The Gaussian Cannon

Projektrapport

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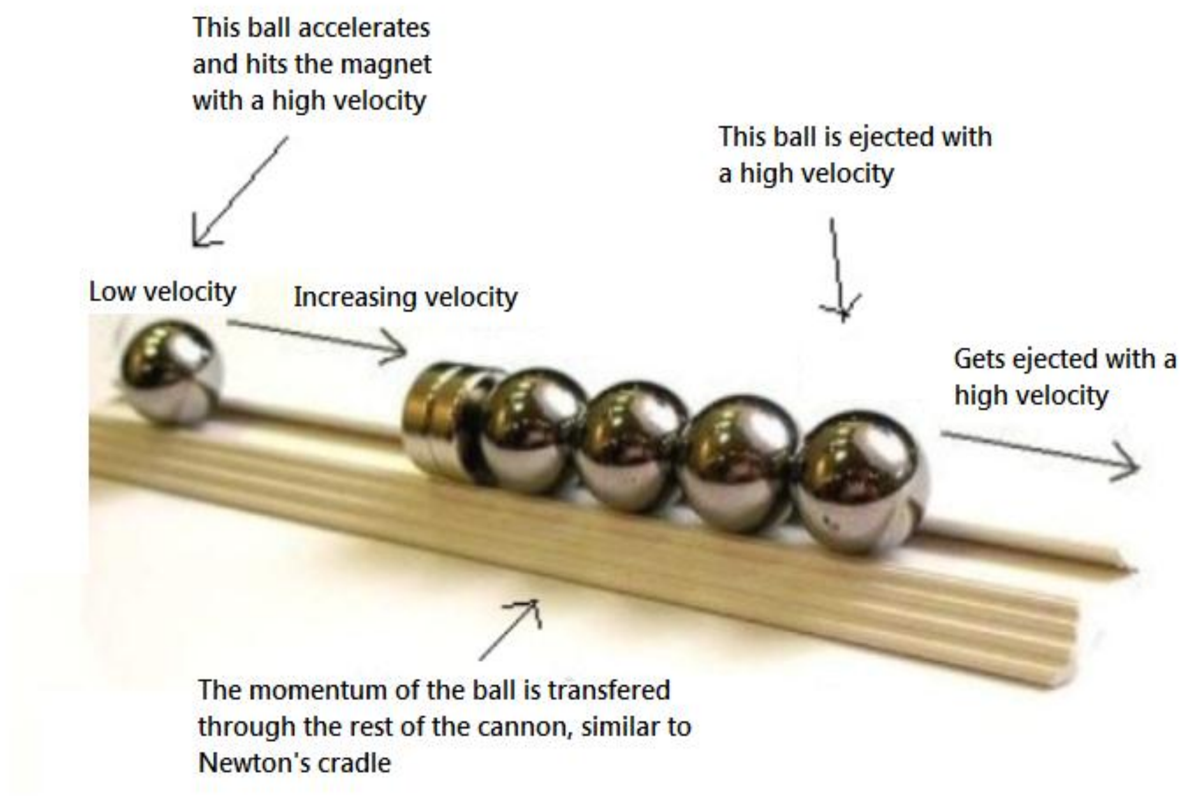
Introduction

The Gaussian Cannon consists of a sequence of identical steel balls and magnets which lie in a nonmagnetic channel. One steel ball is rolled towards them and collides with the sequence. The ball at the opposite end of the sequence is ejected at a surprisingly high velocity. This project aims to optimize the magnet's position and other variables for the greatest effect (the highest velocity).

How does this work? The steel ball that is released is attracted towards the magnet. The steel ball originally has a low velocity, but this increases as the ball is pulled towards the magnet. The closer it gets to the magnet, the higher its acceleration becomes. This happens too fast for the human eye to see. When the ball collides with the magnet, it has a very high velocity, and the momentum of the ball is transferred through the magnet and the rest of the canon, similar to how Newton's cradle works. As a result, the ball at the end of the cannon is ejected with a high velocity.



Summary of Investigations

A number of different parameters were investigated: The number of balls after the magnet, number of magnets and magnetic flux density of the magnet were tested in experiments; the position of the balls to the magnet, size of the steel balls and the initial velocity of the first ball were simply observations. Momentum was used to explain the phenomenon and the results from the observations and experiments performed, and to determine under which circumstances the highest velocity would be achieved.

The equipment used included a hi-speed camera set at 1000 frames per second, and a computer to record the results. A ruler was placed next to the railing in order to track the distance travelled by the ball. The time was first measured in frames, then converted to seconds (1 frame = 1 ms). Velocity was calculated using these figures. Parallax was accounted for in some of the experiments.

Results and Disscussion

The first parameter investigated was the position of the steel balls to the magnet. If there are too many balls in front of the magnet, the momentum of the initial ball is decreased as it passes through the balls to get to the magnet. This results in a lower momentum passing through the system, and therefore the ball at the end will have a lower velocity. The initial ball rolling in needs to be pulled by the magnet in order for its velocity to increase. The further the ball is away from the magnet, the less pulling force the magnet will exert on the ball. If there are balls in front of the magnet, the magnet’s pull is weakened before it reaches the initial ball, and therefore the momentum generated is less. The best scenario would be no balls in front of the magnet, so the magnet’s pull will not be weakened and the velocity of the ball at the end will be greatest.

The second parameter investigated was the number of steel balls after the magnet (where the last ball is ejected from the cannon). Velocity increases as more balls are added on the end, since the last ball is further away from the magnet, and the pull of the magnet is therefore less. The ball can break away from the magnet easily. If too many balls are added onto the end, velocity will decrease, since the momentum of the initial ball has to travel through too many balls to reach the end, and kinetic energy will be lost along the way. Although the pull of the magnet is less, the loss in kinetic energy is greater. As more balls are added onto the end, eventually more than one ball will be ejected from the cannon, resulting in a lower velocity since more mass is ejected. Based on the experiments, the optimum number of steel balls after the magnet is 4.

The number of magnets was also investigated. As more magnets are added on, they create a greater pull on the initial ball, which results in a greater momentum being transferred through the system, and therefore a greater velocity of the end ball. If too many magnets are added on, there will eventually be a loss of kinetic energy, because the momentum has to pass through more objects to reach the end ball. The increased strength of the magnet would not outweigh the loss of energy. Based on the experiments, the optimum number of magnets was around 6.

Magnetic flux density of the magnets was also measured as more magnets were added on. The magnetic flux density matched the velocity measurements that were previously discussed. As magnets are added on, magnetic flux density increases, but by a smaller amount each time. Using the magnetic flux density, the pulling force of the magnet could be calculated with the following formula:

$$F = A\frac{B^2}{2\mu_0\mu_r}$$

F is the pulling force of the magnet, A is the cross-sectional area, B is the magnetic flux density, μ_0 is the magnetic permeability of free space ($4\pi * 10^{-7}$), μ_r is the magnetic permeability of air. This formula was not used though, since the cross-sectional area of the magnet was not known. If the pulling force of the magnet was found, the acceleration of the initial ball could be calculated using Newton's second law and give a more accurate result.

Other variables investigated:

Initial velocity – If the first ball had a greater initial velocity, the ball being ejected will have a greater velocity, since the momentum of the first ball would be greater. This was not measured since it was difficult to control the initial velocity.

Material of the railing – The railing should have as little friction as possible to minimize loss of energy. A wooden railing was used for the experiments, but a metal or plastic railing would have less friction.

Size of steel balls – Steel balls that were about the same size as the magnet worked best. Steel balls that were bigger had a mass that was too heavy for the magnet to attract and generate an end velocity, while steel balls that were too small could not overcome the force of the magnet to eject from the cannon.

Fixating the magnet with tape – Testing shows that there is an increase of $0.25ms^{-1}$ in velocity when the magnets are fastened with tape compared to when they are not fastened. If the magnets are not fastened, there is recoil, which means loss of energy. When the magnets are fastened, the energy that would have gone into the recoil is used to increase the velocity of the ball.

Conclusion

The optimal conditions for achieving the highest velocity are: No balls in front of the magnet so the momentum of the ball rolling in will be maximized, four balls after the magnet so the ball at the end can break away easily but kinetic energy loss will be minimized and 6 to 8 magnets combined into one so the magnet will have a strong pull on the initial ball, in order to generate a high velocity. The material of the railing would ideally have as little friction as possible in order to minimize energy loss, and the size of the steel balls should be about the same size as the magnets. Also, the magnet should be fastened in order to prevent recoil and reduce energy loss.

Evaluation

The prediction of decline in velocity as more magnets and steel balls are added on is merely a speculation; there is not enough data to confirm this. There was a limited amount of steel balls and magnets. Also, the high-speed camera is not the most accurate method, but parallax was calculated and accounted for.

What's Next?

If this project was to be continued, some experiments would be repeated to obtain a more accurate result. The cross-section area is important in calculating the pulling force of the magnet, so if that could be found the formula could be then used to calculate the acceleration of the ball, making for a more accurate project.

Bibliography

- The problem was taken from the IYPT 2012 problem set.
- Experiments were done and processed with Fredrik Sjövall
- Momentum and magnet theory was taken from science literature
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