

Magnet Attenuation of Mechanical Collisions on Newton's Cradle

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This study investigates the effects of magnets on mechanical collisions within a Newton's cradle to determine their effectiveness in reducing collision forces. Using a Newton's cradle with steel balls and various configurations of small magnets, we aimed to examine whether the introduction of magnets could diminish kinetic energy of collisions. Our experimental setup involved testing nine different cases with one to two magnets and collecting data on cycle counts and maximum heights reached by the last steel ball. Results indicated that the presence of magnets significantly affected the cradle's performance: with one magnet, there was a 58 to 73 % decrease in coefficient of restitution, 76 to 77 % increase in damping coefficient, and a 25 to 38 % increase in kinetic energy ratio. Statistical significance was confirmed through t-tests performed on the kinetic energy ratio of two of our cases, supporting the hypothesis that magnets reduce collision forces by introducing eddy currents that oppose motion; the p-values were 0.00959 and 0.00971, both well below a significance level of 5 %. This research contributes to understanding how magnetic fields can be utilized to manage energy dissipation in oscillating systems and suggests potential applications in engineering contexts where shock absorption is crucial. Further studies could explore additional physics parameters, such as acceleration, to deepen insights into magnet-based energy reduction methods.

Introduction

Oscillating systems, such as Newton's cradle, are classic demonstrations of kinetic energy transfers and collisions, illustrating fundamental principles of energy conservation and momentum. Historically, these systems have been used to study energy loss, damping effects, and the efficiency of energy transfer. Existing theories, including classical mechanics and the kinetic theory of gasses, provide a framework for understanding these phenomena¹. Although various methods to minimize energy loss, such as using different materials to reduce friction and impact forces, have been explored, the effect of magnetic fields on energy dissipation in such systems remains under-examined². This study aims to address this gap by investigating the impact of magnets on a Newton's cradle system. Eddy currents, which oppose the motion of conducting objects and cause energy dissipation, are known from engineering applications but have not been thoroughly studied in the context of Newton's cradle systems. The primary objectives are to evaluate how magnets affect kinetic energy loss, assess how varying numbers of magnets and steel balls influence energy dissipation, and compare changes in coefficient of restitution (COR), damping coefficient (DC), and kinetic energy ratios (KER). The COR measures the elasticity of a collision between two solids by quantifying the ratio of the relative velocity of separation to the relative velocity of approach along the line of impact, which in other words, represents how much kinetic energy is conserved in a collision process. The mathematical formula for COR is

$$COR = \sqrt{\frac{h_f}{h_i}}$$

, where h_f is the maximum height in meters reached by the last steel ball and h_i is the initial drop height of the first steel ball, also in meters³. The DC is a parameter that characterizes the rate at which oscillations in a dynamic system decay over time due to energy dissipation by quantifying the resistance of a system to motion, which results from various forms of energy loss such as friction or air resistance. The mathematical formula for DC is

$$DC = \sqrt{\frac{1}{1 + \left(\frac{2\pi}{\ln \frac{y_1}{y_2}}\right)^2}}$$

, where y_1 is the maximum height in meters reached by the last steel ball in a cycle, and y_2 is the maximum height in meters reached by the last steel ball in the subsequent cycle⁴. The kinetic energy ratios can be derived from the relationship between the ratios of final and initial kinetic energies (KE), which are equivalent to the ratios of final and initial potential energies (PE). By canceling out the mass and gravitational constant in the equations, we are left with the ratio of final height to initial height. This validates that the kinetic energy ratio can be determined by squaring the COR values, as the COR formula involves taking the square root of the ratio of final height (h_f) to initial height (h_i).

$$\frac{KE_f}{KE_i} = \frac{PE_f}{PE_i}$$

$$\frac{\frac{1}{2}mv_f^2}{\frac{1}{2}mv_i^2} = \frac{mgh_f}{mgh_i} = \frac{h_f}{h_i}$$

Our null hypothesis (H_o) states that energy loss will not increase with the number of magnets and steel balls, while the alternative hypothesis (H_a) posits that energy loss will increase. The study focuses solely on Newton's cradle, excluding other oscillating systems or magnetic configurations. Limitations include potential measurement errors in maximum height reached by the cradle steel balls, variability in magnet strength, and the simplified nature of the Newton's cradle compared to complex real-world systems. Grounded in classical mechanics and electromagnetism, this research employs a quantitative approach, using repeated experiments and video analysis to measure and compare energy dissipation and elasticity across different setups. Eddy currents are induced by the heating of the surface of conductive materials due to ohmic losses associated with Joule effect, or through the generation of a reaction magnetic field that interacts with a main magnetic field⁵. In our setup, eddy currents are generated when a steel ball approaches and impacts another steel ball that has magnets attached. The striking ball, acting as the conductor, disrupts the magnetic field and creates eddy currents. These currents oppose the motion of the striking ball, resulting in a reduction in its kinetic energy. It is well-established that a ball will eventually cease motion after multiple bounces or impacts due to a series of energy transformations and dissipations. Initially, the ball's gravitational potential energy is converted to kinetic energy as it falls, and then to elastic potential energy upon impact. These transformations lead to a progressive decrease in the ball's total mechanical energy, akin to the pendulum-like behavior observed in cradle systems⁶. Related studies have explored the impact of magneto-mechanical materials on collision forces, demonstrating that incorporating magnetic materials enhances energy dissipation, so utilization of magnets in an oscillating system may have similar effects⁷. A study published in 2007 investigated the effects of magnetic fields on pendulum stability and oscillatory behavior. While their focus was on pendulum dynamics and transitions to chaos under magnetic influence, our study differs by concentrating on the total number of cycles and maximum heights achieved by the cradle steel balls in the presence of a magnetic field⁸. Known methods in this literature are compared to introduce the likelihood of observing behavioral changes in total cycles and max heights in our experiment. Six trials were conducted for each of our cases, capturing the number of cycles and maximum heights reached by the steel balls through videotaping. Figure 1 illustrates the different experimental cases, while figure 2 shows the setup and demonstrates how cycles and maximum heights are captured.

RESULTS:

The magnet balls averaged 0.5 cm in diameter, 7.414 mTesla in strength, and 0.475 grams in weight, while the cradle balls averaged 1.8 cm in diameter and 23.0 grams in weight. The number of cycles completed across the nine cases are shown in figure 3.

Three steel balls:

- Introducing one magnet reduced the number of cycles by 67.7 %.
- Introducing two magnets further reduced the cycles by 94.0 %.

Four steel balls:

- Introducing one magnet resulted in a 75.0 % reduction in the number of cycles.
- Introducing two magnets led to a 92.1 % reduction. Five steel balls:
- Introducing one magnet caused a 74.6 % decrease in cycles.
- Introducing two magnets resulted in a 91.0 % decrease.

Overall, the data shows that the introduction of just one magnet significantly decreases the number of cycles completed, with reductions exceeding 50 % compared to the control cases. The addition of a second magnet further amplifies this effect, particularly evident across all quantities of steel balls tested.

Figure 4 illustrates the change in COR for the last steel ball across the nine cases.

Three steel balls:

- Without magnets, 68.1 % of elasticity remained after six cycles.
- With one magnet, 29.2 % of elasticity remained.
- With two magnets, 12.8 % of elasticity remained.

Four steel balls:

- Without magnets, 73.2 % of elasticity remained after six cycles.
- With one magnet, 43.9 % of elasticity remained.
- With two magnets, 10.2 % of elasticity remained.

Five steel balls:

- Without magnets, 58.3 % of elasticity remained after six cycles.
- With one magnet, 26.9 % of elasticity remained.
- With two magnets, 10.2 % of elasticity remained.

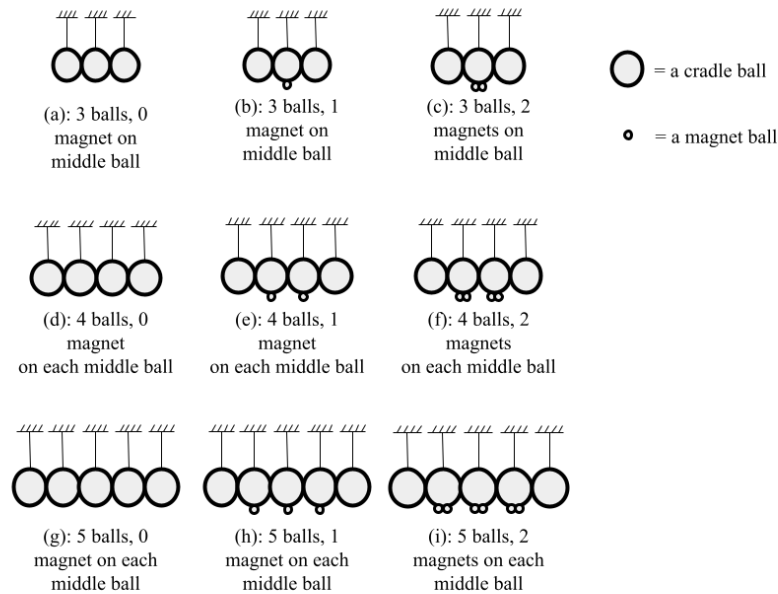


Figure 1: Illustration of our nine cases which we tested.

Overall, the introduction of one magnet significantly reduces the COR of the last steel ball, with reductions of more than 50 % compared to the control case in the scenario with three steel balls, and similarly substantial reductions in scenarios with four and five steel balls.

Figure 5 depicts the change in DC for the last steel ball across nine cases. Note that DC values for the 6th cycle are absent because the DC formula (defined in the introduction) is based on the maximum height of the last ball in one cycle divided by the maximum height in the subsequent cycle, meaning the 7th cycle's height is not used to calculate the DC for the 6th cycle.

Three steel balls:

- With zero magnets, the DC increased by 3.7 % after six cycles.
- With one magnet, the DC surged to 335.3 %.
- With two magnets, the DC further increased to 349.1 %.

Four steel balls:

- With zero magnets, the DC increased by 16.7 % after six cycles.
- With one magnet, the DC rose to 250.0 %.
- With two magnets, the DC further increased to 341.5 %.

Five steel balls:

- With zero magnets, the DC increased by 37.5 % after six cycles.
- With one magnet, the DC spiked to 615.0 %.
- With two magnets, the DC further spiked to 1052.4 %.

Overall, the introduction of magnets significantly increases the DC, with the rate of increase being more pronounced with two magnets compared to one. This suggests that energy dissipation is notably higher as the number of magnets increases.

Figure 6 illustrates the change in KER for the last steel ball compared to the first across the nine cases.

Three steel balls:

- With zero magnets, the KER decreased by 53.7 % after six cycles.
- With one magnet, the KER decreased by 91.4 %.
- With two magnets, the KER decreased by 98.4 %.

Four steel balls:

- With zero magnets, the KER decreased by 46.9 % after six cycles.
- With one magnet, the KER decreased by 80.6 %.
- With two magnets, the KER decreased by 98.6 %.

Five steel balls:

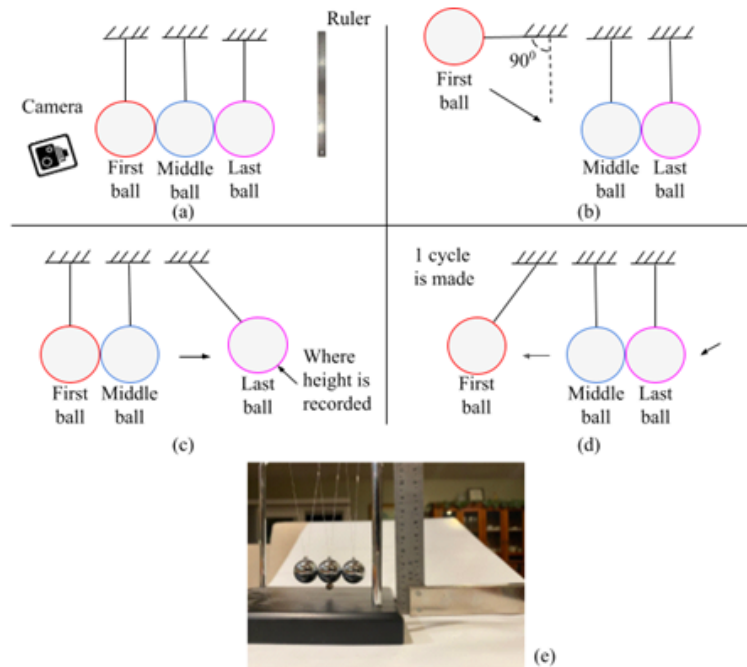


Figure 2: Example illustration of setup with a Newton's cradle. Three of the five steel balls of the cradle are shown.

- With zero magnets, the KER decreased by 66.1 % after six cycles.
- With one magnet, the KER decreased by 92.7 %.
- With two magnets, the KER decreased by 98.9 %.

Overall, the data demonstrates that the KER decreases more significantly with the addition of magnets. Each additional magnet leads to a greater reduction in kinetic energy, indicating an increasing effectiveness in energy reduction as more magnets are introduced.

DISCUSSION:

Our results, as depicted in figures 3 to 6, demonstrate a clear trend suggesting that increasing the number of magnets leads to a reduction in energy. This trend supports our hypothesis that magnets reduce the mechanical collision force in a cradle system. Specifically, we observed a significant decrease in the coefficient of restitution by 58-73 %, an increase in the damping coefficient by 66-96 %, and a reduction in the kinetic energy ratio by 70-91 % with the addition of one magnet. These findings confirm that magnets can disrupt the transfer of energy in such systems, thereby validating our hypothesis that the presence of magnets plays a critical role in energy dissipation. We still want to perform two sample t-tests to prove that the results are

significant and not by coincidence. We'll be performing two t-tests on the kinetic energy ratio data of five steel balls with one and two magnets. The control group will be five steel balls with no magnets. We used the Python module SciPy.Stats to calculate p-values, and the significance level we used is 0.05, or 5 %. If the p-value is greater than the significance level, we fail to reject the null hypothesis. Using the Python code, $pvalue = stats.ttest_rel(y_2, y_1)$, we got p-values of 0.00959 for the first test and 0.00971 for the second test. Both p-values are less than the significance level of 0.05, meaning the results are statistically significant when compared to the control. This indicates that the differences in KER are statistically significant, confirming that the presence of magnets has a measurable impact on energy reduction compared to the control group. These statistically significant results reinforce our hypothesis that magnets contribute to a reduction in mechanical collision forces. One potential concern is the weight contribution of the magnets. As mentioned earlier, a steel ball weighs on average 23.0 grams, and a magnet ball weighs on average 0.475 grams. This means that for one magnet, the added weight is 0.475 grams, and for two magnets, it totals 0.950 grams. By calculating the ratio of magnet weight to the combined weight of the steel ball and magnet, we find that the additional weight accounts for only 2 % of the total.

	Total cycles made by 3 steel balls	Total cycles made by 4 steel balls	Total cycles made by 5 steel balls
0 magnets attached	201±7.6	140±9.5	122±8.4
1 magnet attached	65±6	35±2.7	31±4
2 magnets attached	12±2	11±1.7	11±2

Figure 3: The total number of completed cycles with margin of error at 95%. Figure 1 illustrates how one cycle is counted. All the values are averaged from six trials.

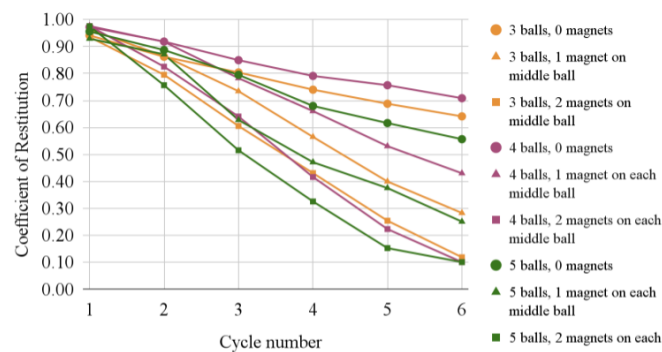


Figure 4: Change in coefficient of restitution of the last steel ball during each cycle of the nine test cases. All values are averaged from six trials.

$$\frac{\text{Mass of magnet}}{\text{mass of magnet} + \text{mass of steel ball}} = \frac{0.475 \text{ grams}}{0.47 \text{ grams} + 23.0 \text{ grams}} = 0.020 \text{ or } 2\%$$

This minimal increase is negligible in the context of our study. Additionally, our key calculations—COR, DC, and KERs—are based on the first and last steel balls, neither of which had magnets attached. Therefore, the effect of magnet weight on our results is minimal and does not impact the overall conclusions. For future research, we recommend exploring the measurement of ball accelerations under the influence of magnetic fields to better quantify the forces involved. With findings of acceleration, we would be able to find the force that is exerted onto the consecutive balls using Newton’s 2nd Law equation

$$\sum F = ma$$

This approach would provide additional insight into the exact force reductions caused by magnets over multiple cycles. Additionally, studying different magnet configurations or increasing the strength of the magnetic field could reveal further nuances in how magnets impact energy dissipation. These areas

could provide a solid foundation for further understanding the mechanical properties of systems influenced by magnetic fields. A major source of uncertainty in our experiment arises from the height gauge used to measure the maximum height of the steel balls. The ruler, with a resolution of 0.1 cm, could have led to slight rounding errors when recording the heights from video footage. We calculated the zero-order uncertainty of the ruler to be 0.05 cm (0.0005 m).

$$U_o = \frac{1}{2}(\text{resolution})$$

This small uncertainty propagates into our calculations of the COR, DC, and KERs, as all are dependent on the height measurements. Further analysis with the formula

shows the relative uncertainty in the captured heights, where t is the t-factor at 95 %, σ is the standard deviation, n is the number of height values, and \bar{x} is the mean of n^3 . Cases with two magnets will be evaluated.

Calculations show an approximate 1 % of uncertainty in the maximum heights, which we consider negligible. Another minor source of uncertainty is the potential for missing the exact

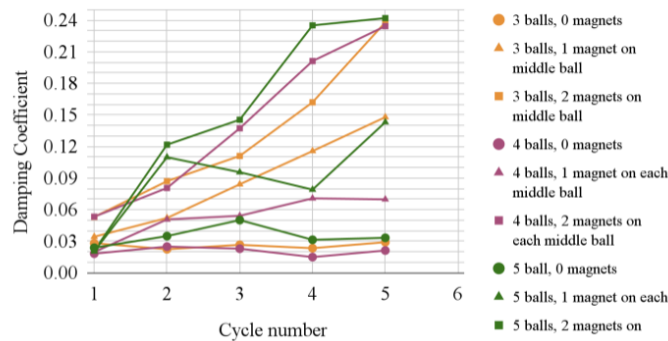


Figure 5: Change in damping coefficient of the last steel ball during each cycle of the nine test cases. All values are averaged from six trials.

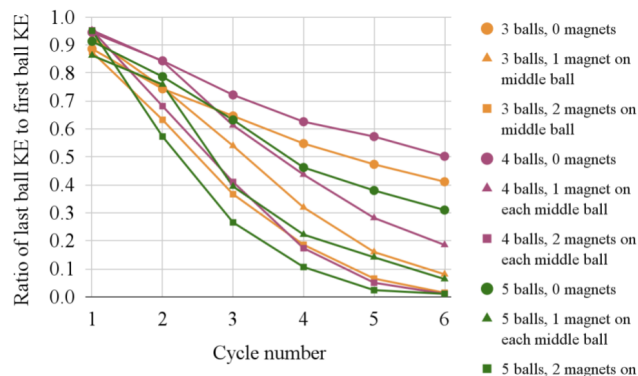


Figure 6: Change in ratio of kinetic energy of the last steel ball to the first steel ball of the nine test cases. All values are the average of six trials.

frame at which the steel ball reaches its maximum height, even when recording at 120 frames per second. This could result in a slight misreading of the true maximum height. Despite these uncertainties, the overall findings remain robust and support the conclusion that magnets significantly reduce collision forces. Future research could focus on improving the precision of height measurements and exploring additional parameters, such as magnetic field strength, to further validate the effectiveness of magnets as shock absorbers.

METHODS:

Our study followed an experimental design aimed at investigating the effect of magnets on the mechanical behavior of a Newton's cradle. We manipulated independent, dependent, and control variables to observe changes in the system's energy

dissipation. The independent variables were the number of magnets (one or two) and the cycle number (from one to six). The dependent variables were the maximum height reached by the last steel ball and the total number of cycles completed. The control variable was the angle of release for the first steel ball, fixed at 90°, perpendicular to the surface. Additionally, the zero-magnet cases served as the control case for comparison. The study did not involve any human participants, and our equipment included a Newton's cradle with five steel balls, small magnet balls, a ruler, and an iPhone camera (model 11). The magnets were selected based on their weight (0.475 grams) and strength to ensure minimal influence from their weight while maintaining sufficient magnetic impact. The magnet balls were taped to the bottom of the middle steel balls in the cradle setup. We collected two types of data: the total number of cycles completed by the cradle and the maximum height reached by the last steel

Cases	3 steel balls with 2 magnets	4 steel balls with 2 magnets	5 steel balls with 2 magnets
Uncertainty (%)	0.997	1.035	1.214

Figure 7: Uncertainty in the captured maximum heights demonstrated by calculation with three experimental cases involving magnets.

ball during the first six cycles. Data collection was performed by setting the camera to 240 frames per second to record the cradle's movement with a ruler placed beside the setup for height measurements. The videos were analyzed frame-by-frame to record the maximum height for the first six cycles and count the total number of cycles until the cradle came to a full stop. All height readings were taken from the bottom center of the steel balls, which was treated as 0 meters in height. We first set up the Newton's cradle configured to the case we are testing (number of steel balls and magnets), ensuring the system was balanced and the balls were properly aligned. The first ball is dropped from a height of 0.112 meters (perpendicular to the surface), and we recorded the cradle as it swung. The videos were played back meticulously to catch the maximum heights of the last steel ball for the first six cycles and the total number of cycles made. With the maximum heights, we calculated COR, DC, and KERS for each trial, with six trials performed for each case to ensure reliable data. These metrics were plotted to observe trends and determine the effect of magnets on the cradle's behavior. Since this study did not involve human subjects or animals, there were no significant ethical concerns. Video analysis was chosen over other measurement options because it ensures accurate tracking of the maximum height reached by the steel balls and the total number of cycles completed. Additionally, high-speed video recording at 240 fps enables the capture of rapid movements and subtle changes that might be missed by the human eye or traditional measurement tools. Overall, video analysis was selected for its ability to provide a comprehensive and precise assessment of the experimental variables, contributing to the robustness of the study's findings.

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