapid changing magnetic flux details. The air gap region and the ccoil domain require finer mesh for the aforementioned reason. The generated mesh is Shown in figure 2.

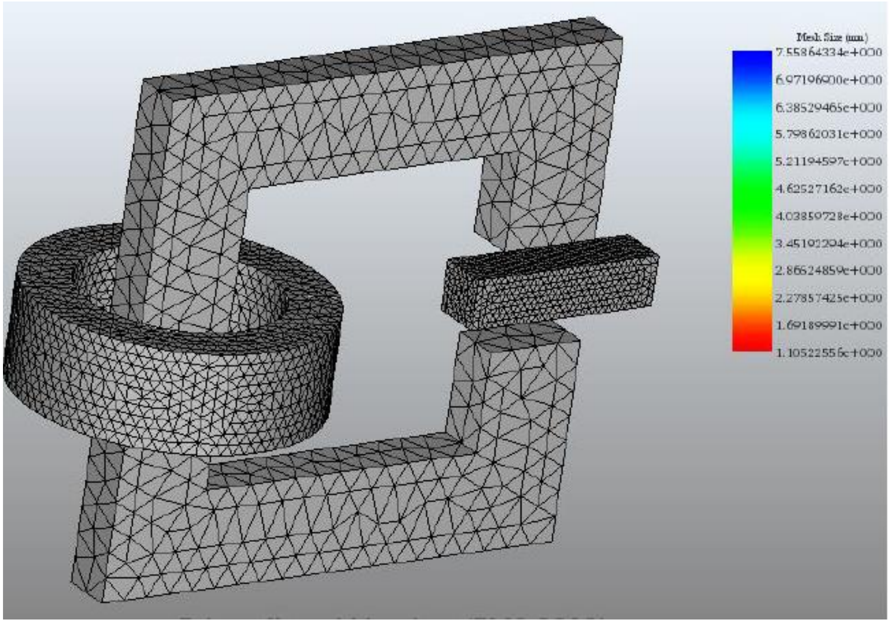


Figure 2. Mesh generation

The magnetic circuit has a moving part (plunger), a stationary part C-shaped core and an excitation coil. The plunger is made of cast iron and its cross-section area is 100 mm^2 . The C-shaped core material is cast iron and the air gap distance is 20 mm.

Table 1. Tme material properties in the simulation setup

Material	**Conductivity [Mho/m]**	**Relative permeability**
Copper Windings	*57 x10⁶*	*1*
C-Shaped Core	*1.1 x10⁶*	*1000*
Air	*0*	*1*

The excitation coil is driven by 3.2 Ampere. The coil is defined as wound coil and its entry and exit port faces are set on the plane of symmetry. The 3D view or the components and the geometric model dimensions are shown in figure 3.

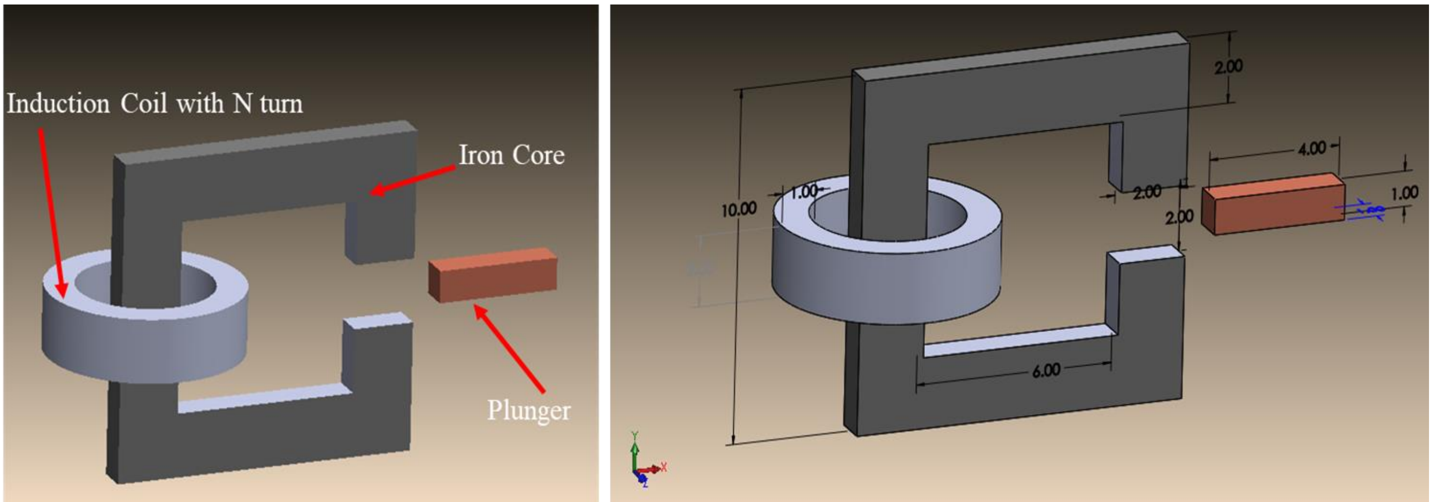


Figure 3. 3D view of the linear actuator system geometry

To make the force calculations there are 3 methods widely known; Maxwell stress tensor, weighted Maxwell stress tensor and work method. The weighted Maxwell stress tensor method is recognized as very robust calculation method and its mathematical desciption is found in the literature (McFee et al, 1988; Nogueira, Computation of forces using mean and difference potentials, 2009) However, since this method requires quite computaional power and takes relatively long time calculations, in this work the virtual work method is preffered. In the virtual work method, there is an approximation that assumes magnetic field changes linearly and system's coenergy is taken as magnetic energy stored in the system (Benhama et al, 2000; Melkebeek & Vandevelde , 2001).

In the finite element model, material properties were assumed linear. The force calculations, the location of the plunger selected with several increments in the x-direction from its initial position and the analyses were run sequentially. The force, magnetic flux and energy results are given in the research and results section.

3. Research Results and Discussiom

In this section, each type of resuts are given in the related section. The magnetic flux results are in section 3.1 and the energy and force results are provided in section 3.2.

3.1. Results of Magnetic Flux Density

The force simulations were performed consecutively by varying the values of plunger distance from the outer edge of core body ranging from -30 mm to +30 mm with several increments. To capture the force profile, the more the number of instances is simulated, the more accurate the outcome of the force estimation will be. Solidworks geometric model of the circuit were created accordingly.

The magnetic flux Density contours are shown in figure 4.

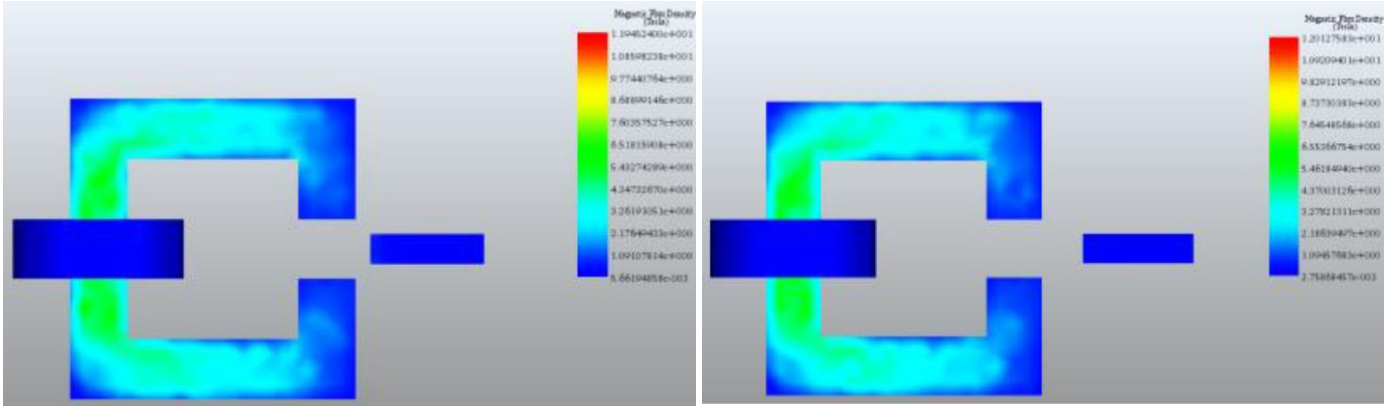


Figure 4. Magnetic Flux Density (Tesla) Plunger positions: 5 mm & 15 mm

The geometric model of the circuit was parametrized relating the plunger position, and simulated again. The subsequent results are shown in figure 5.

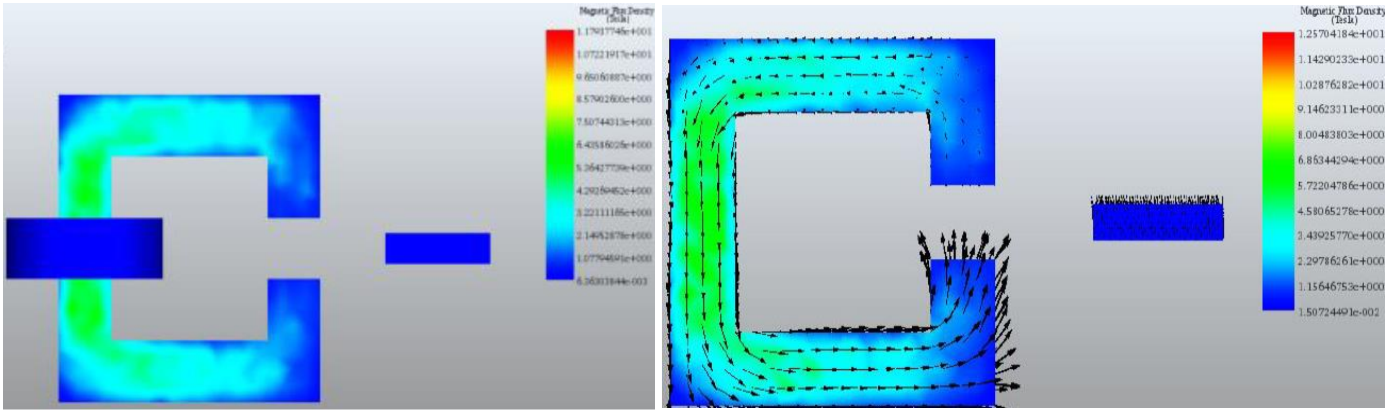


Figure 5. Magnetic Flux Density (Tesla) Plunger positions: 25 mm & 30 mm

For the subsequent case, the opposite positions (with respect to the front edge of the core window) were simulated. The geometric model of the circuit was parametrized with opposite plunger positions, and simulated again. The subsequent results are shown in figure 6.

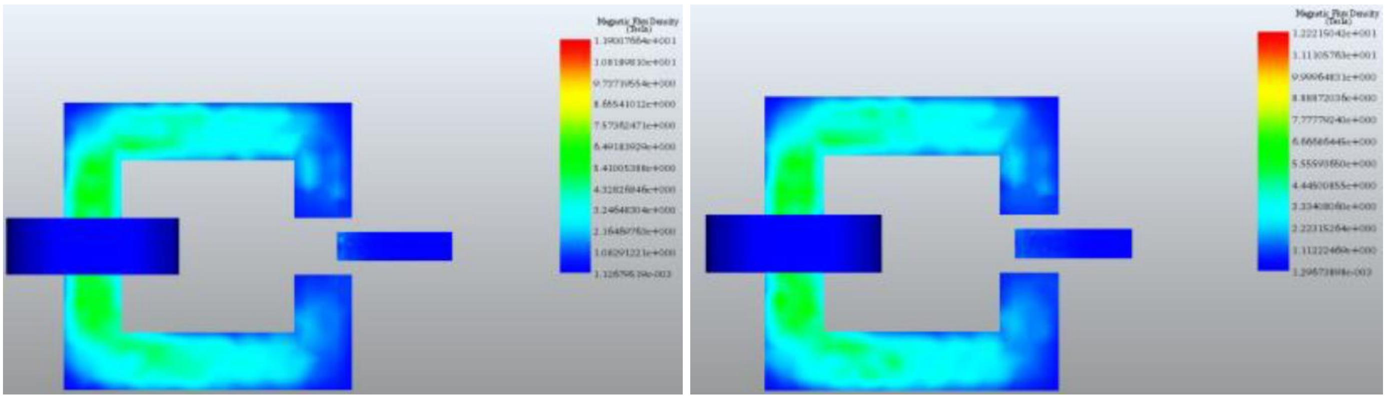


Figure 6. Magnetic Flux Density (Tesla) Plunger positions: -5 mm & -15 mm

For the last case, the opposite position with 30 mm distance was simulated. The geometric model of the circuit was parametrized with opposite plunger position, and simulated. The subsequent results are shown in figure 7.

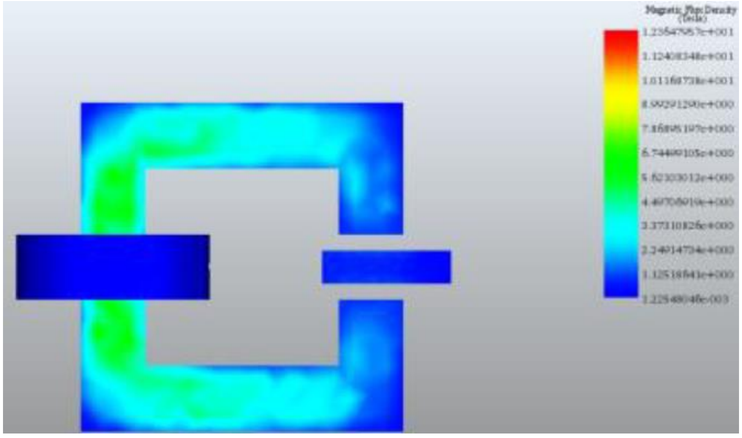
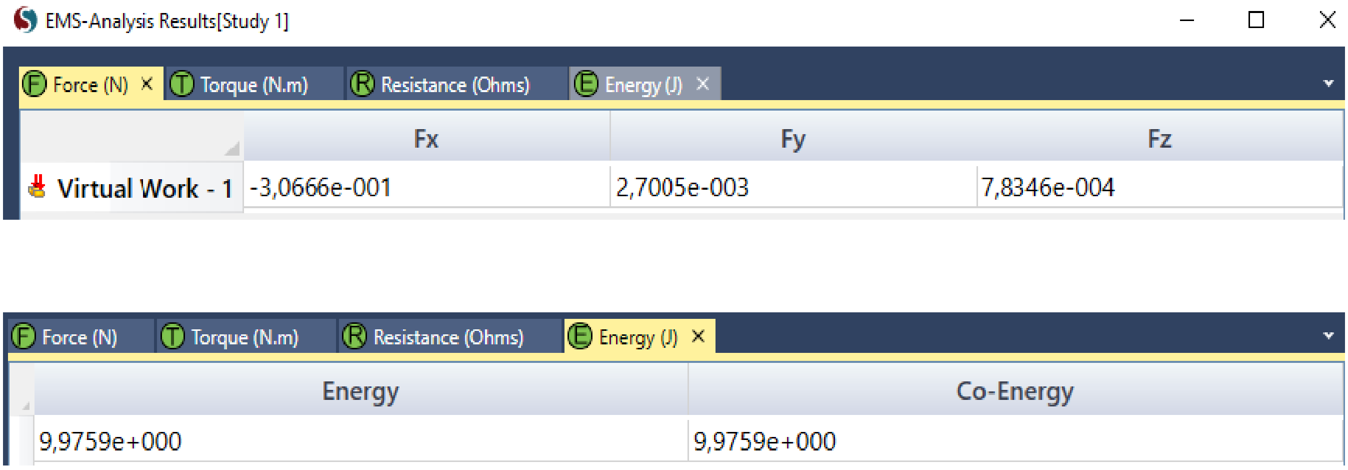


Figure 7. Magnetic Flux Density (Tesla) Plunger position: -30mm

From +30 mm position of the plunger to its final position, the core initially started to attract the plunger, however, when the plunger arrived at its final position it was attracted back to the direction of its initial location. This motion of the plunger is referred as oscillatory motion and the main advantage of this type of motion is mantaining a repeated motion. The excitation coil was driven by current of magnitude 3.2 Ampere. This amount of ampere is easily accessed by a current generator. Requiring this little amount of current is a big advantage fort his kind of devices especially for the sake of energy consumption. The weight of the device strongly dependant on the power consumption and hence the power supply, especially if the device is designed for handheld purpose.

3.2. Results of Force and Energy

The force calculation was made at the position of 30 mm, and the corresponding co-energy was calculated at the same location. The intended final distance of the plunger was estimated in the above procedure. The force and coenergy results are shown in figure 8.



EMS-Analysis Results[Study 1]

Force (N) | Torque (N.m) | Resistance (Ohms) | Energy (J)

	Fx	Fy	Fz
Virtual Work - 1	-3,0666e-001	2,7005e-003	7,8346e-004

Force (N) | Torque (N.m) | Resistance (Ohms) | Energy (J)

Energy	Co-Energy
9,9759e+000	9,9759e+000

Figure 8. Magnetic Flux Density (Tesla) & Energy, Plunger position: -30mm

The EMWorks simulations were done using virtual work method. This method was performed in magnetostatic type analysis. The results were rapidly obtained by the help of the method. The EMWorks simulation programme calculated the force generation as 1,2413 N. The numerical value of the force is negative because of the direction of the motion. The direction of the force is towards the core and so is the direction of the motion.

4. Conclusion

For force calculation, virtual work method is selected for computational cost reasons. The method requires multiple simulations at various positions of the plunger to obtain a force profile. By obtaining the sequencial force results, the force vs position graph can be plotted and the average can be calculated.

In the sequential simulations, it can be interpretted that the c-shaped core attracts the plunger and the plunger slides towards the actuator window. By the help of the electromagnetic simulation software, the movement of the plunger can be demonstrated and one can give plausible decisions related to the problem spesifications. The excitation coil was driven by 3.2 Ampere and the force output was obtained.

Making use of virtual work method EMWorks results gave force calculations as 1,2413 N in –x direction. It is also possible to obtain the force result by using

Virtual Work Difference = Average_Force * Distance

Thanks to the electromagnetic simulation software that enables having an illustration of phemnomena of electromechanical energy conversion with calculation results of force in a magnetic circuit. It is concluded that the software is useful for illustration of electromagnetic phenomena not only in related physics lectures but also electromagnetic engineering problems.

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