2015

Simulation and investigation the dynamics of the chain fountain phenomenon

Emad Abu-Nuwar

ABSTRACT

SIMULATION AND INVESTIGATION OF THE DYNAMICS OF THE CHAIN FOUNTAIN PHENOMENON

Emad Abu-Nuwar, M.S.
Department of Mechanical Engineering
Northern Illinois University, 2016
Brianno Coller, Thesis Director

Steve Mould, a science journalist, performed a simple experiment. He filled a beaker with a beaded chain and elevated the beaker and then he let one end of the chain fall over the edge of the beaker. When the free end of the chain fell below the height of the chain within the beaker, the weight of the chain would pull additional chain out of the beaker. He noticed that the stream of chain lifted well above the rim of the beaker. It is a robust and easily repeatable phenomenon that has been called the chain fountain.

In an article published in the Royal Society's physical sciences research journal, physicists John Biggins and Mark Warner provided an explanation that focuses on individual links as they are lifted off the top of the pile of chain. Pulling upward on the top link of the chain in contact with the pile induces a rotation. To prevent the translating and rotating top link from penetrating the pile, the top of the pile of chain must push upward on the link. This push from the top of the pile is believed to be the impetus that sends the chain well above the rim.

In this research, we developed a relatively high-fidelity simulation of the chain dynamics to reproduce the chain fountain effect and to test the explanations proposed by John Biggins and Mark Warner. By changing inertial properties of the chain links and by changing boundary conditions, one can add or remove effects that are thought to create the fountain.

NORTHERN ILLINOIS UNIVERSITY
DE KALB, ILLINOIS

DECEMBER 2015

SIMULATION AND INVESTIGATION OF THE DYNAMICS OF THE CHAIN FOUNTAIN PHENOMENON

BY

EMAD ABU-NUWAR

A THESIS SUBMITTED TO THE GRADUATE SCHOOL
IN PARTIAL FULFILLMENT OF THE REQUIREMENTS
FOR THE DEGREE
MASTER OF SCIENCE

DEPARTMENT OF MECHANICAL ENGINEERING

Thesis Director:
Brianno Coller

ACKNOWLEGEMENTS

I would like to use this opportunity to express deep gratitude and appreciation to my advisor, Dr. Brianno Coller, for his professional guidance, his time, his support, and his cordial encouragement. Without him it would not have been possible for me to complete this work.

I would like to thank Dr. Abhijit Gupta and Dr. Ji-Chul Ryu for being my committee members for this research and for their encouragement and their constructive comments.

I would like to express my deepest gratitude and unending thanks and appreciation to my father, the late Mousa Abu-Nuwar, and to my mother, Sadoof Abu-Nuwar. They always wanted me to be the best in all aspects of life. They spent their lives to educate me. I deeply appreciate their invaluable sacrifices and their efforts which were the cornerstone of my academic success. I would never be able to do them the same favor they did for me.

DEDICATION

To my great father, the late Mousa, to my great mother, Sadoof,

and to my siblings

TABLE OF CONTENTS

LIST OF FIGURES

CHAPTER 1

INTRODUCTION

1.1 Motivation

Recently, Steve Mould, a science journalist, performed a simple experiment, broadcasted it on YouTube, and received more than 1.6 million views [1]. In his experiment, Mould filled a beaker with a beaded chain. He elevated the beaker; then he let one end of the chain fall over the edge of the beaker. When the free end of the chain fell below the height of the chain within the beaker, the weight of the chain pulled additional chain out of the beaker, like a siphon [1] [2].

The interesting part is that as the chain picked up speed, the stream of chain lifted well above the rim of the beaker. Figure 1.1 shows a picture of the chain fountain from the New York Times [3].

Figure 1.1: Chain fountain [3]

It is a mesmerizing phenomenon that has been called the chain fountain. One can watch an online video of the chain fountain at https://www.youtube.com/watch?v=6ukMId5fIi0 [1] [2]. The phenomenon is robust and easily repeatable.

Since the experiment, science blogs and websites have lit up with proposed explanations of the phenomenon. Most explanations are related to inertial effects of a chain pulled quickly out of a beaker. As beads reach the top of the beaker, people argue that their momentum carries them further above the rim. Other explanations focus on a presumed inability of a flowing chain to move around sharp turns, causing it to “flare out.”

In an article published in the Royal Society's physical sciences research journal [4], physicists John Biggins and Mark Warner provided counter-arguments to the most popular theories and proposed an explanation that, to physics and mechanics experts, seems to have garnered the most respect [4]. Their explanation focuses on individual links as they are lifted off the top of the pile of chain. Pulling upward on the top link of the chain in contact with the pile induces a rotation. To prevent the translating and rotating top link from penetrating the pile, the top of the pile of chain must push upward on the link. This push from the top of the pile is believed to be the impetus that sends the chain well above the rim. John Biggins and Mark Warner justify their explanation through analysis of the effect on a much-simplified theoretical model of the streaming chain [4].

In this research, we developed a relatively high-fidelity simulation of the chain dynamics in an effort to reproduce the chain fountain effect and to test the explanations proposed by John Biggins and Mark Warner. By changing inertial properties of the chain links and by changing boundary conditions, one can add or remove effects that are thought to create the fountain. Also, one can investigate the role of link contact mechanics on the bottom of the pile.

1.2 Literature Review

Biggins and Warner [4] discuss how the chains are picked up and pulled into motion by a tension force above the pile and pushed by a force from the stationary pile in the beaker.

According to them the release of the gravitational potential energy causes the chain's flow from the beaker towards the ground, since the weight of the chain is elevated from the ground. But this will not explain the chain fountain behavior. They started their assumption with a simple model consisting of a pile of chain on a table flowing towards the ground. The chain flows first vertically above the pile on the table then reverses the direction of the velocity in small curvature, and then flows vertically down to finally come at rest on the ground.

They first assumed that the curved region is very small, the centripetal acceleration is much larger than gravitational acceleration, so the chain flowing can turn a randomly sharp corner immediately after the rim of the pot. And they explained that if the chain above the table and the chain are moving at constant velocity, no fountain will occur above the pile on the table. They expect that the momentum is provided by the floor.

They introduce a force comes from the pile in the pot; this force provides momentum besides the momentum that comes from the tension in the chain. And they verified experimentally that without having this force coming from the pile there will be no fountain. The links are in rest lying horizontally inside the pot and are pulled directly upward by the preceding links at one end. This upward force rises and rotates the link, but because the rod is set on the pile as a horizontal surface, the pile supplies an upward reaction force at the link. Furthermore, when the link starts to move, it may first move horizontally, causing collisions with the stationary pile that would cause an upward reaction force.

To have a more complete model, they discuss a full shape of the fountain, and they consider the chain is in a steady state so the moving part of the chain moves and makes an angle with vertical. So it induces force parallel and force perpendicular to the tangent of the chain. The force perpendicular provides the centripetal acceleration to the chain for moving round as a curvature.

According to Biggins and Warner the rapid change in transverse velocities leads to the formation of waves above the pick-up point. The waves are stationary and contain part of the dissipated energy in the pick-up process. They explained that since the chain speed and the wave speed are the same, the wave is stationary above the pick-up point.

Biggins and Warner's result is that when a pick-up force is applied at the end of the chain, a reaction force from the pile is induced, causing the chain fountain or further consequences. So this will increase the rate of deploying the chain and increase energetic efficiency of the process. So maximizing this effect might have consequences in areas where the efficiency is critical, such as space engineering.

Hamm and Geminard [5] discuss the problem of a vertically falling chain that impinges on the pan of a scale. They explained how the minimum radius of curvature causes an additional tension in the falling chain which accelerates the falling chain and pulls it towards the ground. Transverse waves are formed at the bottom; these waves can climb through the chain.

For better understanding of this behavior and to explain why the chain stays straight, they consider the velocity and the tension at the bottom and find that the velocity at the bottom is always smaller than the fall velocity, so the chain will never move laterally. And since the energy is not conserved, the falling time is less than the fall free. Their model is to study the apparent weight of the falling chain and they find that the temporary apparent weight of the chain diverges while the chain is getting close to the bottom and explains why the free end of the chain reaches the bottom earlier than the mass in the falling free.

According to Anoop Grewal et al. [6] the correct calculation depends on the structure of the chain, the way of falling, and the surface which the chain falls on. One of these assumptions is that the chain is slowed by the table and accelerates by the gravity. The other one is that the energy is conservative in the chain problem and the chain is falling by acceleration greater than g, and the collision with the table slows the links.

Anoop Grewal et al. show that the assumption that there is no interaction between the link and the ground is not accurate. They showed that when a falling chain hits the ground, it speeds up and falls faster than falling free. They show how the impact pulls the other falling part of the chain downwards.

They find that the assumption that the last link in the falling chain stops and disconnects from without any relation to the rest of the falling chain is not always valid. They suggested that the interaction between the last link and the rest of the falling chain would exert a force pushing up the falling chain or would exert a force pushing down the falling chain.

They designed a chain from rods and ropes where the rods hit the ground from one end, and the free end rotates around the contact point and pulls the rest of the chain downward, causing it to fall more than the free fall by gravity.

1.3 Research Objective

The goal of this research is to investigate the dynamics of a beaded chain picked up from a beaker, validate the theory behind the fountain formation by using a numerical simulation and studying different parameters to explain the phenomenon, and study the behavior and the height of the chain fountain over the time with different parameters.

CHAPTER 2

DESCRIPTION OF SIMULATION AND MODEL

2.1 Rotational Inertia and Upward Force Analysis

John Biggins and Mark Warner’s explanation focuses on individual links as they are lifted off the top of the pile of chain. Pulling upward on the top link of the chain in contact with the pile induces a rotation. To prevent the translating and rotating top link from penetrating the pile, the top of the pile of chain must push upward on the link. This kick from the top of the pile is believed to be the force that sends the chain well above the rim [4]. Figure 2.1 from physicists John Biggins and Mark Warner’s article shows their chain fountain model [4].

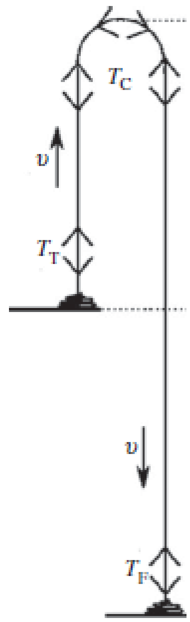


Figure 2.1: Physicists John Biggins and Mark Warner's chain fountain model [4]

Since John Biggins and Mark Warner introduce this upward force coming from the pile and applied on the link [4], we study these forces applied to a single link on top of the pile. We see in Figure 2.2 that T is the pulling force applied on the link and R_y is the upward force applied on the link from the top pile.

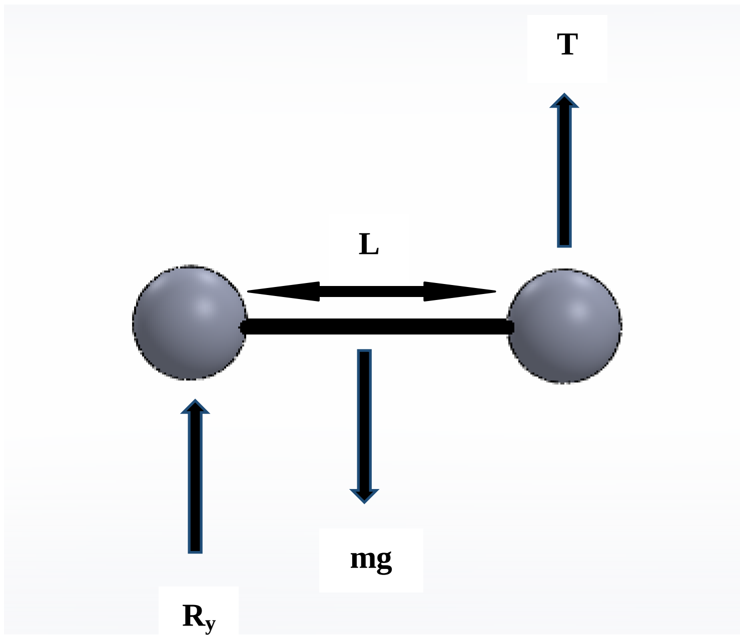


Figure 2.2: Forces applied on a single link

From Newton's Second Law, we find the forces applied on the single link:

$$T + R_y - mg = m\, a_{Gy} \tag{2.1}$$

$$(T - R_y)\,\frac{1}{L} = I_g\ \alpha \tag{2.2}$$

$$(T - R_y)\,\frac{1}{L} = I_g\; a_{Gy} \tag{2.3}$$

We solve Equations 2.1, 2.2 and 2.3 to find that the relation between the upward force R_y applied on the link from the top of the pile and the moment of inertia of the link I_G can be represented in Equation 2.4.

$$R_y = \frac{\frac{L^2}{4} - \frac{I_G}{m}}{\frac{L^2}{4} + \frac{I_G}{m}}\; T \; + \; \frac{g\, I_G}{\frac{L^2}{4} + \frac{I_G}{m}} \tag{2.4}$$

From Figure 2.2, the maximum moment of inertia is

$$I_{G\,max} = \frac{m\,L^2}{4} \tag{2.5}$$

Plug Equation 2.5, the maximum moment of inertia, into Equation 2.4 to find that the minimum upward force equals half of the link weight.

$$R_{y\,min} = \frac{mg}{2} \tag{2.6}$$

Plug $I_G = 0$ into Equation 2.4 to find that the maximum upward force from the pile R_y equals the tension force pulling the chain from the pile.

$$R_{y\,max} = T \tag{2.7}$$

From our previous analysis we prove that the smaller the moment of inertia of the link, the greater the upward force applied on the link from the pile. So with a greater upward force R_y from the pile we expect a higher chain fountain. Figure 2.3 shows the relation between the upward force from the pile R_y and the moment of inertia of the link I_G.

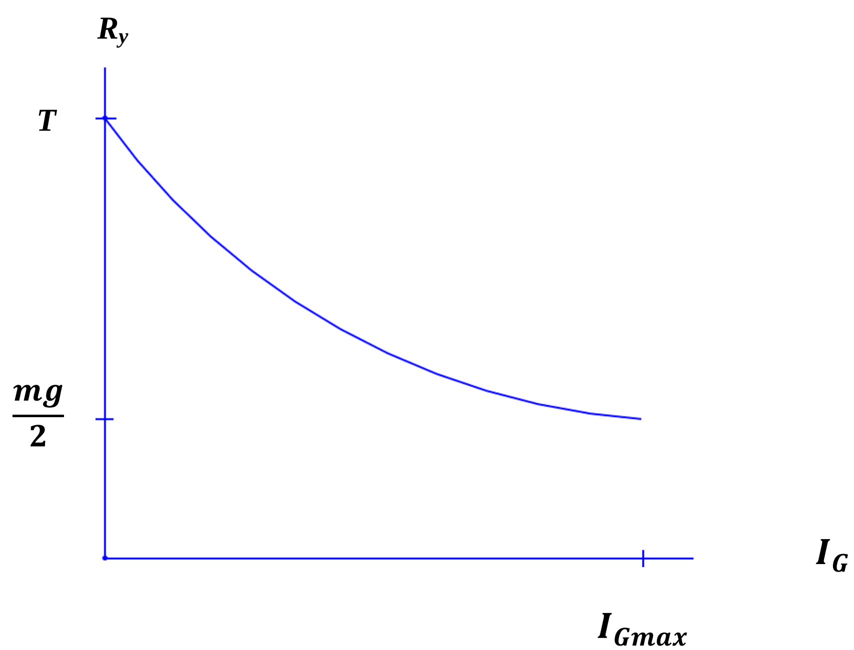


Figure 2.3: The relation between the moment of inertia and the upward force R_y

2.2 Simulation and Model

Suitable software was developed for simulating and investigating the dynamics of a beaded chain being “siphoned” from a container. Our goals are to capture the observed phenomenon, to explore a range of parameter values, and to investigate the research questions. We only simulate the part of the chain that is in the stream between the top of the pile in the beaker and the bottom on the ground.

The chain consists of beads connected together with mass rods. Figure 2.4 shows how beads are linked together; between points A and B is one link.

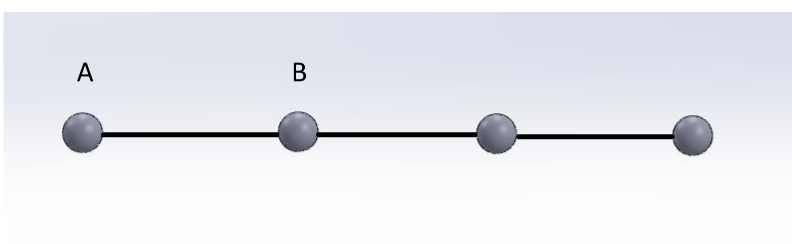


Figure 2.4: Original chain model

In order to change the rotational inertia of the chain link in our experiment, a model consisting of three inner masses connected to two end masses is introduced. All masses are connected with massless rods with constant distance; Figure 2.5 shows how points A and B make the new model of our link.

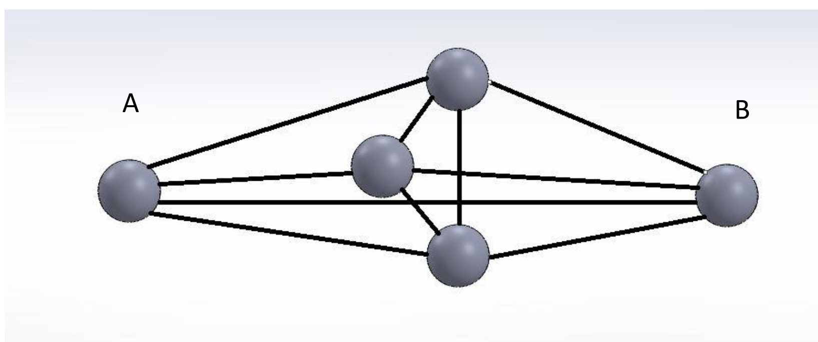


Figure 2.5: Five-bead model

The simulation started with a link making a ball joint with the top of the pile, Figure 2.6, until the link is high enough to lift the next link from the top of the pile so the new link has the ball joint. The bottom pile also has a ball joint, so when the falling link hits the ground, it makes a ball joint with the bottom of the pile form its end against the ground. When the two ends of the link reach the ground, this link is out of the simulation.

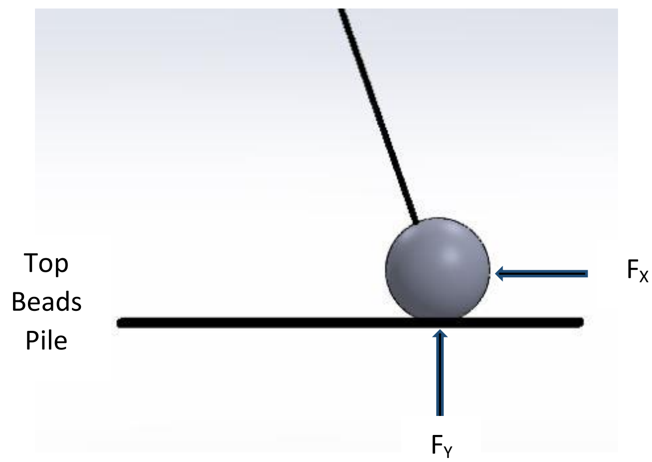


Figure 2.6 Bead makes ball joint with the top of the pile

Mounting the ball joint at the center of the rim is the simplest, so unlike the usual experiment, the chain moving around ball joint is committed to the center of the rim. And when the link gets pulled up and dropped down, there is a spring force to push it up again.

When links are connected together with massless rods that keep them in a constant distance from each other, each bead is connected with other four beads, so there are four tension forces acting on each bead (Figure 2.7).

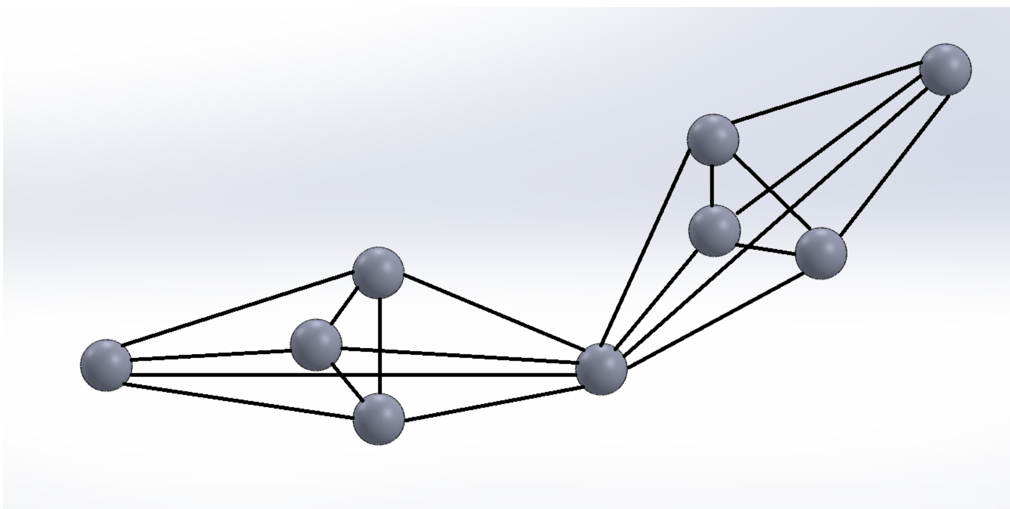


Figure 2.7: Two neighboring links

Each bead has four tension forces acting on it from the other connected beads, in addition to the force acting on the beads due to the gravity. And while the simulation is running, the beads collide with each other and with the rim causing an additional two forces acting on each bead. Figure 2.8 shows the forces acting on the bead.

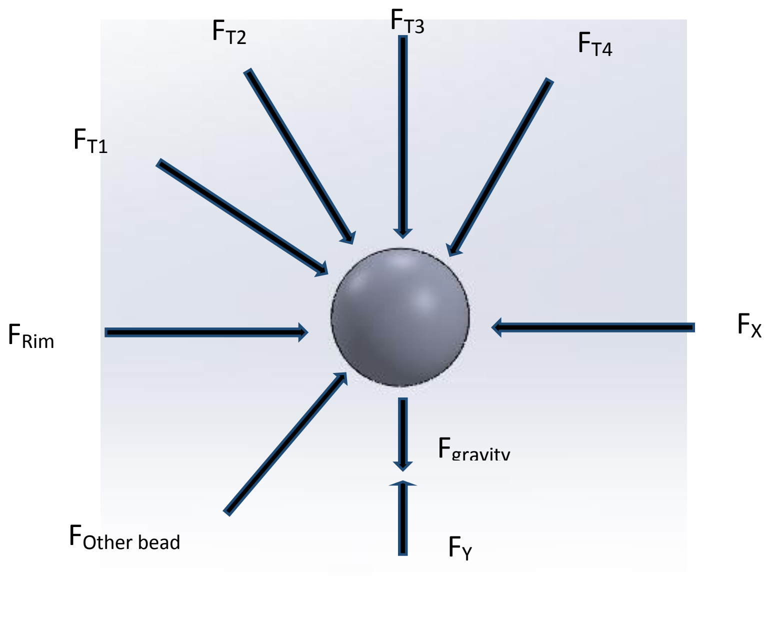


Figure 2.8: Forces acting on bead

2.3 Mass Ratio of the Five Beads

Since our model consists of three inner masses connected to two end masses, by changing the internal mass and the end mass value we have different moments of inertia to run the simulation. Running the experiment with different moments of inertia allows us to prove the effect of the inertia on the chain fountain phenomenon.

The distance between beads is 0.005 m, the end bead radius = 0.0015 m and the total link weight is 0.00057 kg; total link mass consists of the mass of one end bead plus the internal masses. We anticipate that the higher the inertia, the less chain fountain formation. For the five-bead model, the total mass is

$$M_{Total} = 3\ M_i + 2\ M_e \quad \textbf{(2.8)}$$

where M_i is the internal bead mass and M_e is the end bead mass. And we calculate μ, the fraction of internal mass in the total link mass, and we expect to have a higher chain fountain with the greater mass ratio.

$$\mu = \frac{3\ M_i}{3\ M_i + M_e} \quad \textbf{(2.9)}$$

We expect that when the inertia of the five-bead model is equal to the inertia of a thin rectangular rod (Figure 2.9), we have the optimum chain fountain phenomenon.

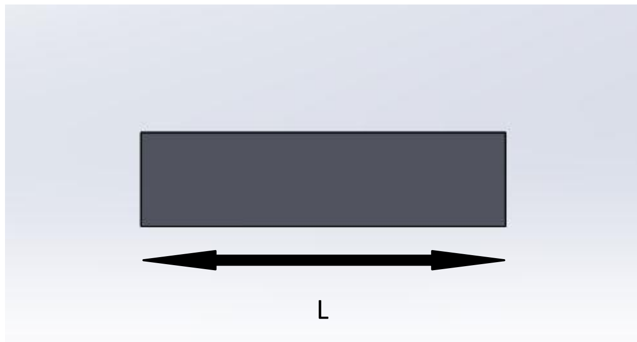


Figure 2.9: Thin uniform rectangular rod

Where L is the length of the rod, so the moment of inertia of a thin rectangular rod is

$$I_{Rod} = \frac{1}{12} M_{Total} L^2 \quad \textbf{(2.10)}$$

The inertia of the uniform rod should equal to the inertia of the five-bead model to get the required mass ratio $\boldsymbol{\mu}$ to run our experiment. The five-bead model inertia is:

$$I_{Model} = 2\,M_i\left(\frac{\sqrt{3}}{2}\,d\right)^2 + 2\,M_e\left(\frac{L}{2}\right)^2 \qquad \textbf{(2.11)}$$

We find that when the inertia of the rod equals the inertia of the five-bead model, the fraction of internal mass $\boldsymbol{\mu} = 0.889$.

CHAPTER 3

PARAMETER CHOICE AND RESULTS

3.1 Mass Ratio μ = 0.889

For our five-bead model and from the moment of inertia analysis we have done in the previous chapter, we expect to have a chain fountain for 0.889 mass ratio. Boundary condition for simulation with mass ratio $\mu = 0.889$ starts from time = 0.0 seconds when the chain is completely lifted up above the rim and the beaker (Figure 3.1), so that we can get rid of the swinging effect at the beginning (Figure 3.2). Then our data started from time = 1 second.

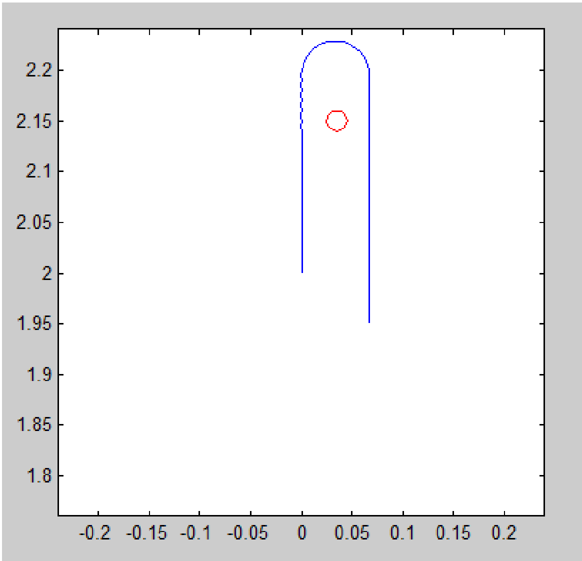


Figure 3.1: Beaded chain lifted up above the rim at time = 0 second

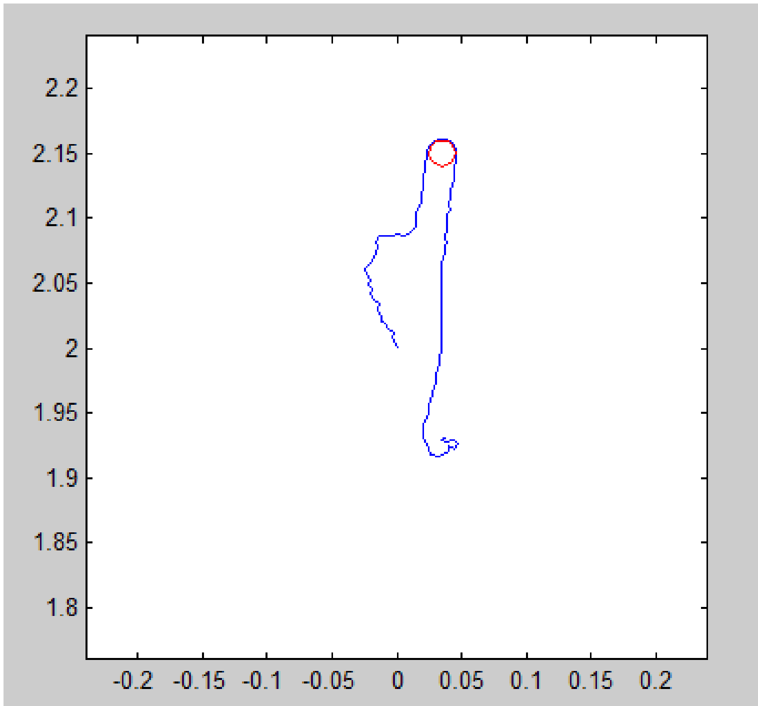


Figure 3.2: Beaded chain swinging at time = 0.3 second

From running the simulation for mass ratio 0.889 we notice that the chain fountain phenomenon starts at 0.7 seconds. And after 5 seconds of running the simulation we get rid of the rim in our simulation so there is no colliding between the chain and the rim of the beaker. Figure 3.3 shows the chain fountain after 7 seconds of running the simulation. Figure 3.4 shows the chain fountain after 12 seconds of running the simulation.

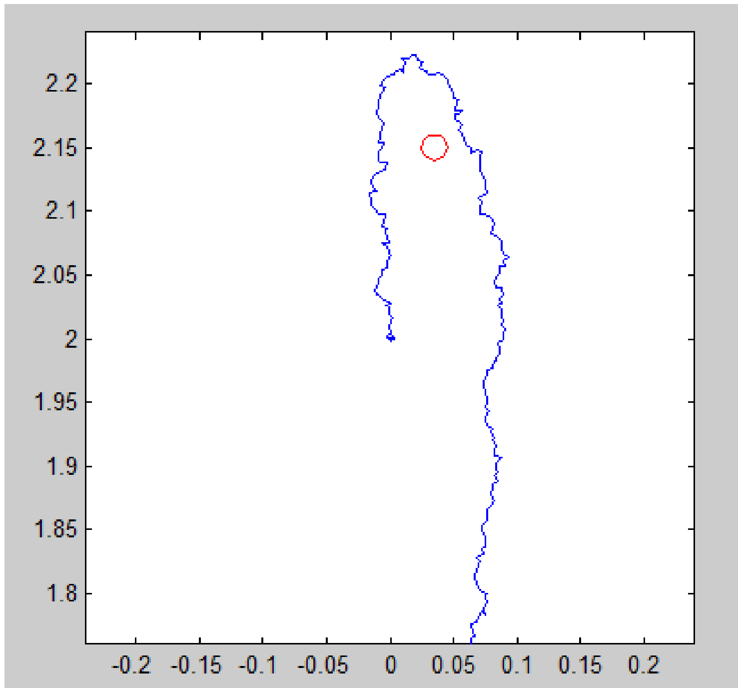


Figure 3.3: Chain fountain with 0.889 mass ratio at time = 7 seconds

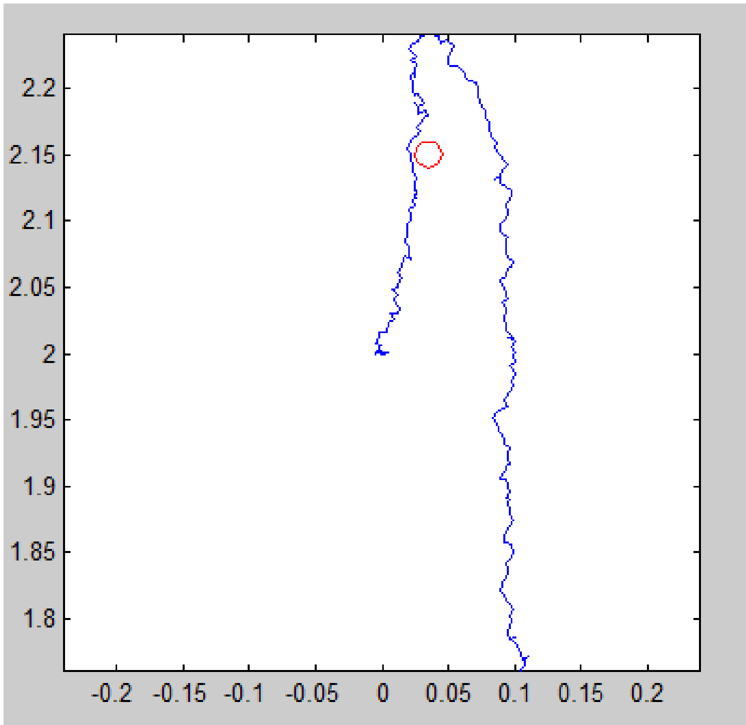


Figure 3.4: Chain fountain with 0.889 mass ratio at time = 12 seconds

Figure 3.5 shows the change of the chain fountain height over the time for a chain with mass ratio 0.889. We find that the average height of the chain fountain for the 0.889 mass ratio chain is 2.2285 m. We expect to find a smaller chain fountain height for chains with smaller mass ratio.

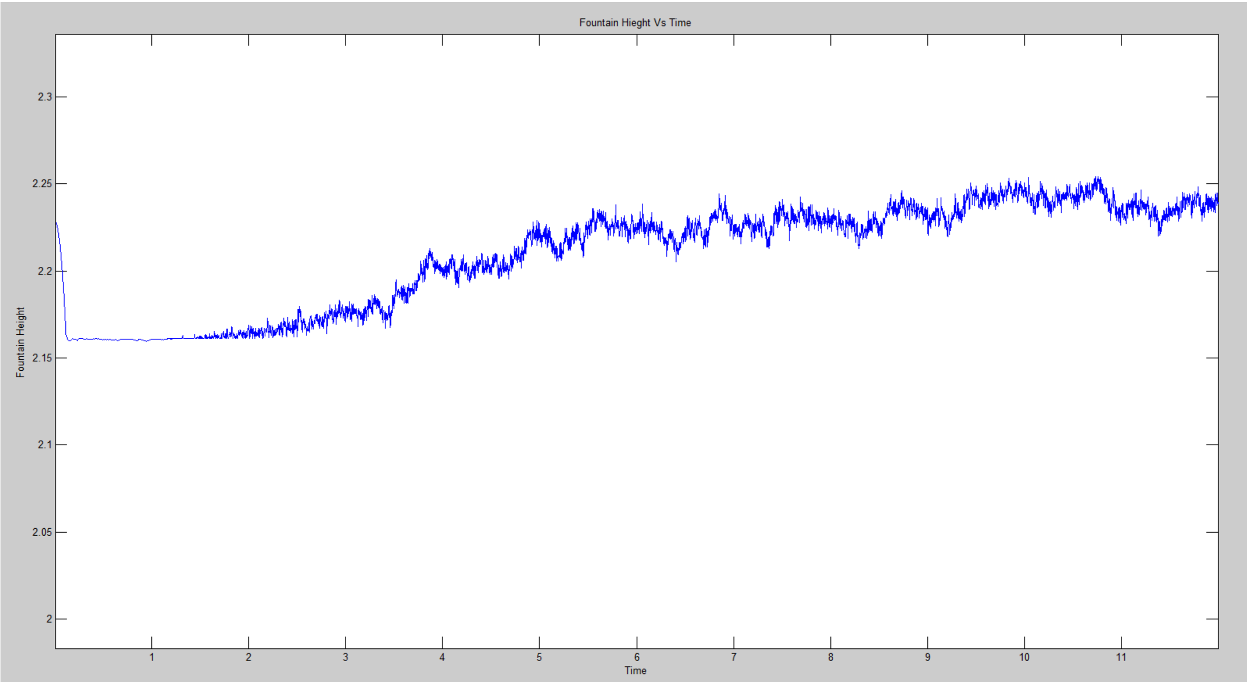


Figure 3.5: Fountain height of the 0.889 mass ratio chain over the time

From the data collected from the simulation we find the average speed of the chain in time period between 5 to 12 seconds equals to 10 m/s (Figure 3.6).

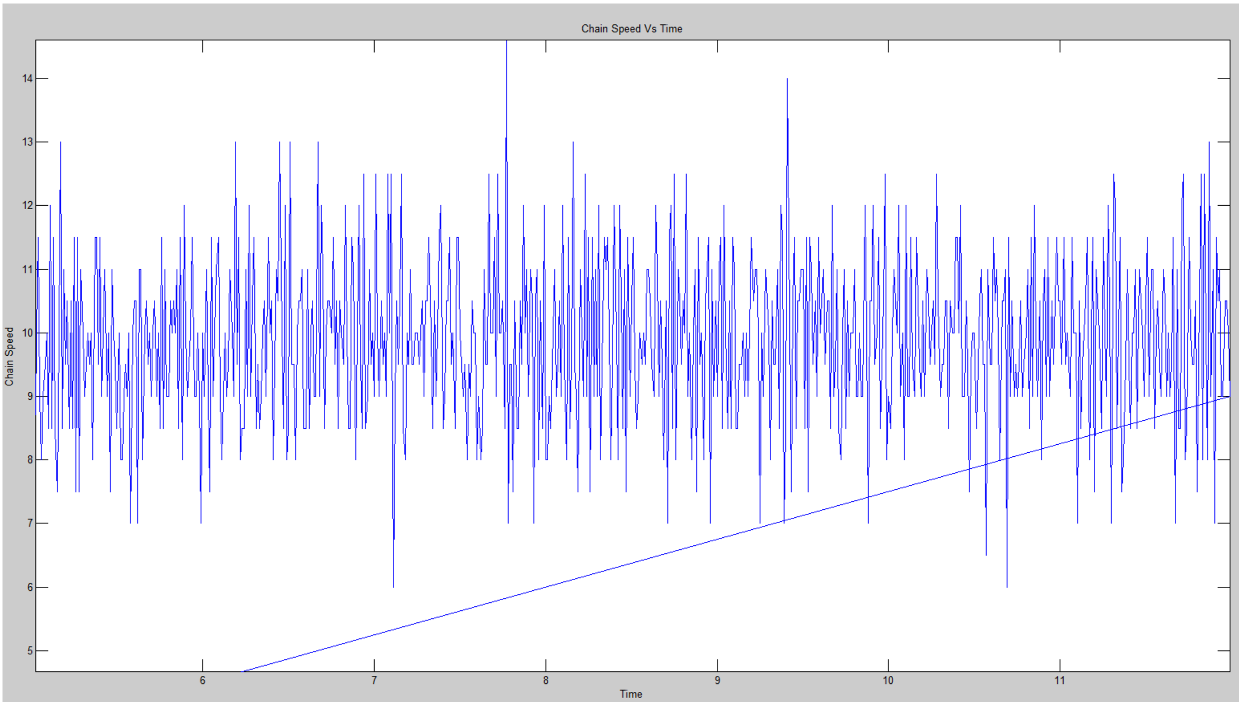


Figure 3.6: Speed of the chain over the time with 0.889 mass ratio

Figure 3.7 shows the change of the chain force over the time for the chain with 0.889 mass ratio. We also find that the average force of the chain between 5 to 12 seconds is 0.55 N. We expect to find a smaller chain force for the smaller mass ratios.

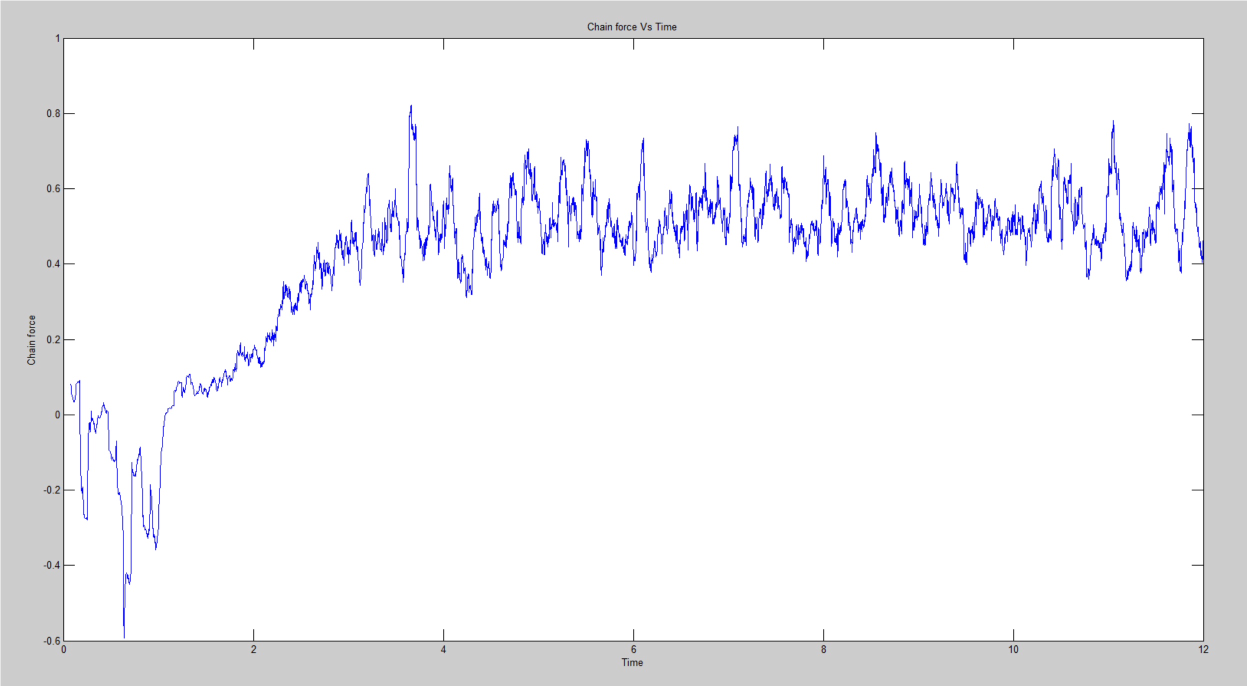


Figure 3.7: The force of the chain over the time with 0.889 mass ratios

3.2 Simulation Results for Other Mass Ratios

We run the simulation for the chain with different mass ratio to study the effect of moment of inertia on chain fountain phenomenon. We run the simulation for 0.889, 0.8, 0.7, 0.6, 0.5, 0.4 mass ratios.

3.3 Height of Chain Fountain with Different Mass Ratios

From studying the average height of the chain fountain for different mass ratios, we find the greater the mass ratio the greater the height of the chain fountain (see Figure 3.8), which proves the effect of the moment of inertia on the chain fountain phenomenon.

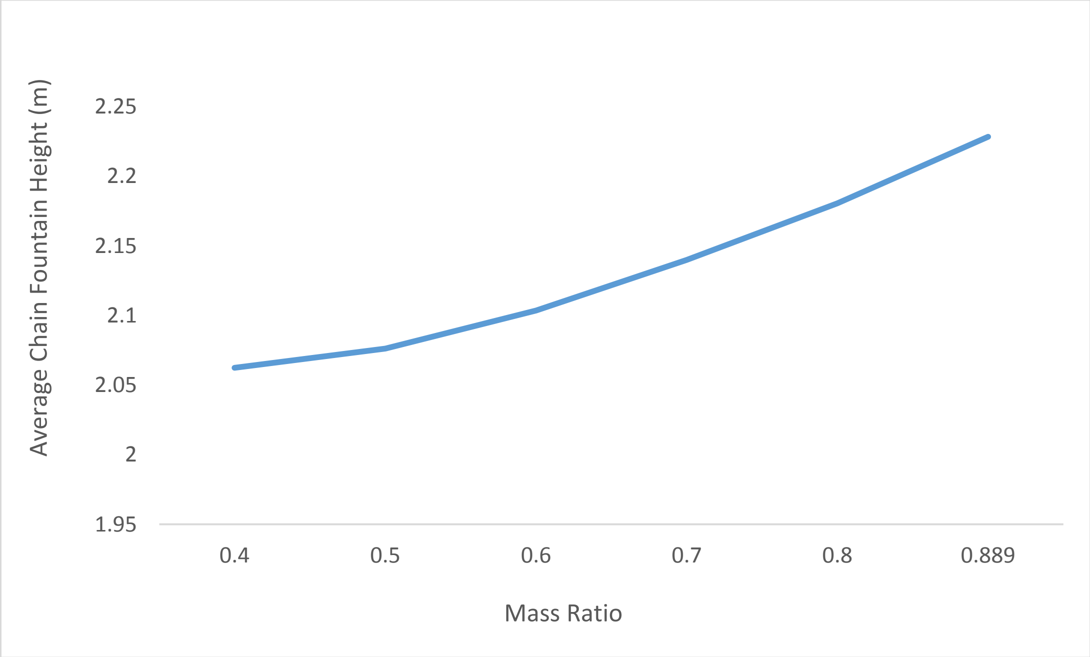


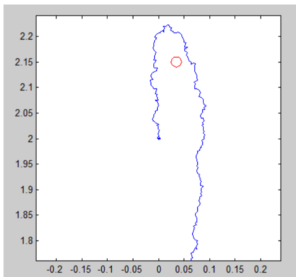
Figure 3.8: Average height of the chain fountain for different mass ratios

We also find that chain fountain does exist for mass ratios 0.889, 0.8, 0.7, 0.6, 0.5. But with mass ratio 0.4, chain fountain collapses. Figure 3.9 shows the chain fountain for different mass ratios after 7 seconds. In our simulation, we remove the beaker's rim after 5 seconds to eliminate the colliding effect between the chain and the rim.

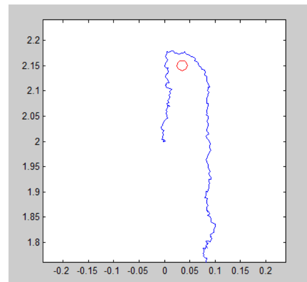
3.4 Speed of the Chain Fountain for Different Mass Ratios

We find that the speed of the chain fountain appears to be the same for different mass ratios, Figure 3.10 shows how the average speed of the chain fountain between 5 to 12 seconds is the same for different mass ratios. Speed data prove that the centripetal mechanism has no effect on the chain fountain formation.

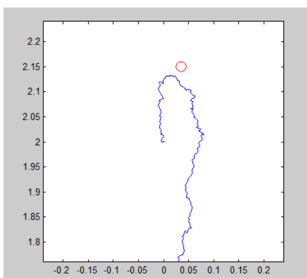
Mass Ratio = 0.889



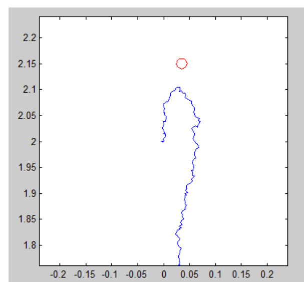
Mass Ratio = 0.8



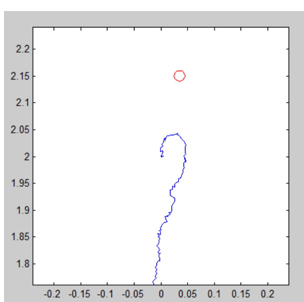
Mass Ratio = 0.7



Mass Ratio = 0.6



Mass Ratio = 0.5



Mass Ratio = 0.4

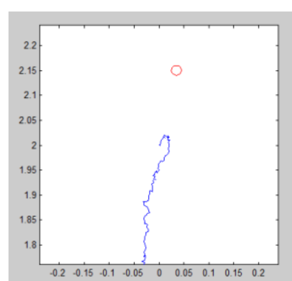


Figure 3.9: Chain foundation at time = 7 seconds for different mass ratios

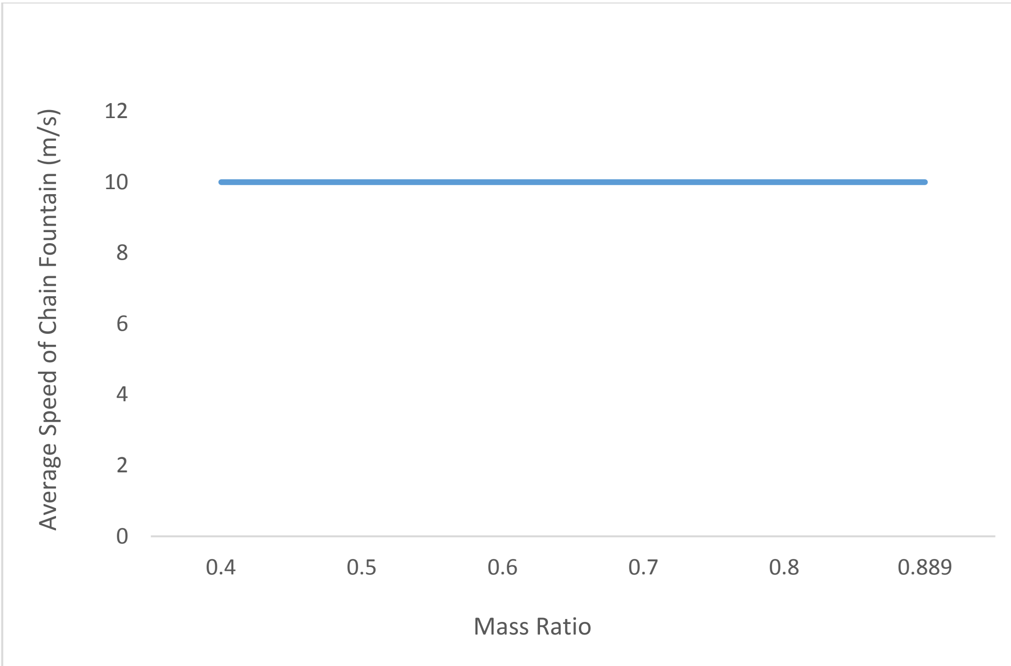


Figure 3.10: Average chain fountain speed for different mass ratios

3.5 Force of the Chain Fountain with Different Mass Ratios

We find that the greater the mass ratio, the greater the chain force. Figure 3.11 shows how a greater mass ratio leads to a greater chain force, and Figure 3.12 shows the chain force versus the time, so we can see the force value for each mass ratio changes over the time.

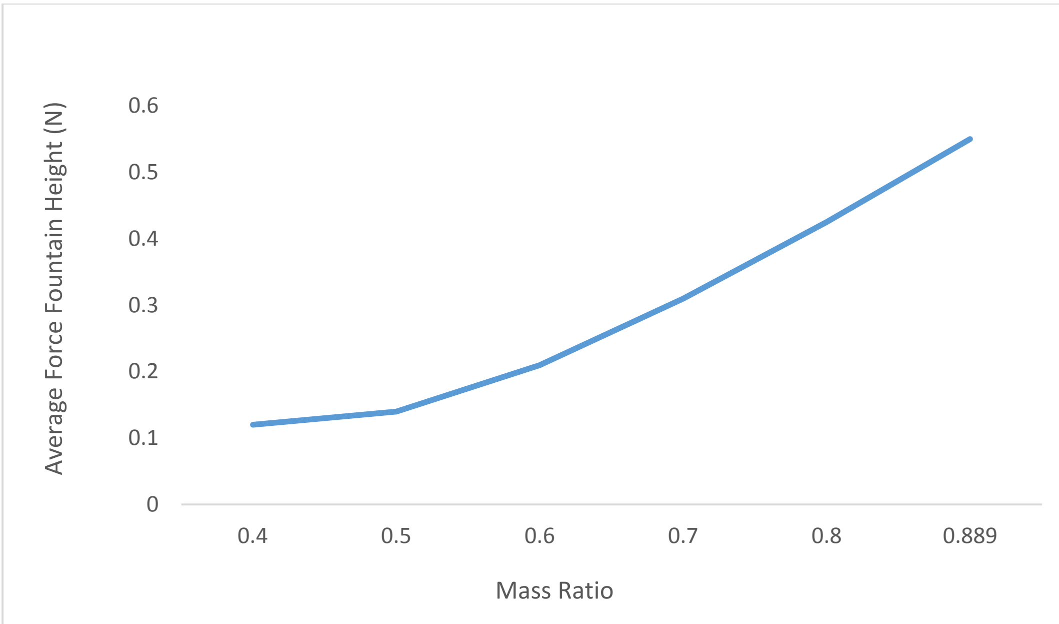


Figure 3.11: Average force of the chain fountain for different mass ratios

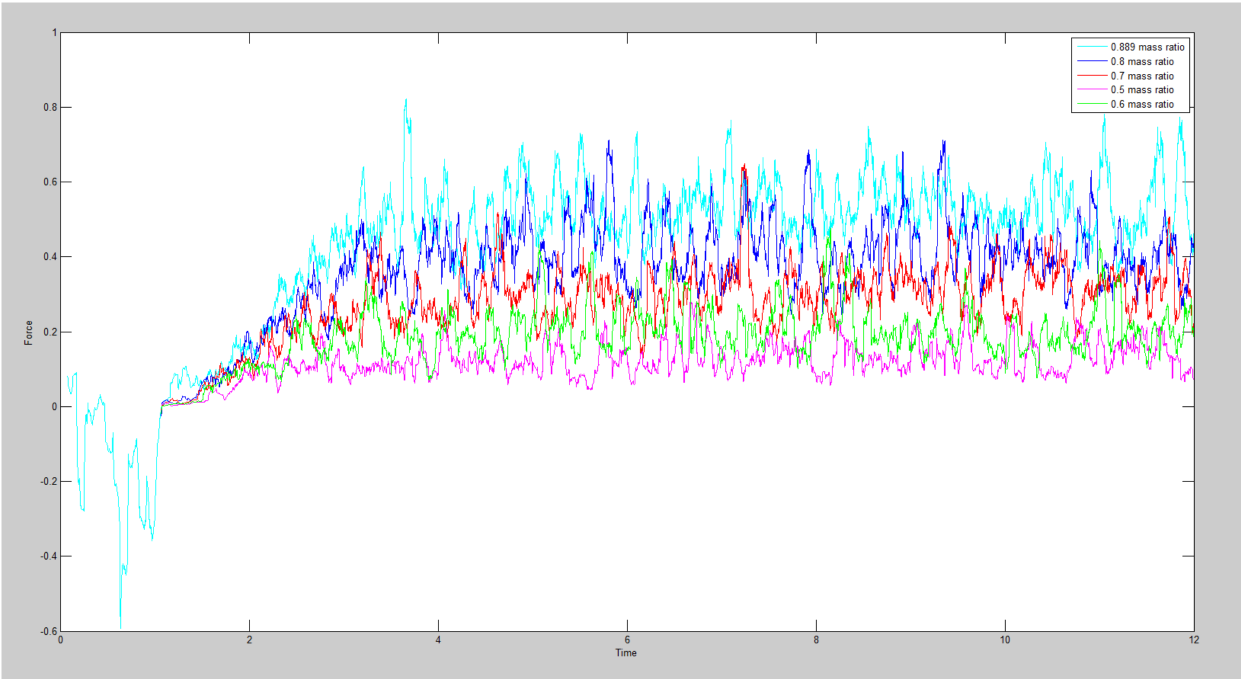


Figure 3.12: Force of the chain over the time for different mass ratios

CHAPTER FOUR

CONCLUSIONS

We reproduced the chain fountain effect and tested the explanations proposed by John Biggins and Mark Warner by changing inertial properties of the chain links. We found that the theory of an upward force from the top of the pile on the link by physicists John Biggins and Mark Warner is supported by simulation.

Form the results of our experiment we find that the moment of inertia effect appears to dictate chain fountain height and existence, as we can see from the force data. We also can see that speed data refute centripetal mechanism for chain fountain, which supports the phenomenon of the moment of inertia behind the chain fountain formation.

REFERENCES

[1] https://www.youtube.com/watch?v=6ukMId5fIi0.

[2] Mould S. 2013. Self-siphoning beads. http://stevemould.com/siphoning-beads/

[3] http://www.nytimes.com/2014/03/04/science/the-chain-fountain-explained.html?_r=0

[4] Biggins JS, Warner M. 2014. "Understanding the chain fountain." *Proceedings of the Royal Society*. A 470: 20130689.

[5] Hamm E, Geminard J-C. 2010. "The weight of a falling chain, revisited." *American Journal of Physics.* 78, 828; doi: 10.1119/1.3429983.

[6] Grewal A, et al. 2011. "A chain that speeds up, rather than slows, due to collisions: How compression can cause tension." *American Journal of Physics.* 79, 723; doi: 10.1119/1.3583481.