MEEM 3502 - Product Realization 2 Final Project

Analysis of the Pogo Stick

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Executive Summary

Gimbal Engineering has chosen to analyze the design and manufacturing of a Pogo Stick. Pogo sticks are traditionally comprised of a spring, shaft and foot pegs, designed for the fun and enjoyment of children. Gimbal Engineering composed of Brian Haupt, Garrett Dubie and Jack Babcock, who are all mechanical engineering undergraduate students at Michigan Technological University. Gimbal Engineering has gained its credibility and experience through a series of rigorous engineering classes and projects. Pogo sticks are designed to accommodate a leaf spring, rubber bands in tension, or simple coil springs to generate a response appropriate for the given age group of the intended audience. Main design practices include testing for forced input to determine frequency of system response and to determine the failure modes associated with pogo stick use. The main goal of analysis for this report will focus on the types of material used to manufacture pogo sticks, the vibration response of the system and the cycle life of an average pogo stick.

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Background

The pogo stick is most commonly known as a toy used to jump up and down off the ground through the use of a shaft, spring, and pedals to stand on. The idea for the pogo stick originated from a patent filed by George H. Herrington for stilts that utilized compression springs. Figure 1 is an image of the idea from 1881 [1].

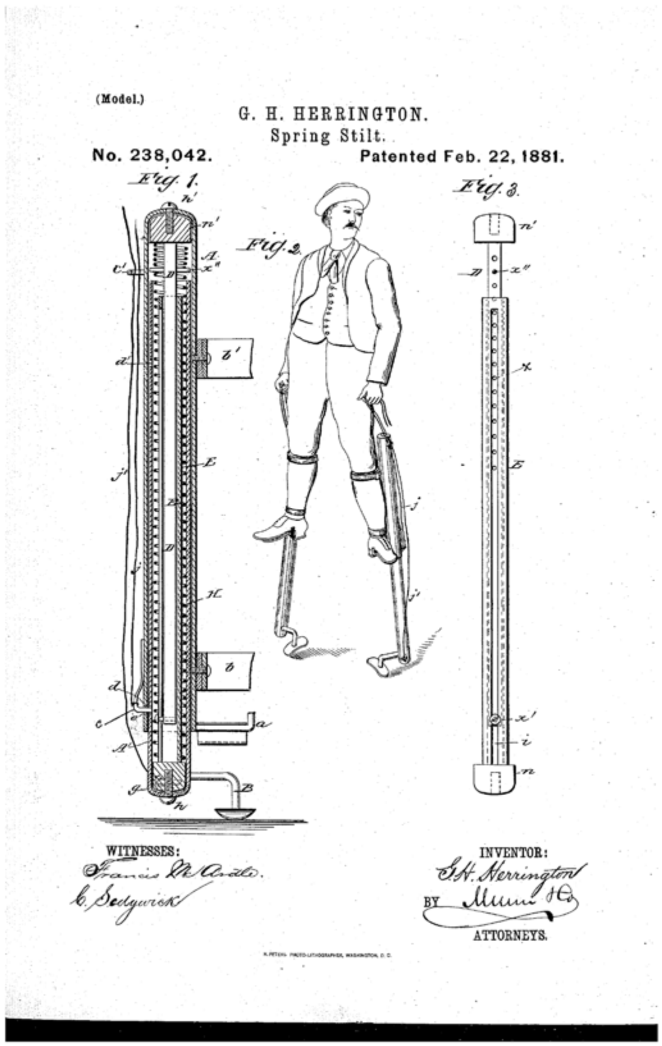

Figure 1: The illustration shows the compression springs that surround the two hollow shafts that are able to slide in and out of each other and also how the user would operate the stilts.

The purpose of this patented invention was "for leaping great distances and heights," according to Herrington. However, there were a few more innovations to the spring stilt that made it become more like the pogo stick most people know of today. The name “pogo” is thought by some to come from the names of the inventors of the more modern-looking pogo stick from Germany. Hans Pohlig and Ernst Gottschall filed a patent in Hanover in 1920 [2]. This pogo stick was made specifically for entertainment purposes and its German name, literally translated, means “spring end hopping stilt.” The final, most common, design was patented by George B. Hansburg in 1957. This design is the two-handle design seen on nearly every iteration of the pogo stick since. Figure 2 is the patent illustrations from 1955 [3].

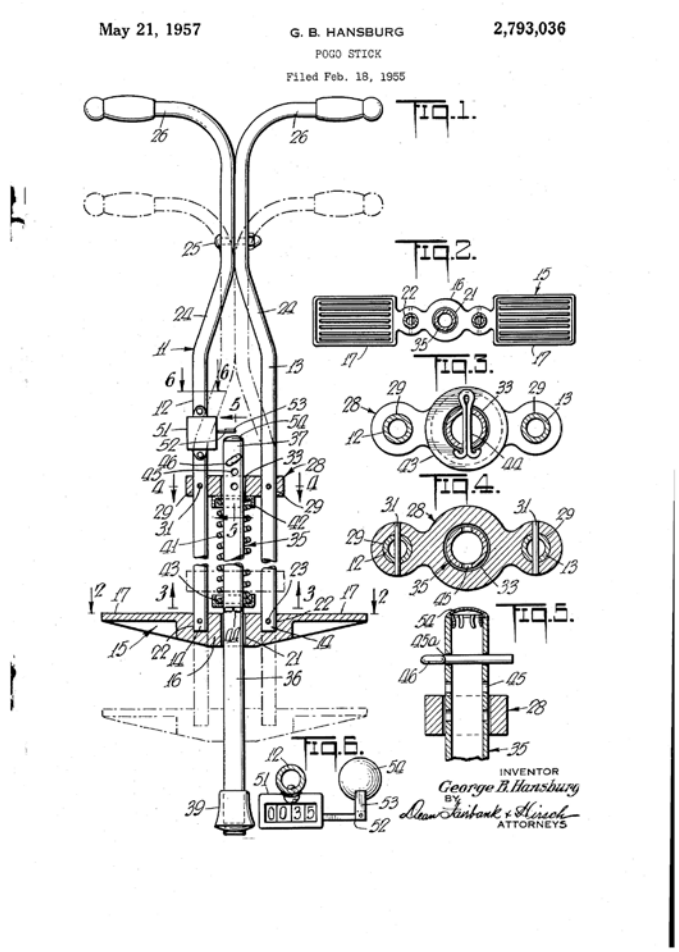

Figure 2: Common, “two-handle,” pogo-stick design.

The group decided to analyze and research the pogo stick because of its simple design (that offers many different variations to analyze) and the potential for improvement on the latest trends. The technology and design choices that goes into the latest models of pogo sticks is a great opportunity to see different systems that essentially do the same thing. Also, since this product is also a toy to potentially be marketed towards children it is interesting to see the safety precautions that are implemented in the design.

Componentry/Functionality of Main Components

There are many different kinds of pogo sticks which will be discussed later. However, they all consist of a few main components.

1. The handlebars.
2. Pegs, or pedals to stand on.
3. The internal system that transfers the kinetic energy from falling to potential, and then back again to kinetic energy making it possible to jump up and down.

The handle bars serve as a source of balance for the user of the pogo stick. Since the handlebars are not a part of the critical component design, it is up to the designer and manufacturer to make sure that they do not get in the way of the user or other components yet still provide a reliable grip so that the user can maintain their balance.

The internal system that converts the energy is the most important part of the pogo stick. Without it, it would only be a shaft with handles and pegs. The most common is similar to the initial invention seen in figure 1. Others consist of multiple, high-strength rubber and rely on its elasticity to spring back, providing transfer of energy and motion. The last common design is a leaf spring or a bending rod that is put into compression, bends and flexes back providing the transfer of energy. These designs will be discussed later and in greater detail.

Manufacturing Aspects

The original pogo sticks, crafted of wood, can be seen on a manufacturing scale as more of a prototype than a manufactured product because of the very low production volumes. As the pogo stick became a full scale product and was being shipped around the world, the wood was replaced with bent steel tubing to avoid rotting of the sticks during shipping [4]. During this era the sticks were composed of this bent steel tubing and held together by bolts. The spring was more than likely a simple spring steel coiled /forged on a mandrel and heat treated and coated (most likely painted in this era) to avoid heavy corrosion. As production volumes and manufacturing technologies jumped in the late 20th century the pogo stick designs shifted away from the bent steel tubing into a multi-part steel or aluminum extrusion frame which was often welded together. This change was likely a strength and packaging optimization, and the improved automation of the manufacturing allowed to maintain a relatively low cost with the increased number of processes. In this era many parts were probably still painted, however some parts in more recent years may have been powder coated for improved corrosion resistance and available manufacturing technologies. In this era many plastic trim and foam pieces were also added, which will be further discussed in the Latest Trends/Advanced Technologies section of this report. These plastic portions are likely injection molded or vacuum-thermo formed depending on the dimensions of the part because this is much cheaper than machining pieces and can reduce waste materials. The 21st century gave way to cheaper and more accessible materials and processes such as higher strength aluminums, a larger variety of steels, cheaper automation, and better coating technology. These factors again allowed for more complex pogo stick designs (as discussed in the Latest Trends section) without increased manufacturing costs. Many of the pieces, such as the main body of the pogo stick, could be composed completely of aluminum extrusion which may be pre-purchased or prepared on site. Springs can still be made by bending hot spring steel extrusion around a mandrel, but often times in large production settings springs are made using an automated forming machine to decrease the cost and cycle time per part. A smaller scale machine is shown below [5]. The machine operates by uncoiling spring steel from a reel and feeding it through the machine. a series of levers, arms, and dies, are used to form the spring into the desired shape. In this case, the spring is a simple compression spring so the only processes which the machine must perform is the coiling and cutting of the spring. For use in a pogo stick, the springs may be pre-set to avoid deformation but would probably not be ground square.

Figure 3: Automated forming machine for the manufacturing of small springs

With an increase in technology, the 21st century also came with a wave of lawsuits. From dining to transportation, companies are pushing safety more than ever to avoid liabilities, as must be true for companies manufacturing pogo sticks. Often times these safety considerations can add complexity to a design, and can make manufacturing more difficult which could increase the cost of a product. In addition to these safety considerations, there are more stringent policies relating to the waste and manufacturing of goods. One large difference between manufacturing in current times and in the past is the use of scrap materials. Historically, it may have been possible to purchase a product with very little scrap material in it. The reality of the 21st century is that almost any product a consumer would purchase has some scrap material in it. From a manufacturing standpoint this increases the need for quality control of both raw materials and product. As mentioned previously, the extrusions used in manufacturing pogo sticks may be prepared off or on-site. Regardless of where the extrusion is prepared, the metal content can vary significantly based on the scrap that was used in preparing the raw materials, and hence the strength of the material can vary from batch to batch. Luckily, with the increased process automation that was discussed previously it is possible to sample material and product more frequently to ensure low-liability products.

Design Analysis

For vibration analysis, every pogo stick is designed as a single degree of freedom (SDOF) mass-spring-damper system, with a damper optional, depending on child safety versus performance. The entire system is simplified in figure 4, where the spring is the total stiffness of every spring on the pogo stick, and the damper is the total damping in the system. The main design focus, however, is the spring since most pogo sticks are only equipped with rubber stoppers to provide very minor damping in comparison to spring stiffness.

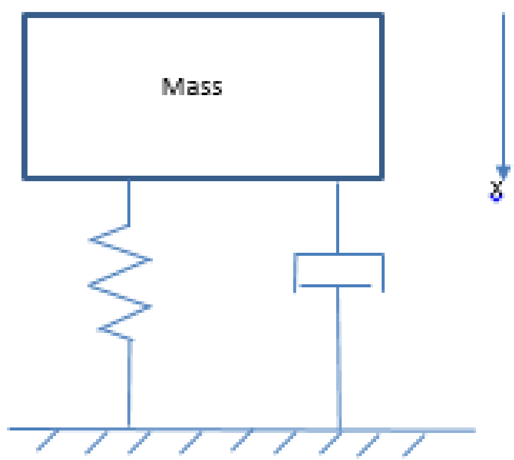

Figure 4: Mass, spring and damper pogo system simplification

By simplifying the pogo stick into a mass, spring and damper system, a free body diagram can be drawn. The forces which act on a pogo stick are the weight, the spring forces caused by initial weight deflection and the response to the input force from the user, and the damping force acting against the input.

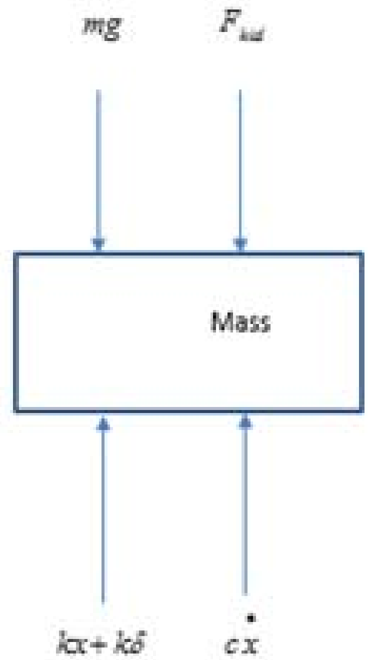

Figure 5: Free body diagram of simplified pogo system

These forces can thus be summed and reorganized to represent the response of the system to a given input. This representation is shown in equation 1 below. The input force will take the form of a step function since the input is the iterative jumping onto the pogo stick.

$$m\ddot{x} + kx + c\dot{x} += F_{user}$$

The main purpose of a pogo stick is to manipulate the amount of excitation is produce per given input, that is, how to regulate the amount of jump produced by a child's input. [6] In order to produce such an intricate analysis, several parameters need to be established through experimentation. The total mass, equivalent stiffness, equivalent damping, and frequency of input are manipulated to achieve the perfect pogo stick design [7].

The total mass of the system is a simple parameter to test for. Apart from simply measuring the pogo stick on a scale, the mass of the user must be taken into account. [8] Average mass values for given age groups is well researched in the health field, with numerous tabulated results for the masses of different age groups. The manufacturer must first establish a desired age group, retrieve the correlating mass, and design around that mass. The most effective procedure to follow, however, would be to test for the upper, lower, and mid range values of mass when testing for stiffness and damping.

Equivalent stiffness is another non trivial experiment. The pogo stick will stay at rest and measured to length. A known mass, preferably within the intended user's weight range, will be placed on the spring, and the deflection is measured. [9] In experiments to follow the full compression forces for a pogo stick spring will be tested for to determine the failure modes.

The amount of damping the system undergoes is also a well tabulated data source. Usual amounts of damping is centered on the rubber stopper against concrete or pavement. [10] The associated damping coefficient is about 250 n-m/s. Other forms of damping is to pressurize the spring housing allowing the spring to act against a pocket of air. This air pocket will act as a damper against the input force and would most likely be installed in children's pogo sticks focused on ultra safety. For the sake of this report, such a system will not be considered, since ultra high performance or super jumping pogo sticks will also not be discussed.

An example for nominal values used to test for pogo stick response will be used to show a typical pogo stick's vibration pattern. Using matlab simulink to reconstruct a mass spring damper , the forced response of the pogo stick X can be determined as a function of time. The model will be for a 30 kg user, which is a rough average for a twelve year old child, operating at a period of one second, a damping value of 256 n-m/s, which is estimated damping between a rubber stopper and concrete, and a stiffness of 1000 n-m, which is within usable pogo stick range. This test resulted in the following response, described in figure 6.

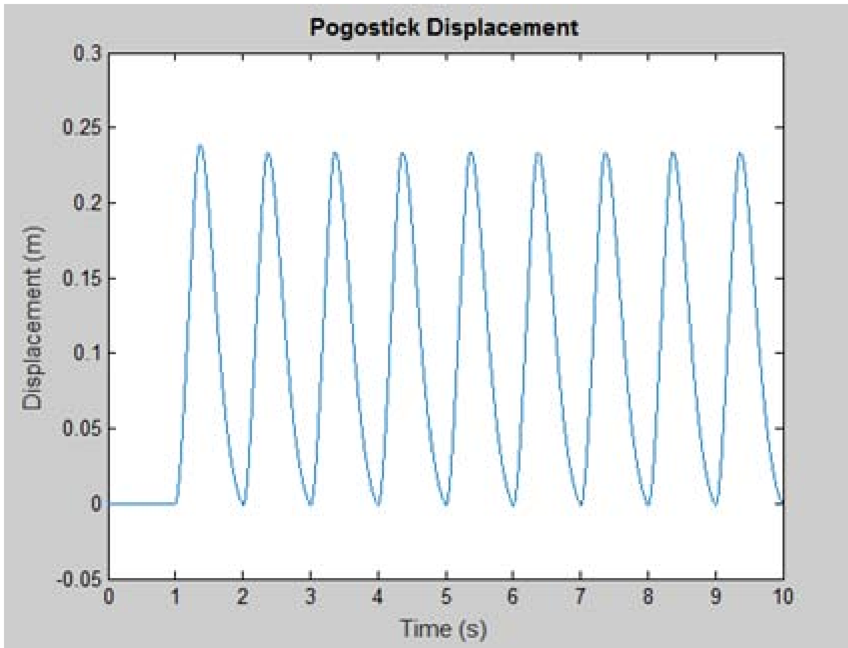

Figure 6: Pogo stick system response

Figure six describes the level of displacement the pogo stick will produce given a twelve year old child's input. The greatest output is about a quarter of a meter, which is expected, on average, on a pogo stick designed for a child. Also, the applied frequency outputs a frequency that matches the initial expected value of one jump per second, as the steady state response of the system reaches a peak at each second.

The only realistic approach at manipulating this response, however, is to change the equivalent stiffness . Since the damping is fixed for a rubber stopper against concrete, the force input frequency is fixed given a child's input, and the mass is an externally controlled variable, the stiffness is the single manipulated design feature to produce different jumps. This reality is desirable, since there is not any complex research and development manufacturer must pay into to produce a better model pogo stick, that is, there is only one variable to the displacement output. This means the response changes linearly as stiffness changes.

For product development analysis, designing for pogo failure becomes the center of analysis. The two types of springs for analysis will be the leaf spring and coil spring design. The third design, comprised of several rubber bands in tension, is a high performance model and beyond the scope of this report. Also to be tested for failure will be the welds on the footpegs.

For coil springs, the ends will be considered grounded and squared to comply with shaft dimensions, as shown in figure 7. An educated guess will suggest the major diameter will fall within a few millimeters short of the shaft inner diameter, and the pitch will vary depending on desired spring stiffness. This type of problem is most closely associated with cam and spring design, where a spring is not statically loaded, but rather succomed to a step input, much like a revolving cam against a spring.

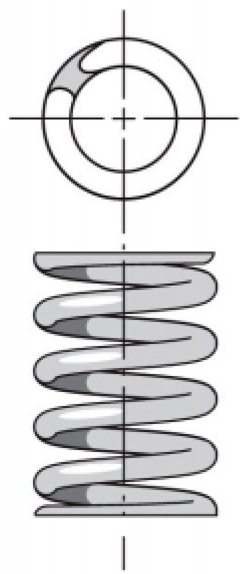

Figure 7: Physical representation of a spring with squared and ground ends

The parameters required to determine the appropriate coil spring design includes the frequency of applied force, the weight of the user, the applied force of the user not including weight and allowable spring length. Spring length can be iteratively found using a base example and changing for different desirable spring stiffness. The clash allowance ought to be assumed as 10% since the weight of the user will vary. The diameter will need to comply with the shaft inner diameter.

With the aforementioned parameters defined, the spring length, coil number, and solid length can be determined. Using equation 2: below

$$Ck_w = \frac{\pi \tau_{max} d^2}{8F_{max}}$$

where tau max is the allowable shear stress the spring can undergo, F max is the maximum assumed force, D is the spring diameter, and CK wahl is the spring ratio multiplied by the Wahl factor for cyclic loading, can the spring ratio and pitch diameter can be found. Ck wahl is used in a stress correction factor chart for helical springs. The spring stiffness will be found experimentally at a known applied force. The number of coils required is known through equation 3 below.

$$N = \frac{dG}{8C^3 k}$$

Where G is the shear modulus of desired spring. Usually this number will be associated with steel or aluminum shear modulus'. The solid length is found using equation 4.

$$l_f = l_s + \frac{F_{Solid}}{k}$$

Buckling is determined using the free length and equation 5. This value will be used to determine if the spring will undergo suntable movement and fail.

$$\frac{l_f}{D}$$

Spring surge does not need to be calculated since the frequency of spring excitation is very small at one Hz compared to the natural frequency.

The next type of spring commonly used is the leaf spring. For iterative loading, the analysis is very similar, but determining the spring rate changes slightly. The type of spring used in leaf spring pogo sticks is the semi elliptic style leaf spring, shown .in figure 8 There is only one leaf to design.

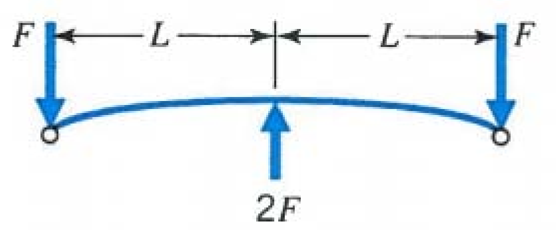

Figure 8: Semi-elliptic leaf spring

The stress of the leaf spring can be determined using equation 6, which can be used for maximum and minimum applied stresses. The length is dependent on the user intended, and the force will be half of the input force on each end.

$$\sigma = \frac{6FL}{bh^2}$$

The only welded component to a pogo stick are the footpegs, and in some cases the handlebars. For the sake of this design it will be assumed that the handlebars are simply bent horizontally at 90 degrees, limiting weld design to only the footpegs. Each footpeg will receive half of the downforce produced by the user. The footpeg welds must be able to withstand iterative down force to avoid failure. The welds will be butt joint welds.

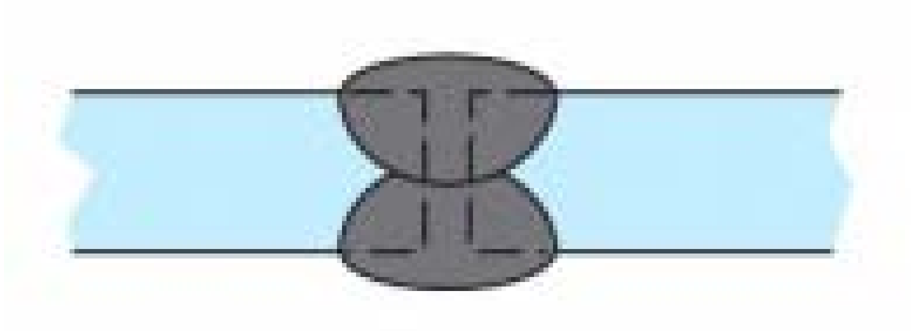

Figure 9: Butt weld for foot pegs

The design of a weld is determined by the safety factor desired by the manufacturer. With a known applied input force and a known yield stress of the desired material, a throat area can be designed for the safety factor desired by the manufacturer. The Safety Factor value will most likely fall between 10 and 15. This relation is given by equation 7 below.

$$F = \frac{.58 s_y A}{SF}$$

Latest trends/Advanced technologies

For most people the first thought that comes to mind when we hear the term “pogo stick” is either an old rusted bit of steel tubing with a rubber foot and a coil spring, or for some it may be even more traditional, such as a wooden framed pogo stick with a coil spring. Over the past century technologies which were once military class have been applied to everyone’s favorite backyard toy, the pogo stick.

In the last few decades improvements to the pogo stick have involved different plastics and foams. From an engineering viewpoint, these changes have been identified as efforts to make a more aesthetically desirable product, to make a product which is lighter (and therefore easier to control for a child) and to reduce the vibrations experienced by the operator during common use. The 90’s came with a demand for vibrant, exciting colors. In order to sell more product, pogo sticks were more than likely given plastic components. Adding these components was likely cheaper than the extra manufacturing step to add paints and stickers and allowed for easy structural reinforcement. As cheap plastics and foams became more readily available it became easy to apply these foams to the handles and bodies of the pogo stick to help avoid injury when falling during use. Additionally, the damping that was added by applying a foam coating would theoretically reduce the vibrations that the rider experienced due to the impact with ground and the ringing of the spring.

Several attempts have been made in recent years to move away from the traditional coil spring and toward a more elegant solution without such harsh noise and vibration performance. Additionally, there has been a push for both a safer stick, and one that will allow the user to jump higher. Perhaps the safest configuration that has been observed is the ball style pogo stick, as it reduces the number of moving parts that could make it a dangerous toy for small children and increases the contact area with the ground (hence reducing the stress that would be experienced if a user hopped on someone's hand or foot).The ball style pogo stick, example shown below, uses a rigid body with a ball of compressed air on the lower and costs around $40 [11].

Figure 10: A safe version of a pogo stick designed for children

Pogo sticks geared toward an older audience come with more sophisticated and sometimes more dangerous designs. There are three designs which can summarize the more advanced configurations for the pogo stick. These three designs are the BOWGO, the VURTEGO, and the FLYBAR as termed by various companies and are shown in the image below [12].

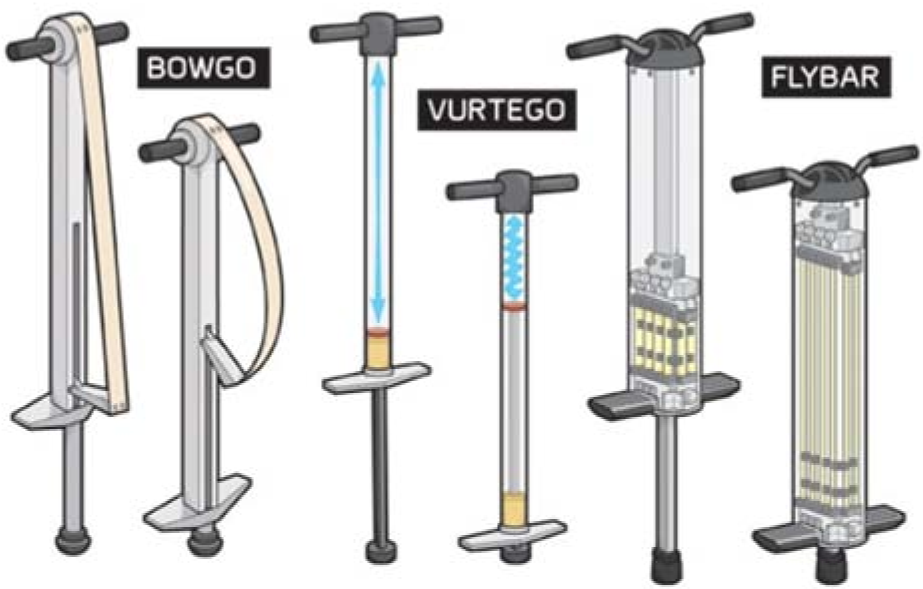

Figure 11: Illustrations of several modern pogo sticks [12**]**

The BOWGO is currently mass produced and sold by Razor (the company that brought us the Razor Scooter a few years back) and operates using a design similar to a leaf spring. It is unclear as to whether the device has a linear or non-linear spring rate, however a non-linear spring rate could allow for a wider weight range of user. As shown in the image below the leaf spring essentially acts in the system in a similar manner to the coil spring, but undergoes a bending loading when compressed. While this version of the pogo stick sells for around $200, there have been many complaints of injuries due to the leaf spring contacting the operator's legs during use [12].

The VURTEGO was designed to be geared toward adult operators, as it allows for a much heavier weight, however it could also be scaled for a child. The VURTEGO operates using a plunger system which creates an air spring when the foot of the pogo receives a load. These pogo sticks have been positively accepted on the market so far, as there is little possibility for injury due to moving parts and allows the user to jump higher than other sticks but comes at the hefty price of up to $400 [13].

The last of the major designs in pogo sticks today is the FLYBAR. With a price tag of around $200, the FLYBAR hit the market receiving mixed reviews. While most users were satisfied with the operation of the device when it was in operating condition, many users complained that the rubber bands, used as springs, “dry-rotted” or snapped within reasonable use [13]. Additionally users said that the device was bulky and heavier than other pogo sticks. An image of the bulky spring system is shown below.

Figure 12: The elastic mechanism within a Flybar pogo stick**.**

Materials Selection

Each brand’s pogo stick uses different materials due to their main component design. A commonality between most pogo stick designs is the aluminum housing and frame. Aluminum provides a cost effective and strong frame for the internal workings of common, “department store,” pogo sticks. However, some manufacturers of higher-end, extreme sports pogo stick have used a carbon-based polymer to encase the inner-workings of the pogo stick. Unlike aluminum, carbon polymers are tough to dent and require a lot of force to fracture the housing. If a user were to jump as high as 10 feet (as some marketers claim is possible), and then fall, the user should be more worried about their own body rather than their pogo stick.

As for materials used in the main components, the many design choices have just as many materials choices. The BOWGO stick uses a fiberglass bending rod to provide the springback. Depending on the type of fiberglass used, it can have a compressive strength from 20 to 50 ksi. This is more than enough to withstand an average adult bouncing up and down for extended periods of time.

The FLYBAR brand pogo stick uses elastomers that determine the force of the bounce. Their website doesn't go into detail, however, these thrusters act like hyper-strength rubber bands and undergo high tensile loads as the user hits the ground then the forces in the elastomers will spring back launching the user high into the air. The FLYBAR pogo stick also employs plastic bearings in the design to provide smooth movement across all of the inner workings. As with any bearing, they recommend keeping them free from sand and other grit so that the fatigue life will be as long as possible.

Finally, the VURTEGO pogo stick utilizes both aluminum and stainless steel designs. Both designs are built for a pneumatic energy transfer system in which the air inside the tube compresses as the user bounces down and that pressure is what springs the user back up. Again, whether it be aluminum or steel, these materials have the strength required to withstand the pressure of the air inside the tube as well as the tensile force the user places on the apparatus every time they slam onto the ground.

Conclusion

In conclusion, pogo sticks are mass spring damper systems designed and manufactured for the enjoyment of children. Pogo sticks come in great variety, and with each different iteration, the amount of jump achieved is manipulated to accommodate the user of the modern day. Pogo sticks have become more advanced, using lighter technology as reminiscent of the space age. Pogo stick competitions are held, which greatly relies on high performance pogo stick designs.

Challenges faced by the team was determining the real history on pogo sticks. Pogo sticks are fairly simple, and do not allow for too much variation. It required a lot of digging to see any real change in how pogo sticks changed. The only remedy for this challenge would be time and the availability of pogo stick history. Another challenge the team faced was determining failure design. Pogo sticks are not fixed to the ground, rather there is an unknown impact force associated with every jump. Although this is outside the scope of the class, having the ability to test for this value would have been useful to produce a more wholesome report.

Comments and Recommendations

Our Team felt as though the work being requested of us for this report was fair and allowed for us to analytically use what we learned in our product realization courses here at Michigan Technological University. While we were not required to perform extensive calculations or generate generic cad models of any kind, we were able to use what we learned without wasting valuable time. We appreciate that we were not asked to create another theoretical product, as this process becomes quite old after Engineering Fundamentals, Engineering Design Process, and Product Realization I. That being said, it initially seemed as though the requested page limit is somewhat extensive for the scale of the project, and could be shortened by 25%. Additionally, it may be beneficial to reduce the group sizes to 2-3 members with these shorter reports, again due to the nature and scope of the project. Our team struggled in selecting what product to analyze and it would be nice if you were able to provide future classes with a list of possible products to help the brainstorming process. We firmly believe that as a first iteration, this project was successfully achieved its intended goals and in the future iterations it will continue to improve.

Acknowledgements

Our team would like to thank Radheshyam Tewari and the other professors of Michigan Technological University for their contributions to the education of each team member in the field of Product Realization and Mechanical Engineering. The knowledge that was gained through these courses will stay with the team in all that we do and we look forward to continued relations with the university.

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