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Proceeding Paper

Analytical, Numerical, and Experimental Analysis of Tangential Attraction and Repulsion Forces Between Parallel Magnets in an Automotive Mechanical System †

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Abstract: This study highlights the importance of magnets in the advancement of automotive technology, focusing on the forces of attraction and repulsion between two magnets in relative tangential motion. The magnets were tested using a tensile machine developed by KnoWow and adapted to measure attraction forces as a function of longitudinal and transversal distances. The data collected made it possible to create a detailed map of the interactions of the forces. To validate the experimental results, a finite element analysis (FEA) was performed. The high correspondence between the experimental and simulated data confirmed the reliability of the method, making it usable for future automotive designs requiring optimization of magnetic forces.

Keywords: automotive; magnet; neodymium; tangential forces of attraction

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1. Introduction

The use of magnets in the automotive industry revolutionized numerous aspects of vehicle design and functionality. This study addresses the determination of the forces of attraction and repulsion between two magnets in relative tangential motion.

In the automotive field, there are many examples of the use of magnets; below, we report some of them.

The first case we want to report is the one described in [1] on a magnetic brake system. The system described in the article exploits the principle of eddy currents. These currents are generated when a changing magnetic field passes through a conductive material, inducing currents that generate a force opposing the movement. In the case of the magnetic brake, the eddy current induced in a conductive material creates a force that slows the vehicle without any physical contact between the parts. The most innovative aspects of this system are the absence of wear and the non-sensitivity to temperature variations. A common problem in traditional brakes is that they can overheat during heavy use and lose efficiency.

Another application based on magnetic forces in the automotive field is described in [2,3], which talks about magnetic transmissions. Magnetic gears work by using the

principle of magnetic forces to transfer torque between two axes, completely eliminating physical contact between components.

Magnetic gears use permanent magnets arranged on two concentric rotors. When one of the rotors is set in motion, the generated magnetic field interacts with the other rotor, transferring torque without direct contact. This system dramatically reduces friction and requires no lubricants, as a result, there are no losses due to friction between components. Furthermore, being more resistant to wear, they guarantee greater durability over time, reducing operating costs. Finally, there is an advantage in terms of noise.

The proposed solution involves testing the magnets using a specially equipped testing machine developed by the University of Messina's academic spinoff KnoWow. This machine, which is a static tensile and fatigue testing machine, after having adapted it to the application, allows the characterization of the attraction force between the magnets as a function of the longitudinal and transversal distances. Through these measurements, a detailed map of the exchanged forces was created as the transverse and longitudinal distances of the magnets varied.

To validate the experimental results, a finite element analysis (FEA) was also conducted. Experimental measurements and FEA simulations produced have curves that start at 0 N when the magnets are aligned, with the force rapidly increasing to a peak a few millimeters away, then decreasing and flattening to zero values. The near-perfect alignment between experimental results and simulations validated the method, confirming its reliability for future design applications.

2. Theoretical Background

The use of magnets in the automotive sector revolutionized numerous aspects of vehicle design and functionality. These components are essential in electric motors and alternators, where rare earth permanent magnets, such as neodymium, enhance efficiency and power. In regenerative braking systems, magnets enable the recovery of kinetic energy, extending the range of electric vehicles. Additionally, magnetic sensors are utilized in engine control systems and transmission management to ensure precise and reliable operation. Magnets also find applications in locking mechanisms, window lifters, and power steering systems, improving driver comfort and safety [4].

Neodymium is a metal that belongs to the lanthanide group, otherwise known by the term "rare earths", naturally present in small quantities in the soil and, indirectly, in plants. Typically, elements of this class and their compounds are widely used in industry across the board, and particularly in the chemical and magnet production fields. Neodymium is a metal by its nature characterized by a shiny and silvery appearance and is widely used in various industries thanks to its incredible characteristics. In particular, neodymium is used for the production of high-coercivity permanent magnets; indeed, magnets made from neodymium are considered to be of superior quality and, not surprisingly, are also commonly called super magnets. Their incredible strength remains unchanged even in very small dimensions and this characteristic classifies neodymium magnets as some of the best produced [5].

A neodymium magnet is a magnet made of an alloy of boron, iron, and neodymium. It is a strongly magnetic alloy. It has a silvery-white color, is fragile, and is easily damaged. There are neodymium magnets of different grades: the grade is a code that always starts with the letter N (short for neodymium) and it is followed by two digits. It indicates the product of force. Lower grades have "less attractive force", higher grades have greater strength. There are magnets on the market with grades between N24 and N55; however, grades higher than N52 are not easily available; in laboratories, the creation of N56-grade magnets has been achieved, while N64 is the theoretical limit [6].

With the significant advancement of rare earth permanent magnets (REPMs) and power electronics over the past two decades, REPM motor drives have gradually been integrated into various automotive applications. These include electric traction and propulsion, as well as various X-by-wire and other electromechanical systems. REPM traction motors for electric propulsion and REPM motor drives for electric power steering (EPS) applications, to name a few, are successful commercial examples in today's automotive market for mass production [7].

The attraction force between sets of magnets can be derived from the total magnetostatic interaction energy of the system E according to:

$$\vec{F} = -grad(E). \tag{1}$$

In the case of two cylindrical permanent magnets with a common axis by choosing the coordinate system with the z axis along the axis of the cylinders, the attractive force acts only along z and can be expressed as follows:

$$F_z = -\frac{\delta E}{\delta Z} = 2\pi\mu_0 M^2 R^3 \frac{\delta J_d}{\delta Z} \tag{2}$$

where μ_0 is the vacuum permeability and J_d the dipolar coupling integral [8]. This integral is defined in [9].

The force of attraction and repulsion between two magnets depends on the distance, the magnetic flux density, and the size of the magnets.

While both forces follow an almost inverse relationship with distance, the intensity of attraction tends to be greater than repulsion. This is especially noticeable when the magnets are very close together, making it difficult to separate them without specific equipment. The research introduces an empirical formula to calculate the magnetic force, highlighting differences in the coefficients for attraction and repulsion, which vary depending on the size and shape of the magnets [10].

There are various ways to measure magnetic forces, starting from the simplest and most basic up to complex methodologies. In [11], we see one of the simple but effective methods. In particular, to carry out the experiment, two bar magnets positioned so that the equal poles repel each other are used. The magnets are mounted on a structure that allows you to adjust the distance between them precisely. A balance is used to measure the repulsion force as a function of this distance. Thanks to this setup, data can be collected showing how the force decreases rapidly with increasing distance. The authors assume that the magnetic poles are located near the ends of the magnets and that they behave as point charges. Although this model is a simplified approximation, it allows you to effectively verify the validity of the inverse relationship between force and distance squared.

Another innovative method for measuring the magnetic force between two magnets is described in [12]. Specifically, the researchers created a device with 3D-printed parts to measure the interaction force between small neodymium permanent magnets.

The method focuses on measuring the force of attraction or repulsion as a function of the distance between the magnets, using a force sensor and control system to accurately adjust the distance. Furthermore, the device is able to record changes in magnetic force as the magnets move, and the collected data are compared with theoretical models predicting dipole–dipole interaction between the magnets.

Another approach is described in the article [13], which focuses on accurately describing the force between two identical cylindrical magnets using a closed-form analytical solution. The model assumes uniform magnetization along the length of the magnets and calculates the magnetic field exerted by one magnet on the other along their orientation axis.

To validate the analytical model, experiments were conducted with two vertically aligned neodymium iron boron magnets. The repulsive force was measured at varying separations and the experimental results closely matched the analytical predictions. However, all the tests and all the articles cited so far refer to two magnets that move axially relative to each other. What is found little or not at all in the literature is the variation in the forces of attraction and repulsion that two magnets exchange when they move away from each other in a transverse direction.

In our study, we decided to examine this case.

The experimental tests, as will be seen below, were carried out using a tensile testing machine. We chose to use this tool because it offers advantages in terms of precision. In fact, the technology with which the machine is equipped allows the force data to be acquired a very high number of times per second. Combining this with the high precision of movement, which allows the magnets to be moved away (or closer) at a very low speed, force measurements are obtained moment by moment.

3. Materials and Methods

The tests were carried out on cylindrical and neodymium magnets measuring 6 mm in height and 6 mm in diameter (Figure 1).



Figure 1. Neodymium magnets.

3.1. Experimental Tests

3.1.1. The Test Machine

The testing machine, shown in Figure 2, used for the experimental tests is the rapid testing machine (RTM), a static tensile and fatigue machine patented by KnoWow. It is equipped with a 2.5 kN load cell on the lower constraint and allows tests to be carried out with a frequency of up to 15 Hz. It is operated pneumatically, and this, together with its small size, makes it easy to handle and transportable.

It is also equipped with cameras and thermal imaging cameras that allow the application of methods such as DIC and thermography for fatigue tests.

The machine makes it possible to carry out tests on a varied range of specimens and materials, compatibly with the dimensions, and is also equipped with integrated software that guarantees rapid data processing.



Figure 2. Rapid testing machine.

3.1.2. The Supports

To adapt the testing machine, designed and built for completely different purposes, to the measurement of the forces exchanged between the magnets, it was necessary to create plastic supports that allowed the magnets to be housed, binding them and holding them in the correct position without damaging them. For this purpose, it was also necessary that the material of the supports was not magnetic, so as not to interfere with the measurements.

The supports used, created with the additive manufacturing technique, were designed and manufactured in-house and are shown in Figure 3. These allowed the desired situation to be simulated exactly.

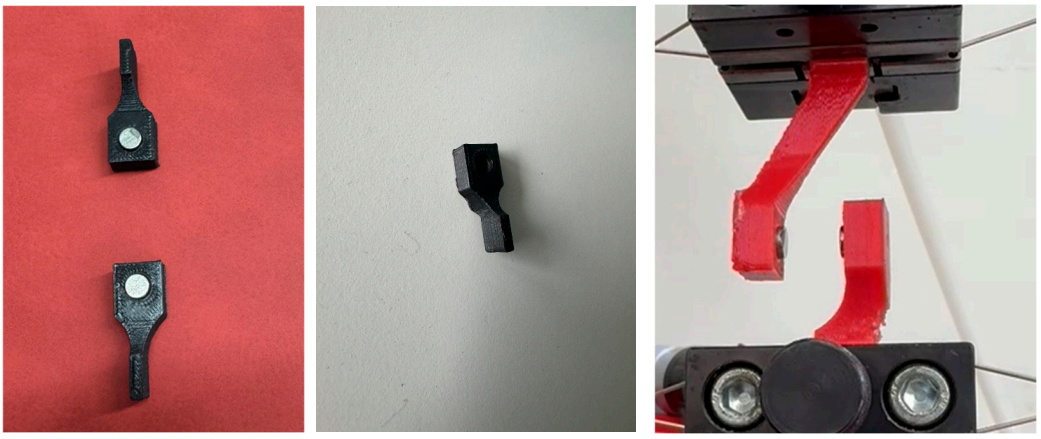


Figure 3. 3D printed supports and machine setup.

Furthermore, by varying the shape of the supports, it was possible to move the faces of the magnets further apart and carry out the same type of test. In this way, a real map was obtained which returns the value of force that the magnets exchange as a function of the longitudinal and transversal distances between the faces.

3.1.3. The Test

Six different tests were carried out by varying the distance between the faces of the magnets: this distance varied from 0 to 10 mm with 2 mm intervals. Furthermore, all six tests were carried out by changing the direction of placement of the magnet in the upper support, even in repulsion, for a total of twelve tests. Each test consisted of aligning the magnets and maintaining the exact distance between the faces, thus making them coaxial.

Subsequently, the measurement was started and the machine and the upper support, together with the magnet housed in it, were moved away in a vertical direction (perpendicular to the axis of the magnets). This occurred at a speed of 0.2 mm/s.

Once the distance between the magnets became such that the magnets certainly no longer exchanged forces with each other, approximately 50–70 mm, the test, and therefore the measurement, stopped. Figure 4 shows two photos of two different tests.

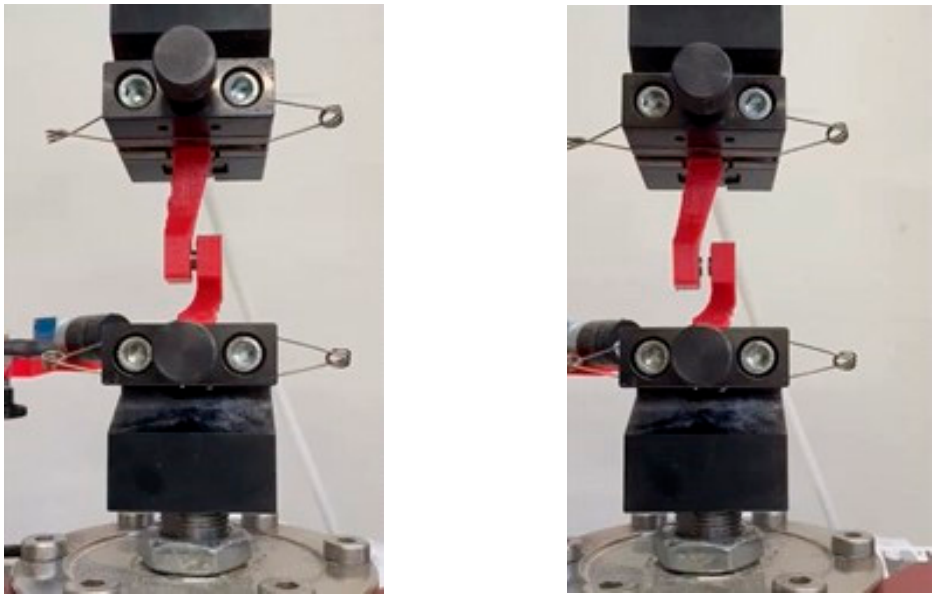


Figure 4. Experimental tests carried out.

3.2. FEA Model

To validate the experimental tests, an FE model was also created that replicated the test using the Ansys "Magnetostatic" module (Figure 5). The Ansys version is 2024R1.

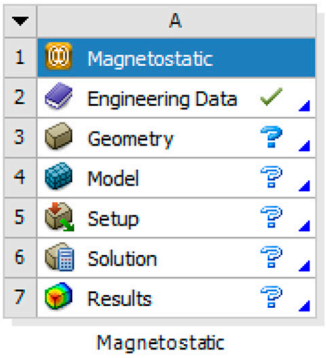


Figure 5. Ansys Workbench Magnetostatic Module.

3.2.1. CAD and Mesh

First, the CAD model of the magnets was created using the "SpaceClaim" program, parameterizing, in this model, the transversal distance between the magnets. In this way, by varying this distance, the movement of the magnets was simulated.

Furthermore, a box was created that simulated the environment in which the magnets acted.

Once the CAD was created, the components were meshed using a dense mesh for the magnets, with an element size of 0.3 mm, and a free and fairly large mesh for the environment. The number of mesh elements, including magnets and environment, was 78,492, as seen in Figure 6.

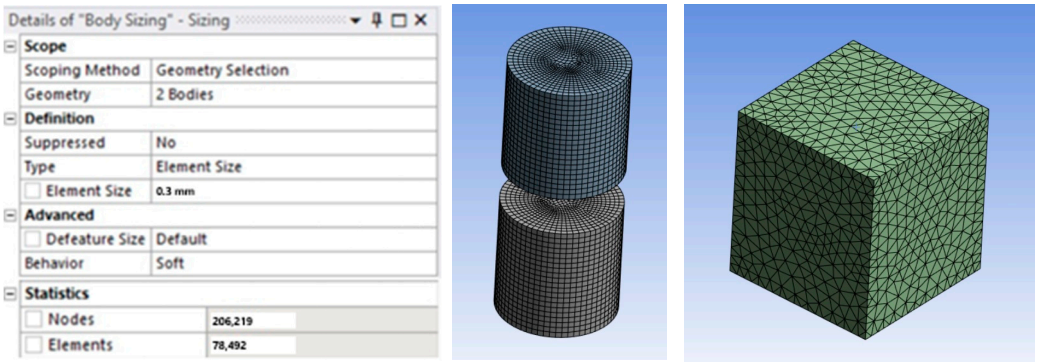


Figure 6. Details on the mesh used for FEM simulations.

3.2.2. Setting

After meshing, the boundary conditions were imposed. These consisted of the assignment of materials, both to the magnets and the environment, and the polarization of the magnets. Neodymium was assigned to the magnets, with the characteristics that belong to it, and air was assigned to the environment.

The magnets were polarized in the axial direction, and, depending on whether the test was with magnates in attraction or repulsion, the direction was the same or opposite. Figures 7 and 8 show some screenshots of the setting.

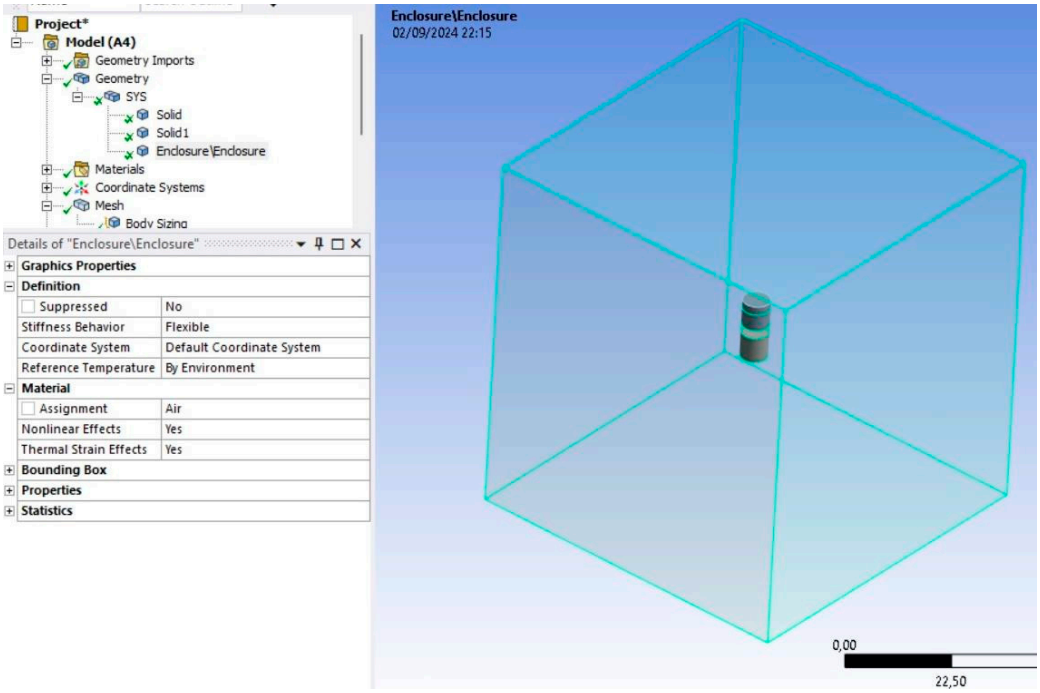


Figure 7. FEM model setting—geometry.

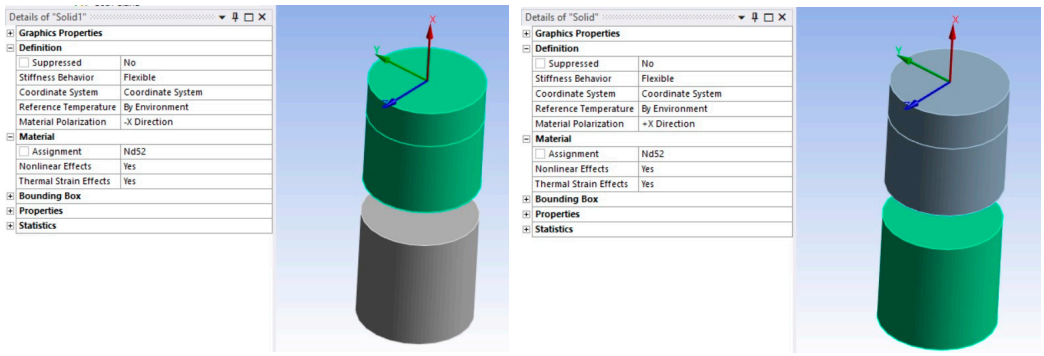


Figure 8. FEM model setting—FE characteristics.

Finally, by varying the direction of polarization and the distance between the faces of the magnets, as many simulations were carried out as there were cases taken into consideration. For each simulation, the force to which the upper magnet was subjected was evaluated as the transversal distance between the magnets varied.

4. Results

4.1. Experimental Results

In all the tests carried out, as can be seen from Figures 9–14, curves were obtained that started from the value of 0 N when the magnets were facing each other, and, as the transversal distance between the magnets grew, the force value grew rapidly, until it reached a peak a few millimeters away; subsequently the curve decreased rapidly, gradually flattening until it reached zero value.

It is also observed that starting from a distance between the faces of the magnates of 6 mm, the force exchanged between them remains approximately constant as a peak value (about 0.4 N) and can be considered negligible. The noise recorded by the machine during the measurements, in fact, could prevail over the actual force exchanged between the magnets. In the following graphs, the curve net of noise is indicated by the "net curve". The "filtered curve" was obtained with the "butter" function of MATLAB (version R2021b).

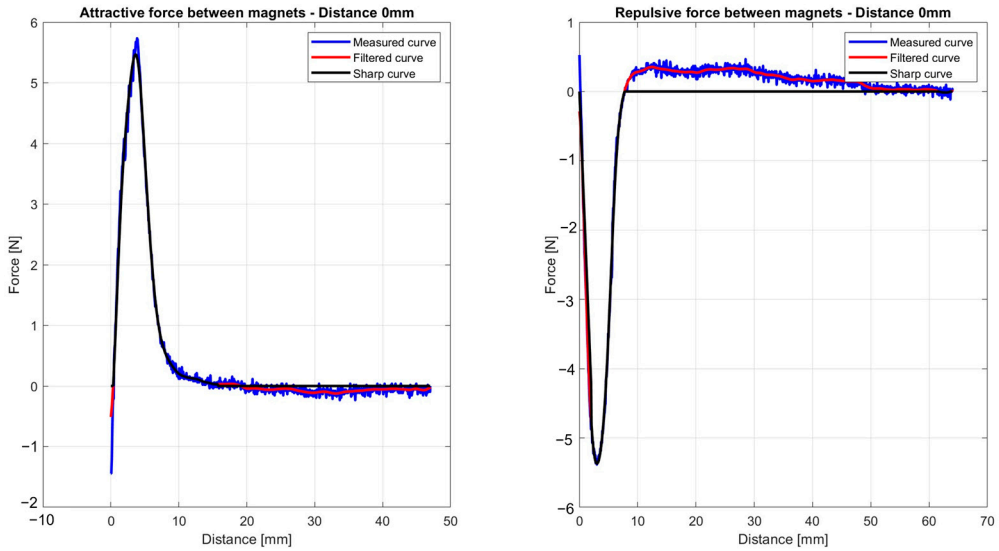


Figure 9. Results obtained experimentally—magnets with distance between faces equal to 0 mm.

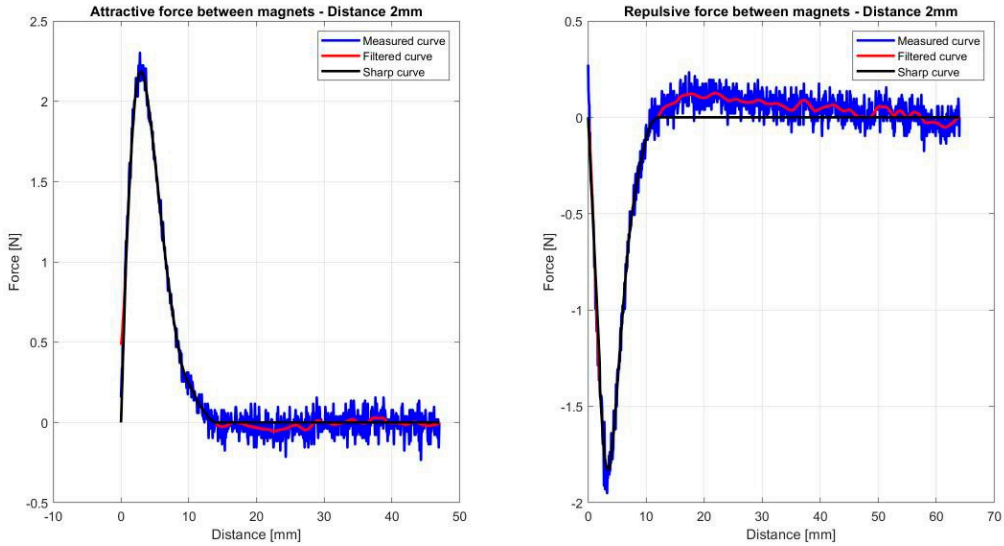


Figure 10. Results obtained experimentally—magnets with distance between faces equal to 2 mm.

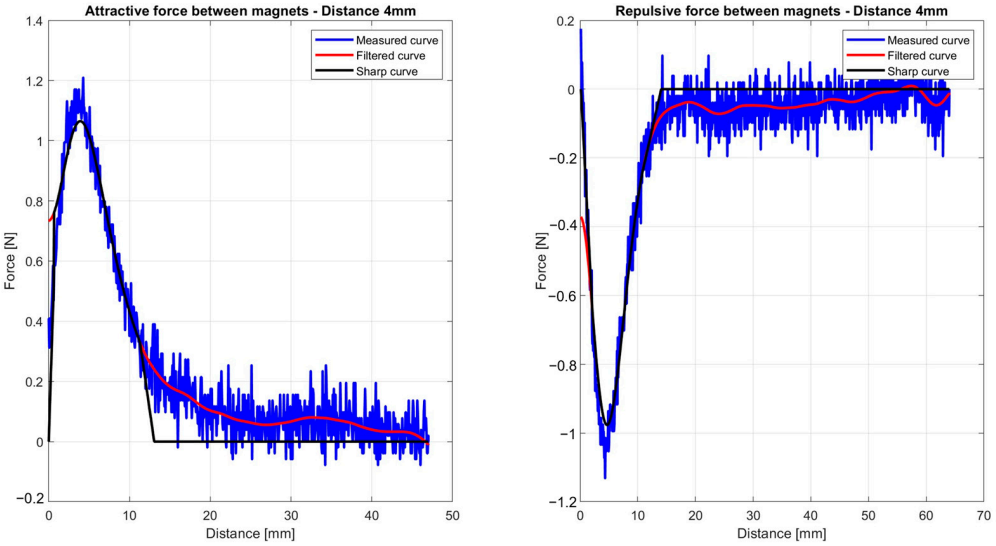


Figure 11. Results obtained experimentally—magnets with distance between faces equal to 4 mm.

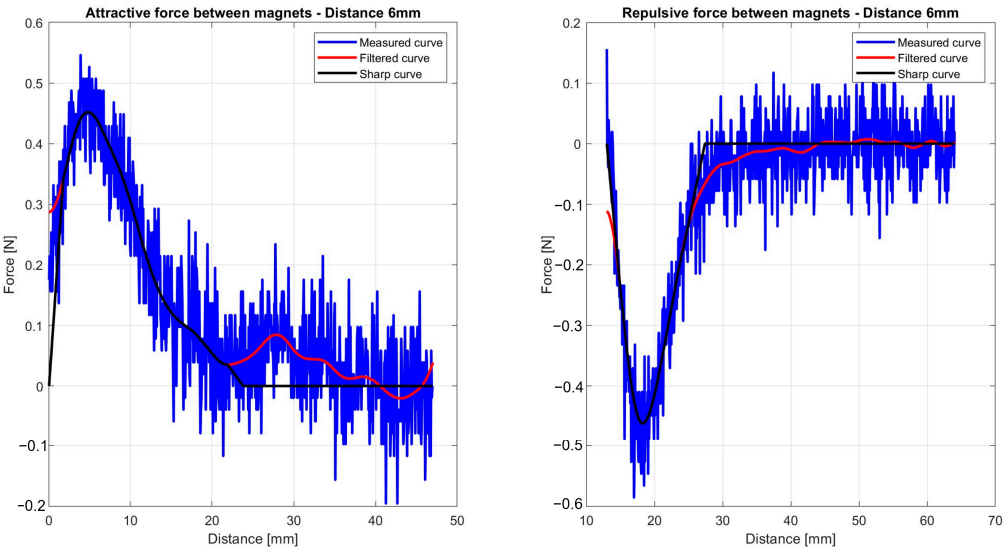


Figure 12. Results obtained experimentally—magnets with distance between faces equal to 6 mm.

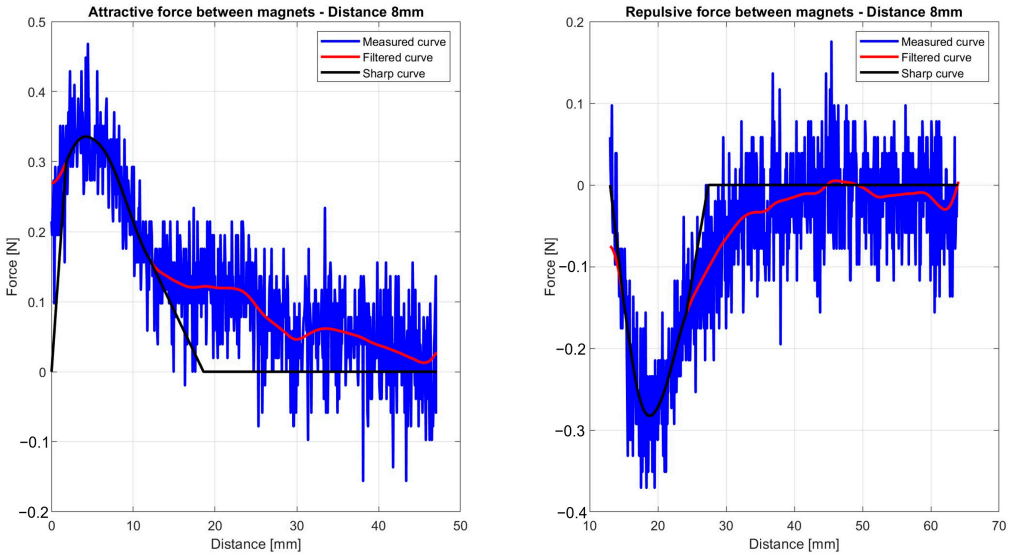


Figure 13. Results obtained experimentally—magnets with distance between faces equal to 8 mm.

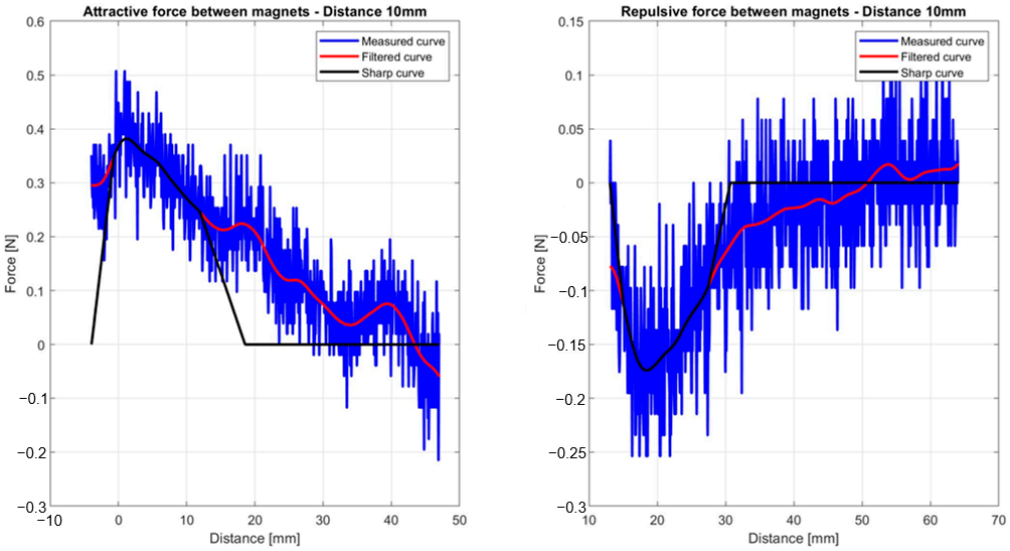


Figure 14. Results obtained experimentally—magnets with distance between faces equal to 10 mm.

4.2. FEA Results

The results obtained experimentally and those obtained via FEA simulation, reported below, coincide almost perfectly, as we can observe in Figures 15–20. It is also confirmed that, when the distances between the faces are large, the noise prevails over the actual force measured; in fact, in the case of magnets 10 mm apart, the force calculated using the FEM is much lower than the force measured experimentally.

In Figure 21, it is possible to see a comparison between the peak (maximum) forces, for the various tests carried out by varying the distance between the faces of the magnets, obtained with the two different methods.

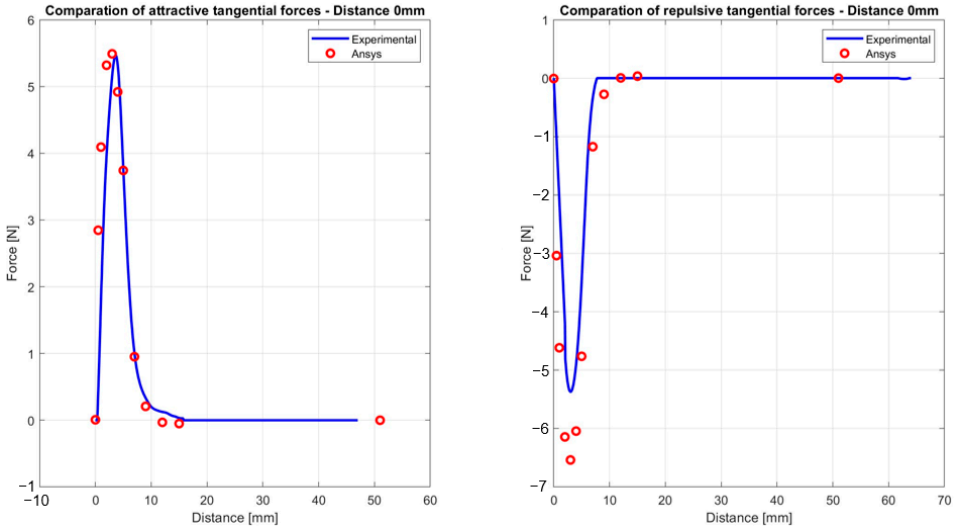


Figure 15. Comparison of results obtained experimentally and FEM magnets with a distance between faces equal to 0 mm.

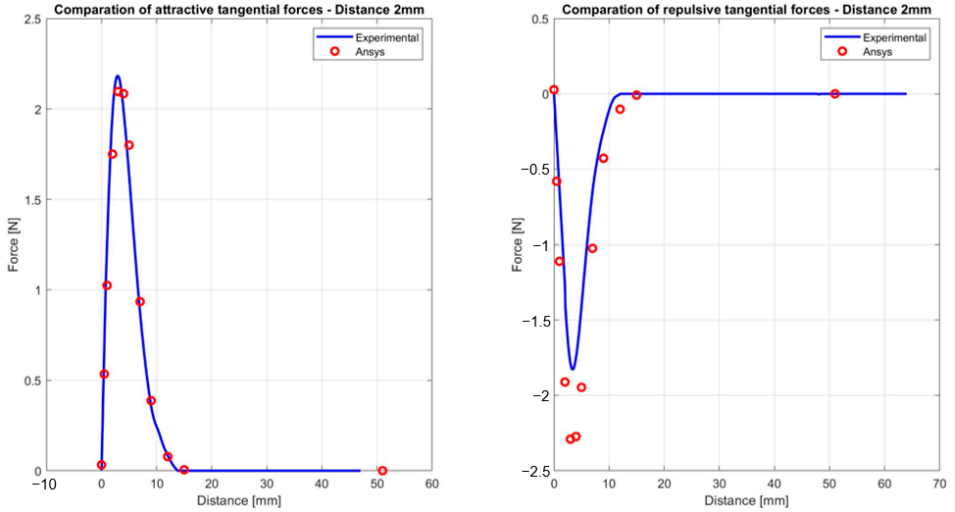


Figure 16. Comparison of results obtained experimentally and FEM magnets with a distance between faces equal to 2 mm.

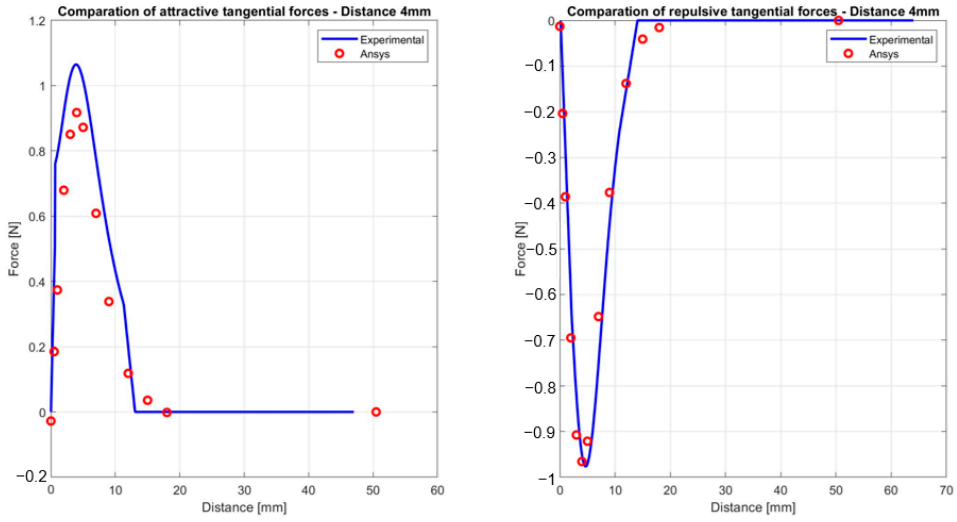


Figure 17. Comparison of results obtained experimentally and FEM magnets with a distance between faces equal to 4 mm.

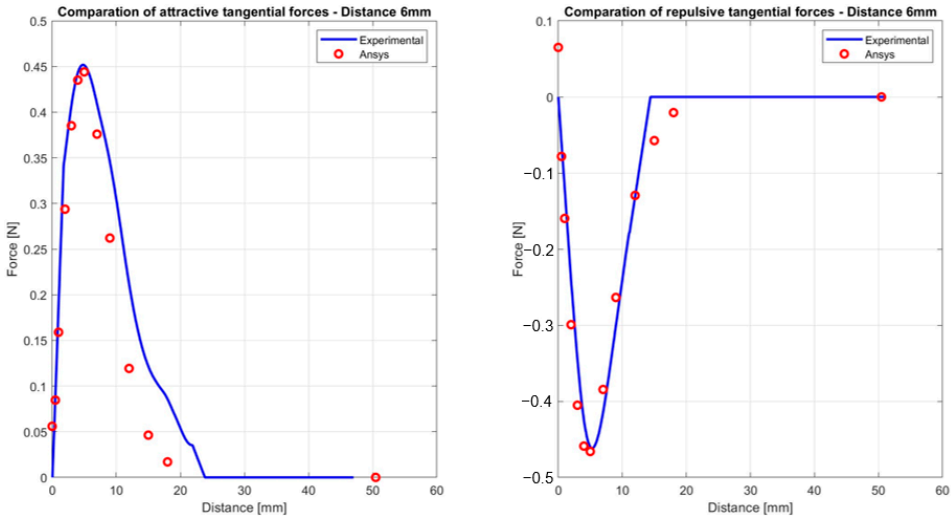


Figure 18. Comparison of results obtained experimentally and FEM magnets with a distance between faces equal to 6 mm.

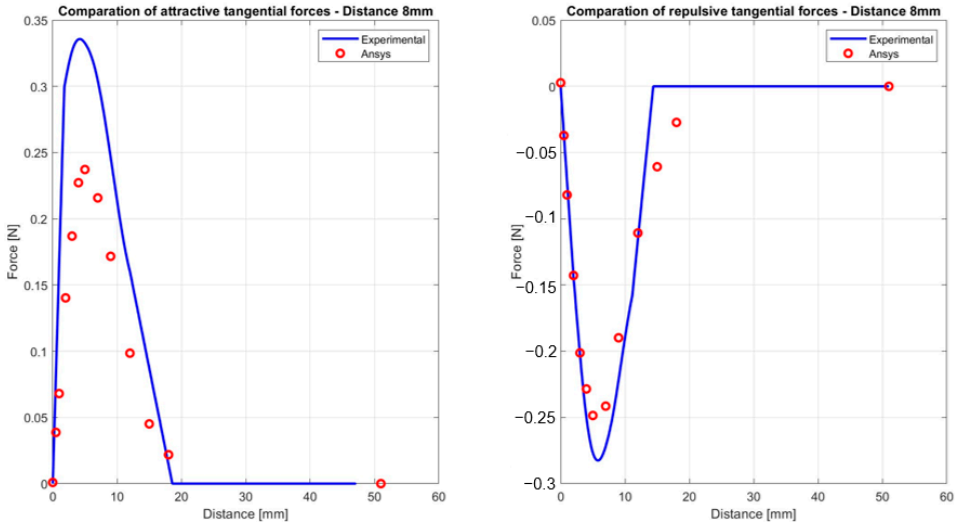


Figure 19. Comparison of results obtained experimentally and FEM magnets with a distance between faces equal to 8 mm.

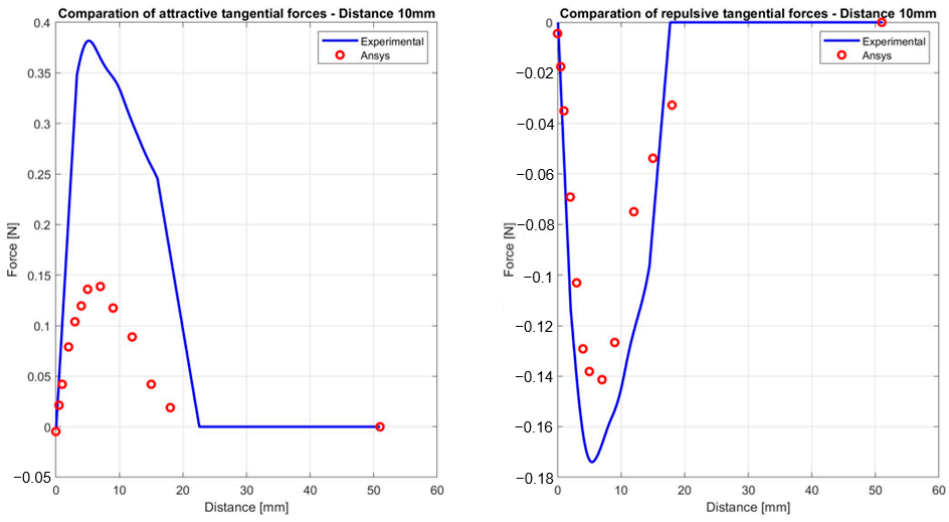


Figure 20. Comparison of results obtained experimentally and FEM magnets with a distance between faces equal to 10 mm.

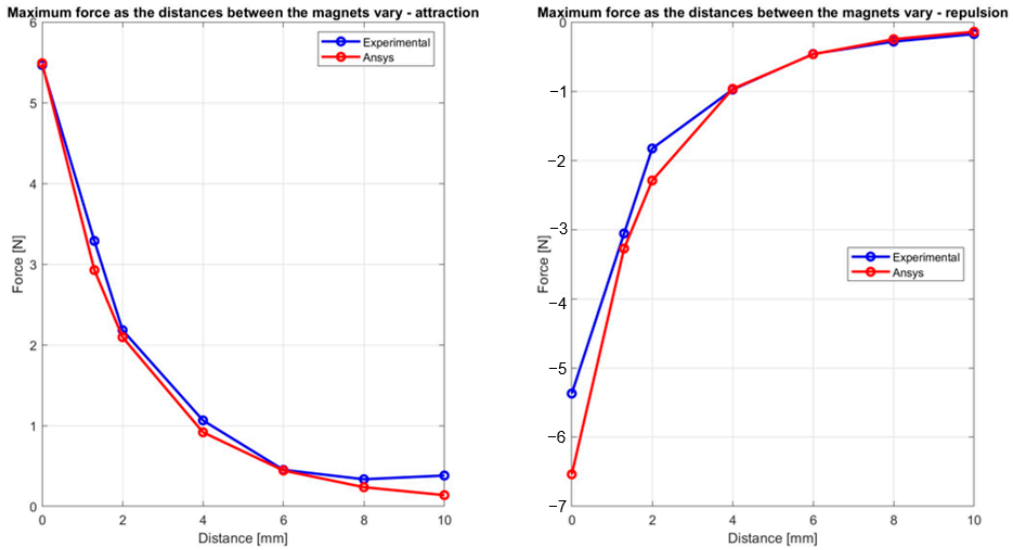


Figure 21. Comparison between the peak forces, for the various tests carried out by varying the distance between the faces of the magnets, obtained with the two different methods.

The small discrepancies between the experimental results and the simulation results, which can be noticed especially when the distance between the faces of the magnets is large, are attributable to the moments that are created during the experimental test. The force that the magnets exchange, in fact, could be thought, with a good approximation, to be directed along the line joining the two centers of the cylinders. When the two magnets are spaced transversally, this force can be broken down into two components: a component directed along the axes of the cylinders, which attracts or repels the magnets, without however creating any moment; and a transverse component which instead creates a moment. This moment, acting on the magnets, deforms the plastic supports, bringing the magnets closer or further apart, and therefore slightly varying the distance between them, and consequently, the force. It should be highlighted that this study is preliminary, and the creation of rigid plastic supports is, in the first instance, an economic choice. This problem could be solved by building supports for the magnets in non-magnetic metallic material (for example aluminum) in such a way as not to deform under the effect of these couples.

5. Conclusions

At the end of the work, it can be stated that the measurements carried out using the testing machine, even if created for different purposes and in different contexts, are very valid and reliable.

Furthermore, it was possible to obtain a valid numerical calculation tool, validated through experimental tests, which allows the evaluation of even very complex applications of systems in which magnets of any type, shape, and size are used.

Furthermore, it is possible to refine the experimental results even further by making the supports for the magnets in non-magnetic metal material instead of plastic material. In this way, any measurement errors due to deformations of the supports caused by the forces that the magnets exchange during the tests would be eliminated.

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