The Exploration of Quieter Actuation in Animatronic Toys

by

Paul Fathallah

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Signature of Author..
Department of Mechanical Engineering
May 9, 2008

Certified by..
David R. Wallace
Professor of Mechanical Engineering
Thesis Supervisor

Accepted by..
Lallit Anand
Professor of Mechanical Engineering
Graduate Officer, Department of Mechanical Engineering

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ABSTRACT

The main objective of this research was to find ways to actuate animatronic toys quietly. A practical assessment was conducted to evaluate a variety of quieter actuation methods for animatronic toys for Hasbro®, the client. Also, an evaluation of acoustical enclosures was carried out to determine if they were an effective way to reduce the sound from gear-boxes and actuators that currently actuate the line of animatronic toys made by the client.

Several actuation methods and enclosure materials were considered and evaluated based upon their performance, relative quietness, and their viability in the application into animatronic toys. Qualitative and quantitative comparisons were made of each of the actuation methods and were eliminated based upon their ability to satisfy the design constraints based upon their safety, acoustical performance, and ability to reproduce the life-like characteristics of the toys. Quantitative comparisons were made of each of the enclosure materials using a sound control box and a decibel meter to measure the output sound pressure level of each enclosure configuration.

Among all the evaluated alternatives, from advanced actuation methods to acoustically attenuating enclosures, the acoustical enclosures performed the best. The acoustical performance rating of the polyurethane-neoprene based composite layering was far superior to the other materials tested, but was not the most economical of the acoustical enclosure materials. Acoustical enclosures can be implemented in the current line of animatronic toys and do not require any mold changes, modifications to the product architecture. Material acquisition and forming are the only steps needed to achieve the sound attenuation performance they effectively provide.

Thesis Advisor: David R. Wallace
Title: Professor of Mechanical Engineering

Table of Contents

List of Figures

List of Tables

1. Introduction

1.1. Motivation

Animal-like robotic toys have been in existence since the mid 1950's when the Japanese came out with a battery powered fuzzy poodle toy, driven by a small DC motor [1]. As the years progressed, and technological advancements reduced the cost of components needed for automation, animal-like toys have developed into interactive robots that respond to various stimuli through the use of DC motors, gears, cams, sensors, and other mechanical, electrical, and electro-mechanical elements. These technological advancements have led to inexpensive, realistic, animatronic toys. For example, see Figure 1 for an image of a FurReal Friend™ animatronic toy horse named Butterscotch.

Figure 1: Image of the animatronic toy horse manufactured sold by the project sponsor Hasbro® that retails for $299.99 (batteries not included).

The horse, seen in Figure 1, has a myriad of motor skills enabling it to convey pony-like characteristics through the use of linkages, springs, cams, and other mechanical elements. It also comes with a plastic carrot and brush that it responds to when they come into close proximity to the horse. While this toy was on the high end of the animatronic toy line, retailing for $299.99, Hasbro® produces a wide range of toys ranging from $12.99 to $69.99 which includes puppies, cats, kittens, dogs, lions, monkeys, chimps, tigers, cubs, leopards, parrots, bunnies, and bears. However, there consistently persists a problem consistently in the animatronic toys: they are loud. This problem diminishes the life-like nature of the toy and provides the motivation for this research to find ways to quietly actuate the animatronic toys while maintaining their realistic animal-like nature.

Currently, animatronic toys are actuated with DC motors and some combination of cleaver linkages, cams, and gears to simulate motions. Toy manufacturers are looking for ways to heighten the end-user's experience through greater complexity and biomemetic capabilities in the toy, without excessive cost. Since quieter actuation methods are traditionally costly, prohibitively so for economically viable application in animatronic toys, toy manufacturers have decided to weigh their options and continue to use inexpensive plastic parts and DC motors. Furthermore, since technology and cost reduction do not often go hand in hand, technologies that can advance actuation, reduce unwanted sounds, and provide a realistic end-users experience that are not expensive are at a premium. Is there a better way to actuate an animatronic toy? Hasbro® has developed a few technologies; one of them includes the stacked cams, which provide more degrees of freedom to the toy allowing them to execute more advanced motions and sequences of motions to provide an even more realistic user experience but they have still not come up with an acceptable solution to reducing the sound emitted from the plastic gears and inexpensive high-speed low-torque DC motors. This report will explore and evaluate the possible alternatives for quieter actuation, keeping unwanted noises at a minimum, while maintaining the intended realistic nature of the toys.

1.2. Problem Definition

Find a cost-effective, novel, and universally applicable way to establish quieter actuation in animatronic toys. Also, to create an acoustical attenuation enclosure that can be used to further reduce the noise created by the actuators and transmission boxes in the animatronic toys.

1.3. Objectives

The objective of this research was to integrate the product design process in designing novel ways to reduce the noises produced by Hasbro®'s animatronic toy line, FurReal Friends™. The FurReal Friends™ are a barn house of animatronic plush pets, toys that looked, moved, and sounded, mostly, like animals. The issue is that the actuators inside of them produce noises that acoustically interfere with their intended realistic nature. In satisfying the objective, two approaches were established to potentially realize the main objective: 1.) design a quieter actuator and or 2.) design a way to reduce the undesired noises produced by the current actuators. The toys, and whatever was to come of this research, should be energy efficient, quieter, realistic, and inexpensive to manufacture. The sponsor also wanted the actuators to be universally integrated into their current FurReal Friends™ animatronic toy line, and any future products that require quiet and inexpensive actuation.

1.4. Outcomes

This research led to two promising concepts, namely: a sound dampening acoustic enclosure and a vibratory, flexure driven (VFD) advanced actuator. While the acoustical enclosures can be implemented in the manufacturing of the toys immediately, the VFD actuator shows great promise, still needs development and reduction to practice. The acoustical enclosures do not impede on any architecture of the toys inner structures. However they need to be integrated with the fur coats and facades. New actuators, such as the proposed VFD actuator, will require a modification to the product body architecture for its successful integration. Ultimately, the combination of both noise reduction techniques and quieter drive mechanisms will greatly improve the life-like potential of the toys.

1.4.1. Acoustical Enclosures

The acoustical enclosures seemed to be the most plausible solution for the design problem posed by Hasbro®. While it was not an advanced form of actuation, it can be universally applied to any product that requires acoustical attenuation for the same sound frequency range as the motors of the animatronic toys. The findings of research indicated that these enclosures were able to keep the same hard gearing and DC motor actuation but reduced their impinging acoustic energy propagation by almost 90% (see Table 1 for details) by dampening the higher frequency sounds emanating from the source. This was achieved by covering the transmission box in the toy with the sound dampening polyurethane-neoprene based composite layering. Refer to Figure 2 for an image of the covered transmission box.

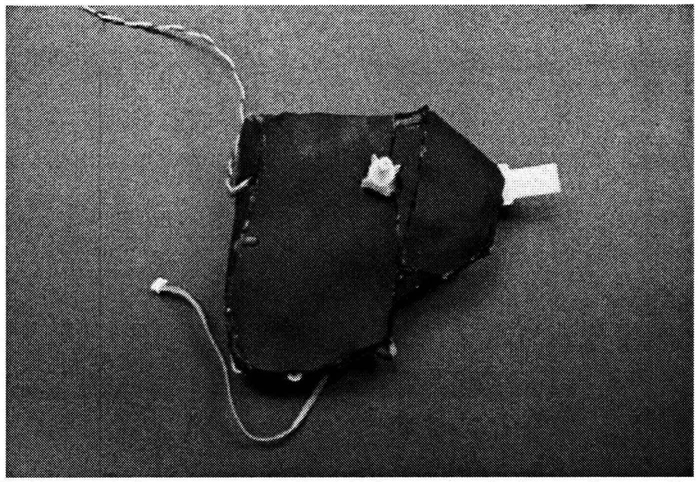

Figure 2: Image of the transmission box covered with the composite layered acoustical enclosure.

This material while being one of the more costly materials tested was vastly superior in sound dampening performance to the other materials that were being tested. Two caveats: first, its optimal performance range does not include all frequencies of the unwanted sounds produced by the toy and second, it's relatively costly; potentially prohibitively so for the toys on the lower end of the spectrum.

1.4.2. Vibratory Flexure Driven Actuator

The VFD actuator is still in the development process. The idea behind its function was to oscillate a voice-coil (speaker diaphragm) at sub-human frequencies to flex a rotary flexure, converting linear motion to rotational motion, thus eliminating the need for high-speed, low-torque, DC motors. Currently, it is being advanced to provide higher torque and power at even lower frequencies. While functional sketch-models have been realized and preliminary prototypes have confirmed the potential of this technology, it has yet to reach a stage where it's able to produce high enough torque at the desired sub-human hearing frequencies but work is being done to accomplish that. Work on the new drive mechanism is being continued by graduate student James Penn [21].

2. Exploring the Possibilities

2.1. Introduction

Before the design process began, it was important to assess the current state of technology in actuation, more specifically toy actuation, and to determine where the majority of the noise came from in animatronic toys. This process began with the acquisition of several robotic toys for dissection and evaluation. Hasbro® sent an animatronic dog, cat, monkey, lion, tiger, horse, puppy, kitten, baby Furby® and the full sized Furby®. The most common modes of actuation were some combination of gears, linkages, negator motors, stacked cams, v-belt drive, internal and external cams, DC motors, and geared transmissions. The most common of those were cams, gears, geared transmissions, and DC motors.

2.2. Current Toy Actuation

2.2.1. DC Motors, Spur Gears, and Geared Transmission Boxes – The Culprits

DC motors convert electrical energy into rotational kinetic (mechanical) energy. Electrical energy is supplied to the motor and causes the armature and, in turn, the output axel, to rotate providing rotational kinetic (mechanical) energy. In most of the Hasbro® toys, a worm gear was typically affixed to the drive shaft of the DC motor in order to achieve the large gear reductions and prevent back-drive, shown in Figure 3.

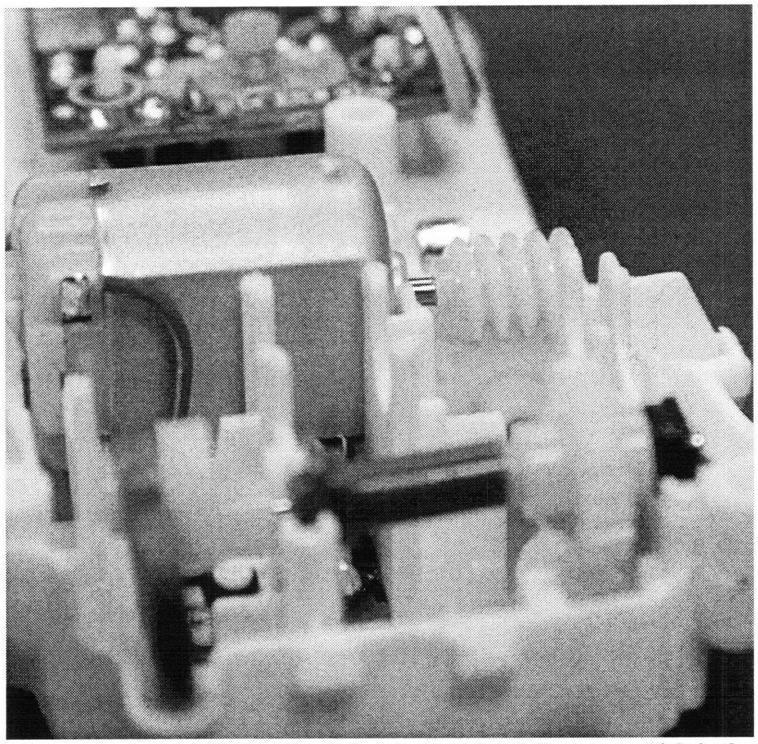

Figure 3: Image of the worm gear affixed to the drive shaft of the DC motor which is the first of many steps of the gear reduction for the animatronic Baby Monkey from the FurReal Friends line by Hasbro®.

Inexpensive high speed and low torque DC motors are used in order in order for Hasbro® to keep costs at a minimum. These motors rotate at roughly 9400rpm and do not produce enough torque to actuate the toys directly. Since additional torque was required to overcome the inertial, dynamic, and static loads of all the driven parts of the toys, multiple and large gear reductions are needed and are achieved with low cost plastic injection molded gears. These plastic gears are typically used to create gear reductions typically between ~1:50 to ~1:250 by means of a transmission or a modular transmission box in the case of the animatronic horse Butterscotch. Due to the tradeoff between cost and performance, the use of the transmission box and the inexpensive DC motors to maintain low cost production leads to a sacrifice in acoustical performance.

The plastic transmissions, used in the animatronic toys, were the main source of noise produced by the toy. The combination of the high speed, low torque, motors and the profile shapes of the plastic gears create substantial mechanical vibrations which are emanating from the air and from the plastic housing that held the toy together. The transmission box that was most closely considered during the course of this research was the geared transmission box shown in Figure 4, a gear box from Butterscotch, a 3ft animatronic toy horse made by Hasbro®. This gear box was used to drive the tail action and the part of the head action; it allowed the tail to sway and the head to shake, and passively actuated the nostril breathing mechanism of the horse.

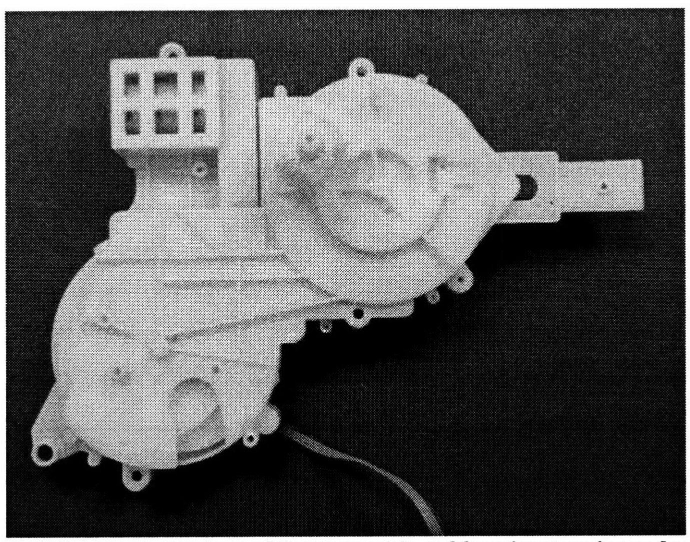

Figure 4: Image of the main transmission box of Butterscotch, a 3ft animatronic toy horse, made by Hasbro®.

Figure 5 shows the exposed underside of the main transmission box of Butterscotch. Note the several worm gears used both for power transmission as well as to prevent back-drive. The overall gear reduction, calculated to be approximately 1:250 for Butterscotch's head and tail transmission box, shown in Figure 4, was needed in order to achieve a high enough output torque to drive the head and the tail using the small DC motor as the input.

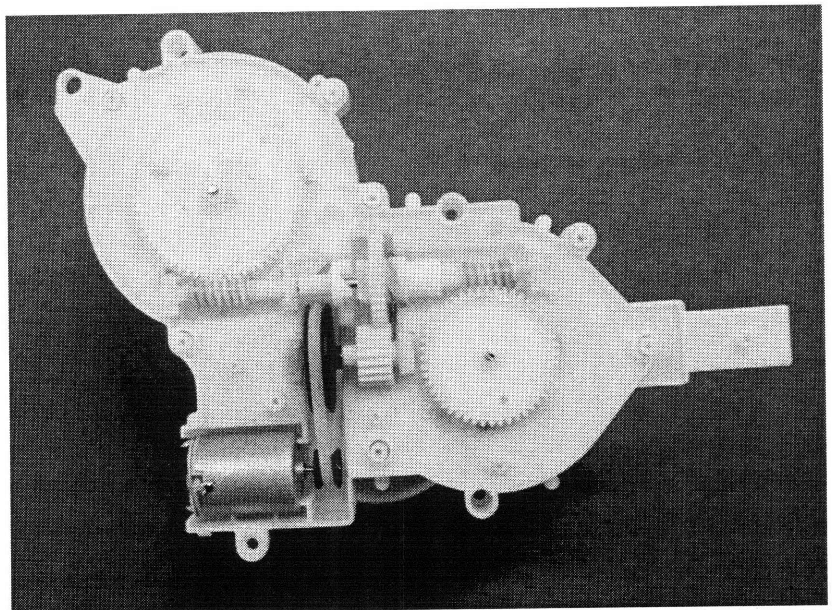

Figure 5: Image of the underside of main transmission box of Butterscotch shown in Figure 4.

The low-cost design constraint added another dimension of complexity to the design problem.

According to a research study done at Purdue University, much of the mechanical vibrations and sounds produced by these power transmission gears are due to the profile of the involute shape defining the gear tooth [Yoon 17]. The actual sound coming from the gear box was caused by the gear going in and out of mesh due to small gear backlash from manufacturing variation perturbations. The high frequency of the gear rotations cause these mechanical vibrations and are generating the majority of the noise produced by the robotic toy. The mechanical vibrations were able to propagate from the gear to the transmission box to the outer shell of the toy and ultimately made audible to the end-user of the toy. Using cubic spline elements, when creating the involute profile, would result in a minimization of unwanted gear noise and mechanical vibrations [17]. However, the cubic spline element models are more mathematically intensive models which may ultimately lead to higher initial fabrication costs.

2.2.2. Internal Cams and the Hasbro® Stacked Cam System

Hasbro® generally creates most of their oscillatory linear motion, in their animatronic toy line, from rotational motion by means of an internal track inside a rotating cam called an internal cam. Furthermore, they use a series of these to control several limbs, appendages, and body parts. See Figures 6 and 7 for images of these mechanical elements.

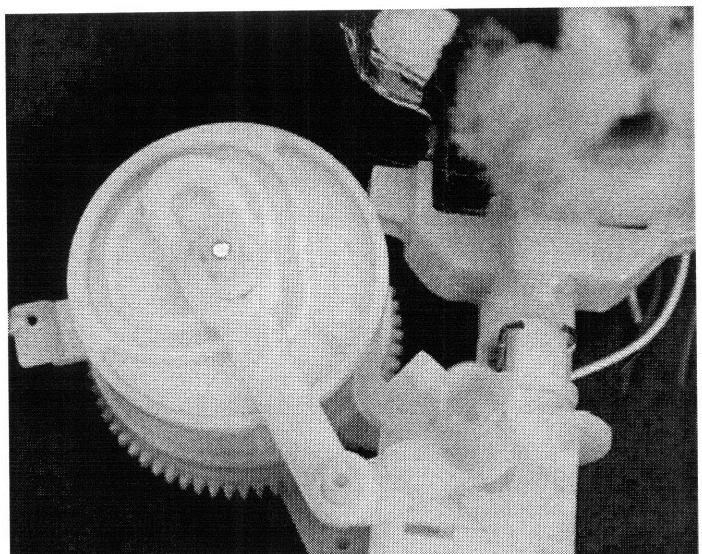

Figure 6: Image of the internal cam track for the animatronic Cat from the FurReal Friends line by Hasbro®.

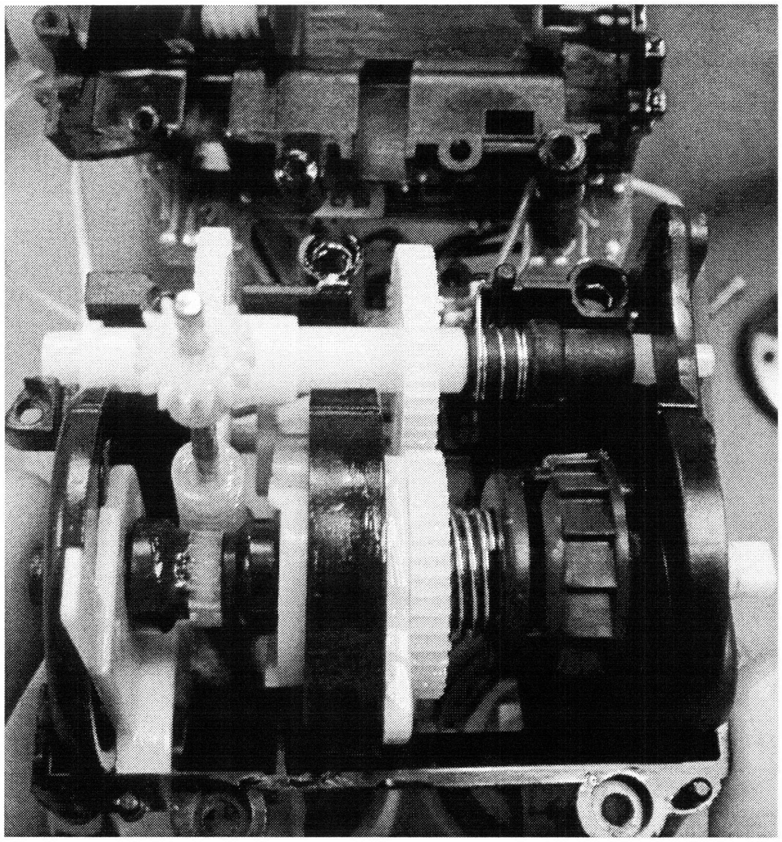

Figure 7: Image of the stacked cam and the one-way clutch inside the Baby Furby™.

The current state of technology in animatronic toy actuation that Hasbro® has implemented in many of their toys is the stacked cam design seen in Figure 6 and Figure 7. A one-way clutches was used in the Furby™, also seen in Figure 7, in order to achieve semi-independent actuation of certain functions. In the case of the Furby™, the one-way clutch prevented the toy from being back-driven in the event the end-user was so inclined as to force the Furby™ to move in a direction opposite of the direction it was currently moving. The Furby™ uses the stacked cam allows for multiple semi-independent outputs for a single input enabling the toy to execute a greater variety and combination of motions and motion complexity; ultimately at a low cost. Furthermore, the use of the stacked cam and internal cam, seen in Figure 6, can provide linear oscillatory motion as an output from a rotational motion input which has been what Hasbro® has done with almost all of the FurReal Friends™ line.

There was no real direct downside to the use of the stacked cams, internal cams, linkages, or gears other than the noises they generated. The sounds produced by the stacked cams, internal cams, and linkages were of a lower frequency then the sounds produced by the motor and gears. Therefore, they could not be resolved, eliminated, or reduced with the same acoustical attenuation approach used for gears.

2.3. Customer Need

In order to get the best understanding of the client needs, it was important to enter self-submersion into their products and develop a thorough and complete understand of the problem they faced with the animatronic toys. The client was looking for better ways to actuate the animatronic toys that would eliminate the undesired noises that the toys produced. Ultimately, they were interested in ways that were cheap, universally applicable, and simple to manufacture mechanisms that did not take away the toy's realistic function and appearance.

2.4. Brainstorming

In order to come up with a few good ideas many ideas were generated. One way of achieving this was to conduct some brainstorming sessions in order to attract many ideas from the participants to establish some ground rules for the brainstorming session, they started with the most important rules during the session: to encourage wild ideas and to defer judgment. In doing so, ideas could fire and people would not withhold the participant's creativity. Another result of the brainstorming session was to develop new and unique perspectives of the problem and of the possible solution space. A combination of ideas could stem from a few interesting ideas, and the participants would continue to build on them, which also can inspire new ideas. All the participants were given a stack of paper and a marker so when they came up with an idea, they would draw it out, pointing out the key characteristics of the idea and then would give it a few-word description or title. One conversation was held at a time during the session and participants were to stay on topic. Two sessions were held, consisting of roughly six people each. The groups were large enough to keep the conversations going yet small enough to keep everyone engaged and on topic. The ideas generated included:

- DC Motors
- Linear or Rotary Solenoids
- Hydrogen Peroxide
- Baking Soda and Vinegar
- Shape Memory Alloys
- Combustion
- String and Pulleys
- Steam and Thermal Gradients
- Magnets
- Bulk Flow and Hydrostatic Pressure
- Pressure Differentials
- Corriolis Forces
- Wind-up Toy Mechanisms
- Piezoelectrics
- Light Peristaltic
- Solar Differentials
- Photovoltaic Cells
- Balloons and Pneumatics
- Springs
- Rubber Bands
- Elastics
- Gravity
- Wind Power
- Heat
- Chains
- Gears
- Second Law of Thermodynamics
- Conservation Laws
- Sound Waves
- Capillary Action
- Centrifugal Forces
- Centripetal Forces
- Collisions and Momentum Conservation
- Laws of Motion
- Flexible Drive Shafts
- Viscoelastic bag
- Dwell Gears
- Combined Dwell Gears and Flexible Drive Shafts (single input, multiple output)

Once these ideas were reviewed, sketches were made that illustrated the application of some of the most promising of the concepts. The selected concepts included: shape memory alloy (SMA) applications, bimetallic strips, viscoelastic bags for sound control, pneumatic actuators, hydraulics, baking soda and vinegar, DC motors and gearing, piezoelectrics, and magnetic forces. Please refer to Figure 8 through Figure 17 for sketches of the selected concepts.

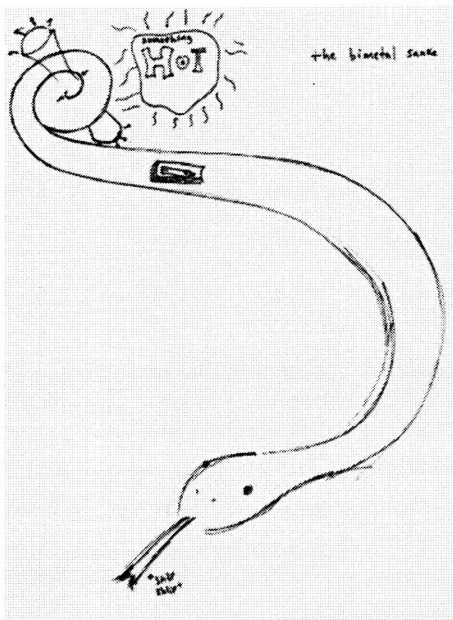

Figure 8: This concept illustrates the implementation bimetallic strips inside a snack. It shows the tail curing around a hot object.

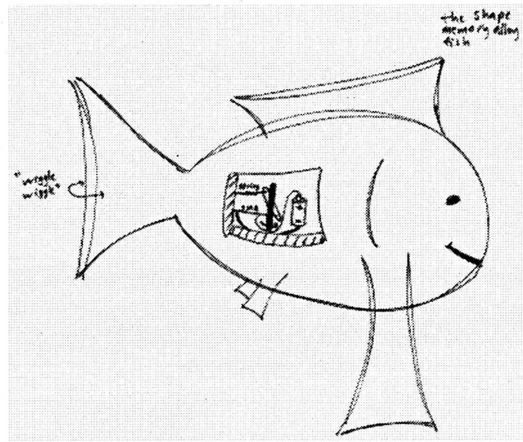

Figure 9: This concept shows a fish actuated with shape memory alloy (SMA) wire actuators. These can actuate either as a response to a thermal load or an electrical load.

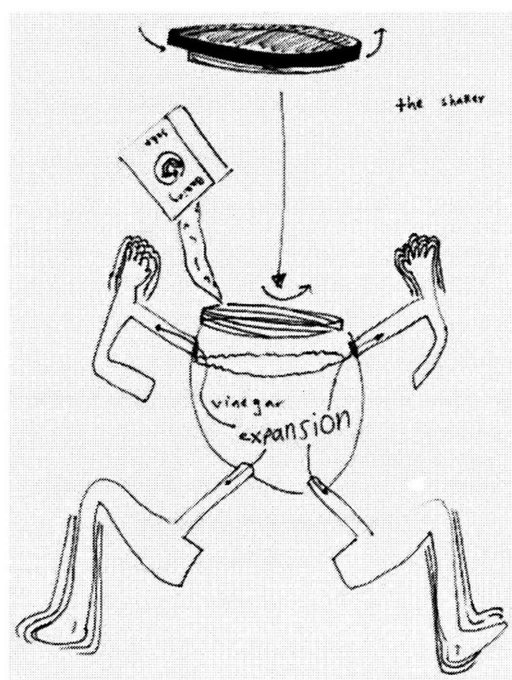

Figure 10: This image is the concept for the baking soda and vinegar method of actuation which uses expansion to actuate various body parts.

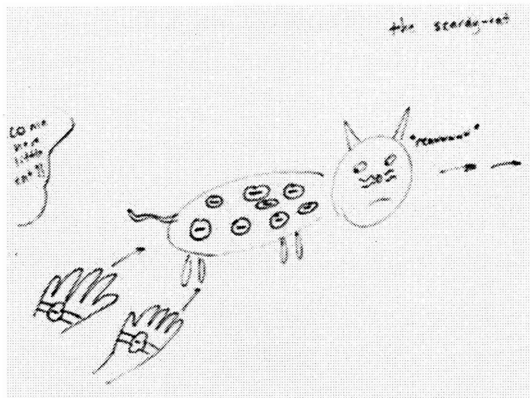

Figure 11: This concept sketch shows the use of like-like charge repulsion to get a "scardy-cat" to scurry along in the presence of the like charge hand controllers.

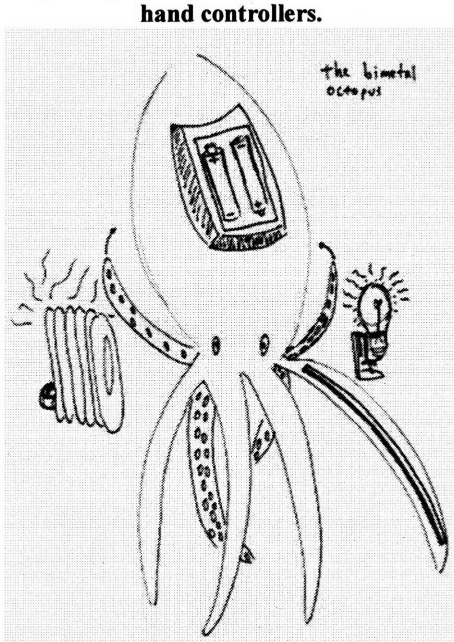

Figure 12: This figure shows an octopus actuated by a bimetal strip. Its tentacles curl up when the octopus is put on an incandescent light bulb or a radiator and crawls around as the bimetallic strips heat up and cool down.

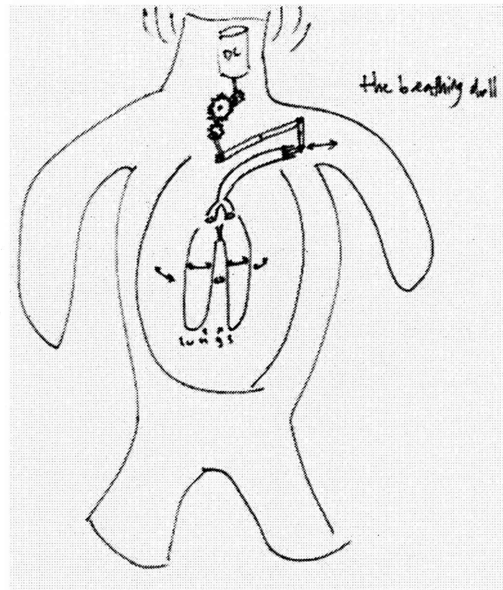

Figure 13: This figure illustrates the use of pneumatics, hydraulics, and DC motors to create a breathing effect in a toy.

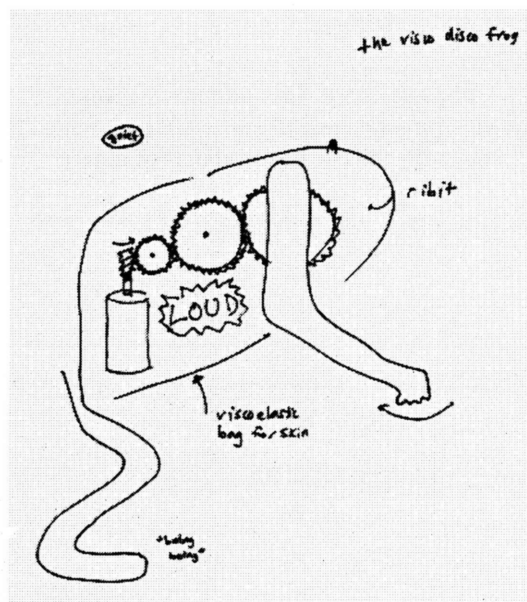

Figure 14: This concept drawing demonstrates the idea behind using a viscoelastic bag as an acoustical attenuator to make the observed noise produced by the toy quieter then it is inside the viscoelastic bag.

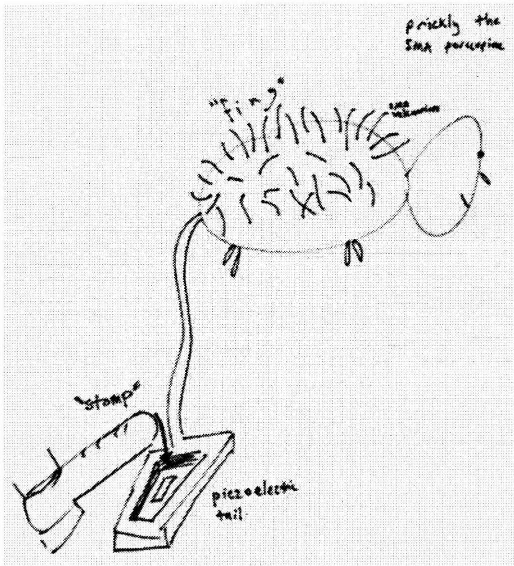

Figure 15: This drawing shows the use of piezoelectrics and SMA wires in an animatronic porcupine to actuate the quills.

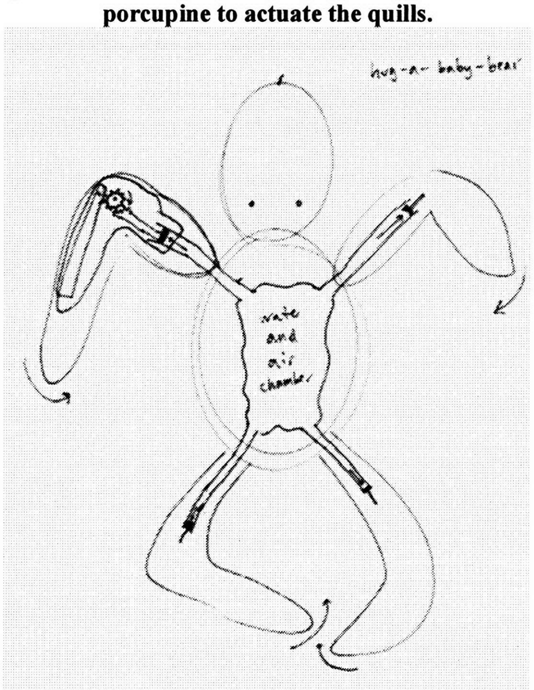

Figure 16: This figure shows the use of pneumatics, hydraulic, linkages, and gearing to create toy that hugs the user when the user hugs the toy.

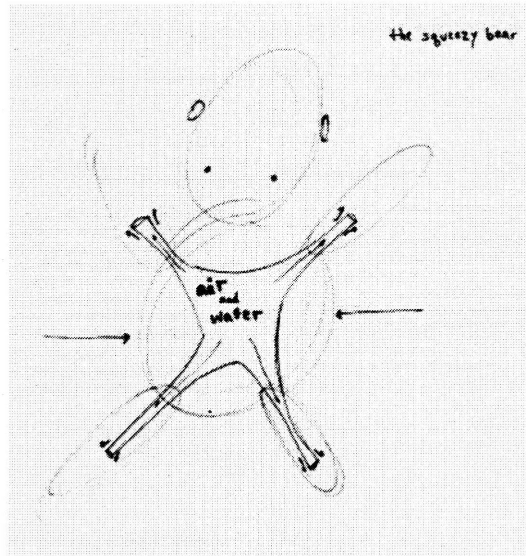

Figure 17: This concept is a simpler version of the concept shown in Figure 16. It illustrates a bear that has its digits actuate when it is hugged through the use of pneumatics.

This external search allowed new perspectives of the design problem to be established in exploring the scope of new possible solutions to the problem beyond the self discoveries made during the internal search stage. Of the 37 total concepts, the concepts seen in Figure 8 through Figure 17 were built on to further evaluate their ability to potentially satisfy all the constraints in the design problem.

3. Developing the Ideas

3.1. Introduction

From the 37 ideas generated during the brainstorming session, 6 were selected to be taken to the next level of the development. After assessing the feasibility of some concepts, many were eliminated. The more promising ideas included Shape Memory Alloy, SMA, applications, flexible drive shafts, bi-metal strip actuators, voice coils, acoustical enclosures, and the VFD actuator. The VFD actuator did not actually stem from the brainstorming session but from a sourcebook on mechanical devices by Chironis and Sclater [3]. These selected concepts then went through a series of steps starting with an understanding of the theory behind their uniqueness, sketch models to illustrate the concept, and then a feasibility assessment to see if it could make the next steps beyond the concept exploration model phase.

3.2. Concept Selection

3.2.1. SMA Applications

Shape Memory Alloy, SMA, actuators are wires made of a blend of nickel and titanium and when an electrical current is passed through it, or they are heated up, they dynamically change their microstructure due to the changes in temperature. Unlike most metals, SMA wires contract due to those temperature increases, where as other metals undergo thermal expansion. Contract forces of SMA wires are very high, ranging between 7.0g and 3.5kg [Dynalloy 5]. Please refer to Figure 18 and Figure 19 for sketches of the SMA wire actuator concepts.

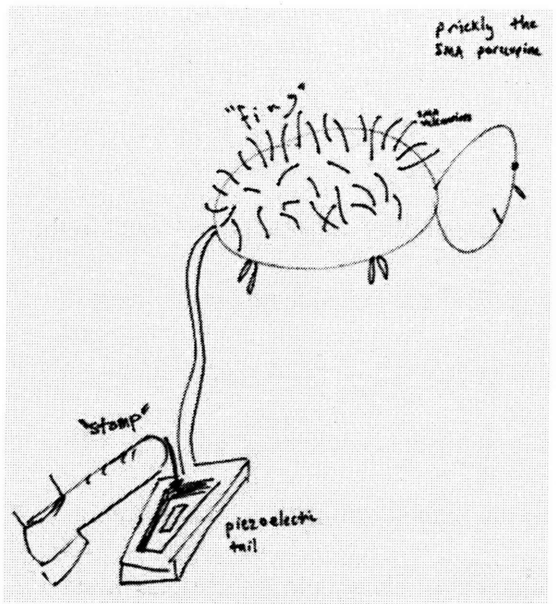

Figure 18: Concept sketch for the SMA wires as actuators for an animatronic porcupine.

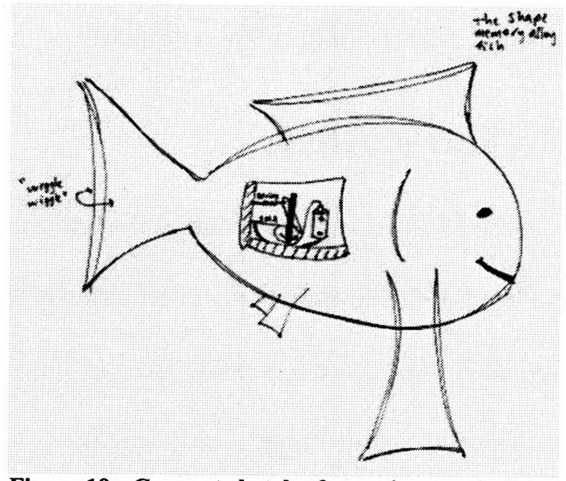

Figure 19: Concept sketch of an animatronic fish using SMA wires as actuators.

The best part about SMA actuation is that it is silent and smooth. However, some downsides to it are that contractions are a small percentage of the overall length of the wire, the wires have to be "trained" by cycling it through the motions over and over, and SMA wires have an inherently poor shelf life [19].

3.2.1.1. Theory and Technology

Shape Memory Alloys have very unique properties, unlike many alloys, which is their ability to contract under the presence of an electrical or thermal load. SMAs contract due to microstructural changes resulting from a thermal load input. During heating, the SMA wires are able to undergo a phase transformation between a low temperature martensitic phase and a high temperature austenitic phase and *vice-versa* when cooling. This phase transformation is called the Thermoelastic Martensitic Transformation and is the basis for the thermo-mechanical properties of SMA actuators [2]. Refer to Figure 20 for a schematic of the Thermoelastic

Martensitic Transformation which describes the contraction and expansion effects of the SMA wire during heating and cooling respectively.

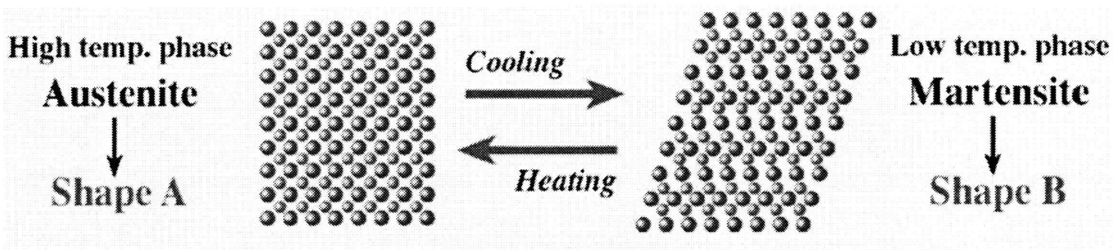

Figure 20: Schematic of the Thermoelastic Martensitic Transformation from Lecture given by José M. San Juan on Thermo-Mechanical Properties of SMA [2].

This effect, shown in Figure 20, gives reason to why SMAs are so unique in their ability to contract and expand during thermal loading and unloading, respectively.

3.2.1.2. Sketch Model

The SMA sketch model was a fish that was created out of foam core and were actuated with the silent SMA wire actuator. An image of this sketch model can be found in Figure 21 which shows the fish, the SMA actuator, and the bias spring.

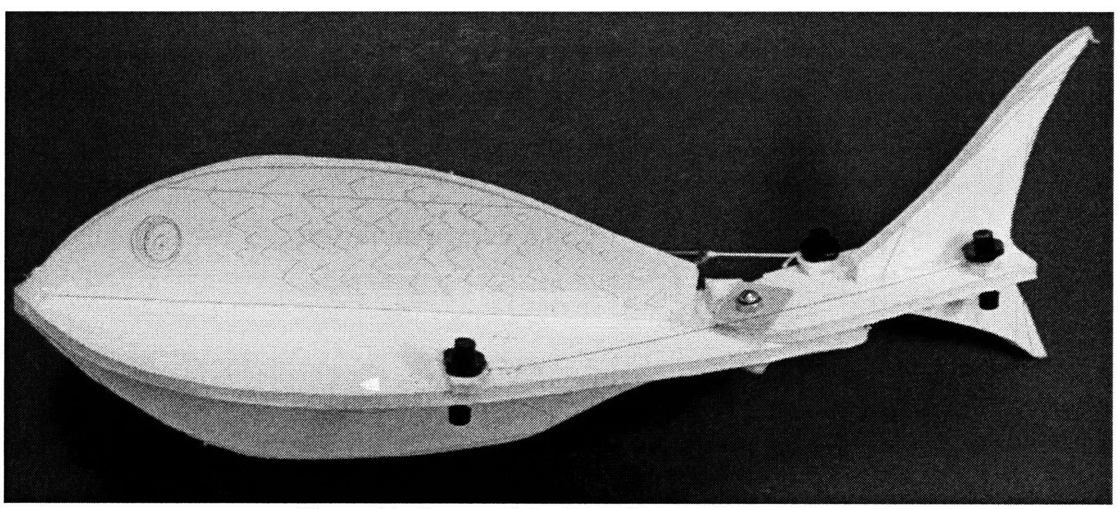

Figure 21: Image of the SMA fish sketch model.

The combination of the SMA actuator and the bias spring allowed the tail to move back and forth simulating the motion a fish tail makes. This motion was, however, relatively slow for an animatronic toy. The way the SMA wire was activated was by shorting it in a closed circuit allowing it to heat up quickly, as directed by the manufacturer, Dynalloy. It took very little time for the SMA wire to heat up and contract; on the order of 2seconds. However, when it was cooling back to its relaxed position, it took substantially longer; on the order of 6seconds which can be decreased if fans or heat dissipaters were used to remove heat from the wire at a faster rate, allowing the wire to return to its relaxed state quicker.

3.2.1.3. Feasibility

After cycling through the fish motion about four times, contraction during the heat up and expansion during the cool down of the SMA wire actuator, the wire failed. Reasons for why this happened were due to the SMA wire being cycled to its 4% maximum strain and the fact that SMA wires can only handle the 4% maximum strain for a few cycles and then they fracture.

When using the shape memory alloy materials in its wire form, and apply an electrical current through it, it will heat up to some steady-state temperature that could potentially be so high that damage will be done to the internal structure of the material ultimately deteriorating the materials single shape memory effect. Also, when current is directly applied to the SMA wire, it will also reach its maximum yield strain (4% contraction) and thus it will not be able to sustain that maximum yield strain for many cycles, which gives reason for why the fish tail of the sketch model kept breaking after only a few cycles. In order to be able to use the wire as an actuator for many cycles, it is best to use it under a controlled fashion by using a controlled heat source that controls the temperature that the wire reaches, allowing it to contract by no more then 2% which would not allow the material to reach its maximum strain of 4% contraction. When the operator uses a current input, the temperature rise of the SMA wire is not directly controlled, thus making it very difficult to control the induced stress of the SMA wire actuator, and ultimately the wire could yield after a very limited number of cycles which was one of the main downfalls of this type of actuator. Amplifiers can be used to maximize the contractions of the wire actuator, however, the resulting pull force decreases and prevents the pull potential of the SMA wire to be utilized.

Designing SMA wires for particular applications is quite difficult. The three parameters that define the thermo-mechanical properties of SMA wires are stress, strain, and temperature [San Juan 2]. These independent parameters give reason for why the SMA wires need to be "trained" in order to get particular behaviors. Training, in SMA wires, is the act of cyclically loading and unloading the wires repeatedly so that they learn the previous shape of the material when going back and forth between the austenitic and martensitic phases. Aging can become a great problem for these actuators, giving a very poor shelf life. Thus SMA wire actuators were not a viable alternative for quieter animatronic toy actuation. Another possibility would be to use tension or compression shape memory alloy springs for actuation instead of using just straight SMA wire. The problem with using springs for actuation is that when a current load was input through the SMA spring for actuation and the metal would heat up and contract (by up to 4% of the total length making up the springs ($L=r\theta$)) but once the current source is removed, the springs would take a very long time to cool since its mode of heat transfer (heat dissipation) is convective (convection) heat transfer from the surface of the wire to the surrounding ambient air. On the other hand, while their more optimal operation range, at around 1% contraction, was relatively little, levers and amplifiers can be used to increase the net effect of the contraction, however, the force output at higher displacements is far less, thus limiting its high-torque capabilities. Overall, while SMA wire applications seemed to be a very plausible actuation method for the animatronic toys, perhaps in ten or so years they will mature as a technology for robust and reliable application in animatronic toy.

3.2.2. Flexible Drive Shafts

Flexible drive shafts are becoming a basic element as a method of power transfer along with gears, chains, and belts according to Chironis and Sclater [3]. However, the advantage that flexible shafts have over the other basic elements of power and motion transmission was that flexible shafts are far simpler in regards to assembly and operation then the other aforementioned methods. This, along with the notion that flexible drive shafts have such great versatility [Chironis and Sclater 3], warranted further evaluation as a method to actuate animatronic toys.

3.2.2.1. Theory and Technology

The Flexible Drive Shaft, FDS, technology came from thinking about current actuation methods in common household tools or appliances. DREMEL®, a manufacturer of small handheld power rotary tools, uses a similar technology to transfer both torque and high speed to the end of a flexible shaft, called the Flex-Shaft. Since one of the main objectives was efficient delivery and quiet transfer high-torque to key locations in the animatronic toys, this seemed to show some promise since they absorbed shock, mechanical vibrations, multiple power outputs from a single input, and have an efficiency range between 80% to 90% [Chironis and Sclater 3].

The bulk of the technology behind the FDS was the polar moment of area of the various components making up the cross-section of the drive shaft. The polar moment of area of the i^{th} element is defined in Equation 2:

$$J_{x_i} = \frac{\pi}{32} d_i^4 \qquad \text{[Equation 2]}$$

Since the polar moment of area describes a bodies resistance to torsional deformation, referred to as the angle of twist, φ, measured in radians, is defined in Equation 3. The resulting angle of twist of the FDS, given an applied torque, T, shaft length, L, the combined polar moment of area, J, and combined shear modulus (modulus of rigidity), G, is:

$$\varphi = \frac{TL}{JG} \qquad \text{[Equation 3]}$$

The hope of the FDS was to take power from the source and disperse it to other locations in the toy. Figure 22 shows the design scheme used when using FDSs for actuation and have multiple semi-independent outputs for a single input.

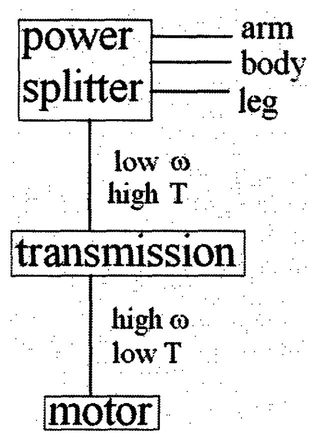

Figure 22: Shows the design layout when using FDSs to actuate an animatronic toy.

Using a single-input multiple-output layout would require the implementation of control signals at the power splitter to provide the appearance of independent motion by programming the toy to sequence through a multitude of different motion combinations.

3.2.2.2. Sketch Model

The sketch model of the FDS actuator was just a mock up from an old gear train from one of the animatronic toy cats. The sketch model can be found in Figure 23 and a close-up of the FDS mounting to the square-ended shaft in Figure 24:

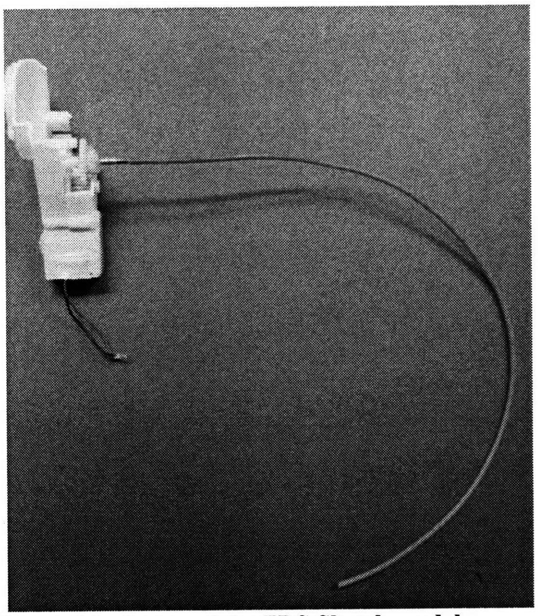

Figure 23: Image of the FDS Sketch model.

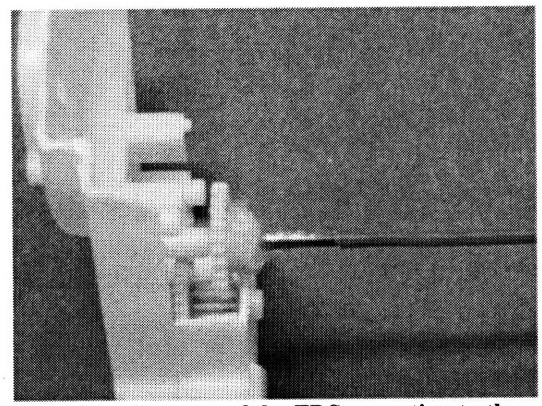

Figure 24: Close up of the FDS mounting to the square shaft.

The metal circular shaft supporting the spur gears, seen in the close-up view in Figure 24, was grinded down to create a flat edge for the mechanical support of the FDS. Angles up to 120° were achieved with minimal angles of twist in the red shaft shown in Figure 23. While this did show great promise in the elimination of linkages in the animatronic toys, it did not change the fact that low torque, high speed, DC motors were being used and geared down in order to product enough torque at the end of the flexible shaft.

3.2.2.3. Feasibility

FDSs, in general, were a simple and effective way to transmit rotational motion from one location within the toy to another. However, in order for the FDS to transmit high torques, a more robust flexible shaft will be needed to reduce the angle of twist within the shaft during actuation. Regardless, the design was quite versatile, was an effective way to transfer power, and was not affected by relative motions as Chironis and Sclater alluded to in their mechanical compendium [3]. Some additional benefits of the FDSs, aside from their assembly simplicity, was their ability to have multiple outputs for a single input which means that each limb or body part in the animatronic toy can be independently driven by means of a controller or a power splitter ultimately leading to more semi-independent motions. However, FDSs store a relatively substantial torsional energy while transmitting appreciable torques [Chironis and Sclater 3]. Thus, the higher the torque being transmitted, the greater the stored torsional energy stored, the greater the backlash when reversing the drive direction making them a less attractive as a possible alternative for actuation.

Since there still needed to be a substantial torque reduction from the small high speed, low torque, DC motors that are used, FDSs proved to be more effective in power relocation, then anything else. The FDSs just served to eliminate long linkages, not as much for reducing the intrusive sound produced by the toy's transmission box; thus the FDSs alone provided no noise reduction of the main sound source. Furthermore, when the FDS was bending around small radii and the resulting wrap angle exceeded 120°, then the FDS would begin to wind around itself, pinch, and collapse. This could be corrected by using a stiffer shaft of greater rotational mechanical integrity; however it still did not address the sounds produced by the motors and the gears and also did not have an impact in the direction of eliminating the sound produced by the geared transmission boxes.

3.2.3. Bimetal Strips

Bimetal strips were developed by clock maker John Harrison to compensate for thermally induced errors in time keeping in clocks [18]. Now, they are most commonly used in household thermostats or outdoor thermometers. Bimetal strips, also called bimetallic strips, are made up of two metals with different thermal expansion coefficients. Bimetal strips convert thermal energy into mechanical energy by means of a disparity in the two material's thermal expansion coefficient. Some concept sketches of the application of bimetal strips can be seen in Figure 25 and Figure 26:

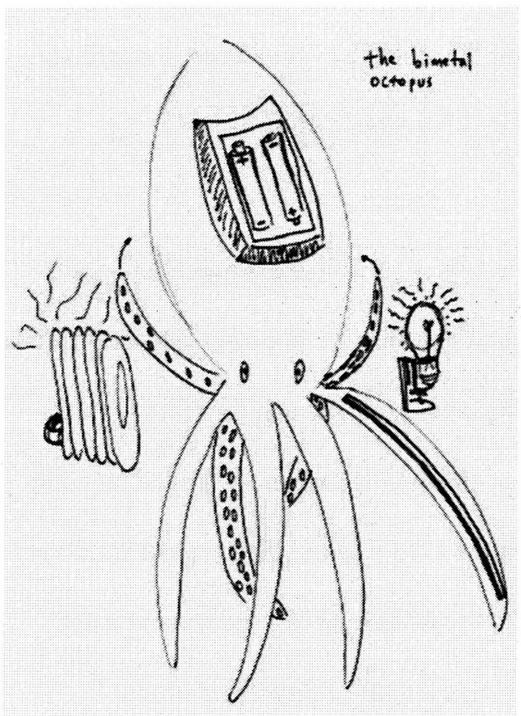

Figure 25: Concept sketch for the bimetal actuator application in an animatronic octopus.

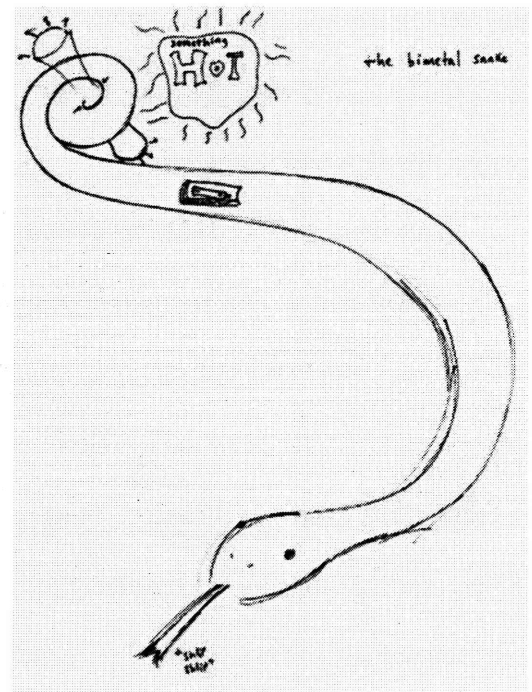

Figure 26: Concept sketch for the bimetal actuator application in an animatronic snake.

Bimetal strips have been a standard in the household appliance industry for years and this further exploration in bimetals will determine the possibility of their potential in the animatronic toy industry as a silent actuator.

3.2.3.1. Theory and Technology

The main theory behind bimetal strips came from the nature of thermal expansion in metallic compounds. When the temperature increases in a metal, the amplitude of the molecular vibrations increase, thus expansion occurs as a result of the increase in inter-atomic spacing between atoms in the metal. When two dissimilar metals are bonded together, to create a bimetallic strip, the mismatched thermal expansion coefficients, in the presence of a thermal load, give reason for why the bimetal strip distorts angularly [12].

Since bimetal strips are made up of two metals with different thermal expansion coefficients, an intrinsic material property that defines how much a material changes in length as a result of a temperature change. See Figure 27 for information on the effects of a misfit strain in bimetallic strips:

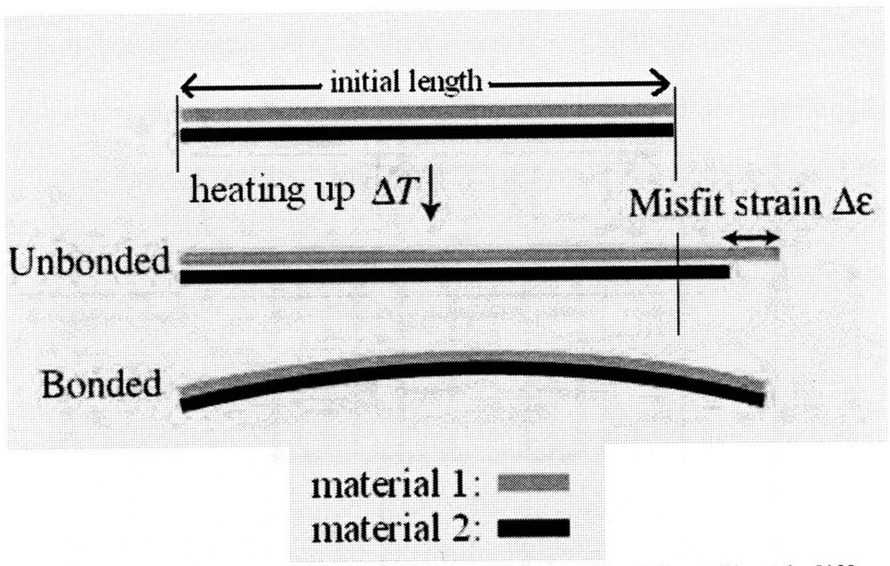

Figure 27: Schematic of the effects of a misfit strain in a bimetallic strip [12].

When the two dissimilar metals are bonded together and undergo some heat differential, the resulting misfit strain would cause the bonded strip to curve with curvature 1/R:

$$1/R = \kappa = \frac{6E_1E_2(h_1 + h_2)h_1h_2\Delta\varepsilon}{E_1^2h_1^2 + 4E_1E_2h_1^3h_2 + 6E_1E_2h_1^2h_2^2 + 4E_1E_2h_1h_2^3 + E_2^2h_2^2} \quad \text{[Equation 4]}$$

Where:

$$\Delta\varepsilon = (\alpha_1 + \alpha_2)\Delta T \quad \text{[Equation 5]}$$

Where E_1, E_2 are the elastic modulii, h_1 and h_2 are the thicknesses, and α_1, α_2 are the thermal expansion coefficients of materials 1 and 2 respectively. The misfit strain in the bonded metals causes the main reason why the bimetal strip deflects as a result of a thermal load [12].

3.2.3.2. Sketch Model

The bimetallic strips were attained from taking apart two household thermostats. The head of the sketch model, shown in Figure 28, was made from a halved NERF® ball and then painted for effect. The bimetal strip was uncoiled and cut to the desired length in order to demonstrate the potential of it being used as a potential mode of actuation.

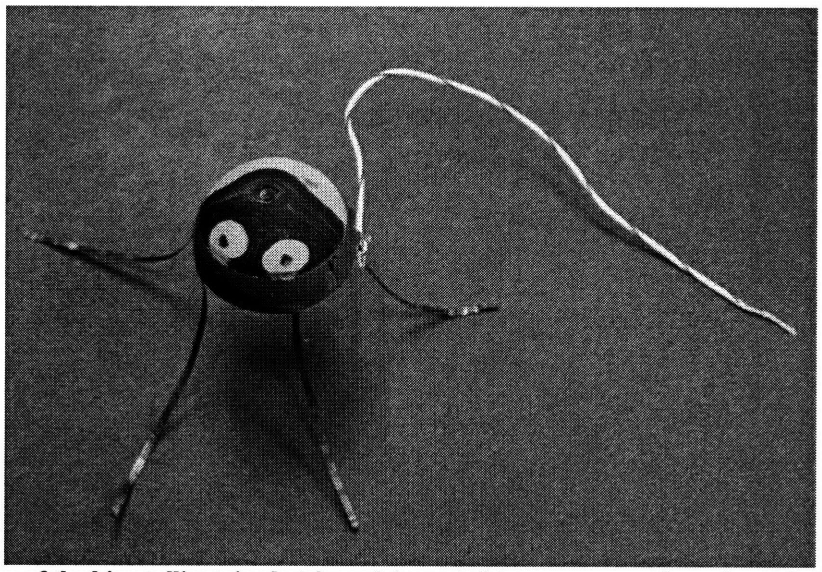

Figure 28: Image of the bimetallic strip sketch model created to answer questions about the feasibility of the bimetallic strip application in animatronic toy actuation.

In order to effectively activate the bimetal strip in this octopus, a substantial heat source was required. Heat sources could be from either a light bulb, electric current, or from an open flame. While some heat sources are relatively safer then others, especially when considering the end-user would most likely be a young child, open flames were entirely out of the question. The sketch model indicated that bimetal actuators were completely silent and illustrated great potential as silent actuators for animatronic toys. However, they had a few downfalls that would lead to the end of using bimetallic strips as actuators for this project.

3.2.3.3. Feasibility

The most promising aspect of bimetallic strip actuators was their silent actuation; no noise. However, there was one very substantial downfall: required extensive heat exposure for sizable distortions of the end of the bimetallic strip. This will be a serious hazard even if the hot strip was shielded using thermal insulators; the slightest exposure of the hot bimetal strip can be a huge safety issue. In order to have been able to produce sizable deflections in the bimetal strip, the material began to smoke up and start turning red hot. Temperatures of metals in the red color spectrum are roughly 900°F [6] which greatly exceeds safety limits for the product. Even when considering the use of thermal insulators or insulating materials like silicone rubber, it still would be an issue for Hasbro® due to safety codes regarding toys being safe for children. It was this that gave reason for the elimination of the bimetal strip as a possible silent actuator used in toy actuation.

3.2.4. V-Belt Drive

One of the several sources of unwanted sounds produced by the animatronic toys were from the gear teeth going in and out of mesh producing a high frequency disturbance, as previously mentioned, according to a study conducted at Purdue University [Yoon 17]. In an attempt to eliminate the sound produced by the teeth, a v-belt drive permutation of the transmission was developed for the transmission box of Butterscotch. The original elements making up the transmission box were either modified or replaced with a version suited for v-belt implementation, with the intent of quieter actuation and power transmission.

3.2.4.1. Theory and Technology

For hundreds of years, v-belt drives, and its variants, have been a common mode of actuation and power transmission along with gears and chains [Chironis and Sclater 3]. There are several advantages to v-belt power transmission which includes its inherent shock absorption and mechanical vibration elimination capabilities since there is no hard adjacent gearing involved in this type of power transmission [3]. Furthermore, v-belt power transmission has the ability to span larger distances by varying belt lengths where as with gears the distance meshing gears can span is defined by the size of the tangent pitch circles. However, unlike hard gearing, belt drives are less efficient but still provide many benefits that hard gearing. The belts considered for this research were of the smallest scale required to transfer power on the order of 2W. In v-belt drives, tension is applied to the belt resulting in a greater frictional load at the interface between the v-belt and the pulley. As power is being transferred from the drive pulley to the sheave, the v-belt is being wedged in to the pulley or sheave enabling it to transmit more torque (due to less slippage) [Slocum 11]. This frictional load allows for the belt drive mechanism to smoothly transfer rotational energy.

While v-belts are robust in their nature, they require attention to three key features, critical to their being successfully designed: 1.) stresses due to wrapping a cable around a pulley, 2.) belt tension, 3.) center-spanning distance between each pulley; according to Slocum [11]. Timing belts are another version of a v-belt drive, the only difference being that they are positive drives rather then friction drives and rely on meshing, like how spur gears mesh, between the belt and the pulley (sheave) for proper actuation and power transmission [Chironis and Sclater 3].

3.2.4.2. Sketch Model

The sketch model, demonstrating the application of belt drives to the transmission box from Butterscotch, was created by modifying the wide spur gear and the sliding spur gear in the original transmission box. The wider v-belt version of the wider spur gear was rapid prototyped from a SolidWorks 3-D model where as the sliding v-belt version of the sliding spur gear was turned on a lathe from the original sliding spur gear. Refer to Figure 29 for an image of the sketch model implementation for the v-belt application:

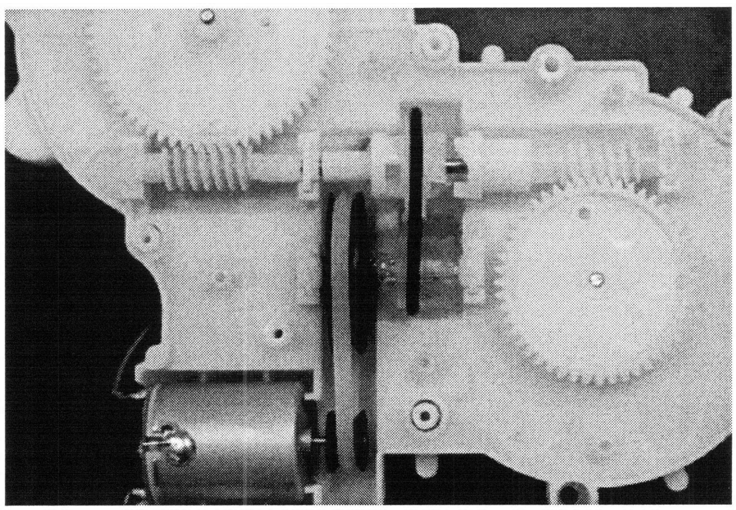

Figure 29: Sketch model of the v-belt drive implementation.

See Figure 30 and Figure 31 for the transmission box shown before and after the v-belt integration.

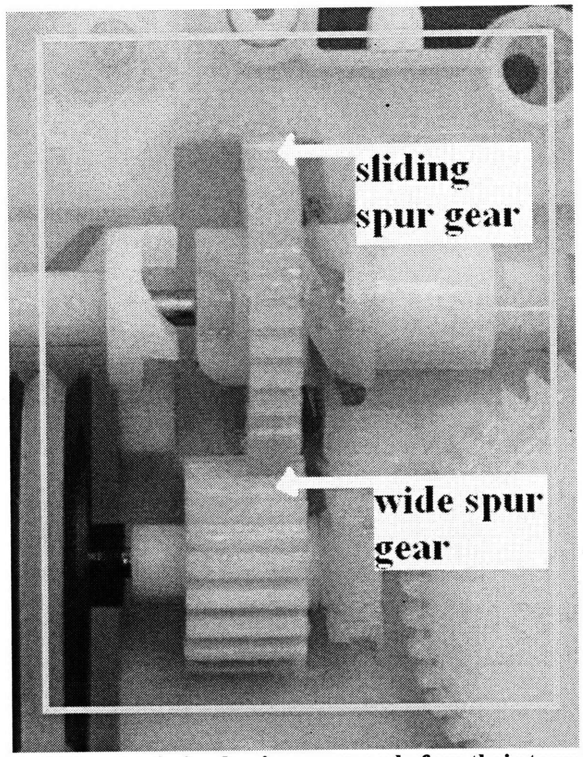

Figure 30: This figure shows the transmission box's spur gear before their transformation to a comparable v-belt version.

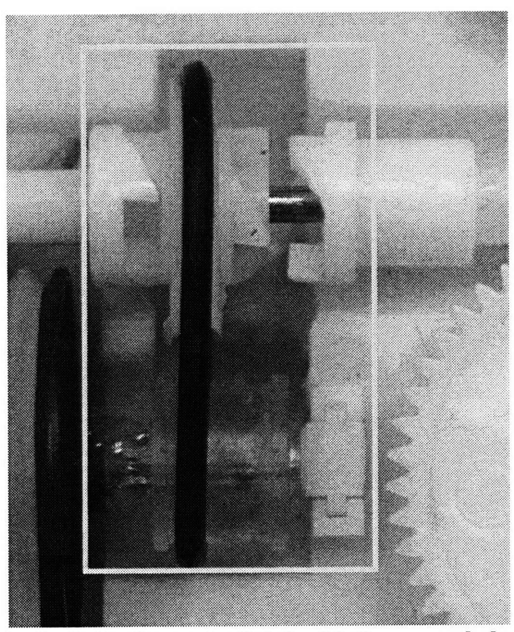

Figure 31: This figure shows the transmission box retrofitted with the new v-belt gears which replaced the wide spur gear and the sliding spur gear.

The development of the v-belt pulley and sheave were key to creating a fully functional sketch model in order to asses the feasibility of v-belts as a way to eliminate the gears for power transmission. The initial design for the sketch model called for both the sliding v-belt pulley and the wide v-belt pulley to be rapid prototyped. Secondary processing, machining, was required to drill the proper size holes for the different shaft mounting clearance for the two prototypes. The wider v-belt pulley needed to be press fit to the shaft it was mounted to where as the sliding v-belt pulley needed to have a sliding fit. The wider v-belt pulley was created with two groves to prevent walking of the v-belt in the two stable positions of the pulley. Each of the groves were deep enough to prevent walking yet shallow enough to allow the belt to move to the free grove then when sliding v-belt pulley reversed directions. Refer to Figure 32 for a side view of the bi-stable wider v-belt pulley.

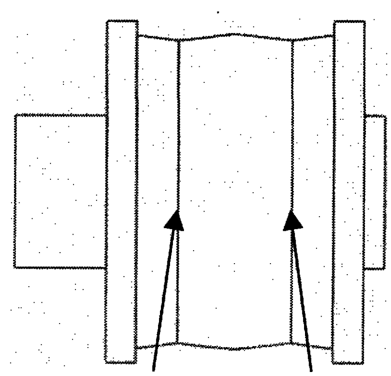

Figure 32: Bi-stable groves of the wider v-belt pulley. The v-belt is able to move from one position to the other is an active motion from the sliding pulley.

The active mechanism that allows the v-belt to traverse smoothly from one grove to the other in the wider v-belt pulley, shown in Figure 32, was a result of changes in direction of the motor rotation and the passive double clutching mechanism of the sliding v-belt gear. Furthermore, the groves are deep enough to eliminate walking of the v-belt yet not so deep that the v-belt is not able to move from one bi-stable position to the other.

The way that the sliding v-belt pulley engaged and transmitted the power to the worm gears was also a result of the passive double clutching mechanism which simulated semi-independent actuation. The double-clutching mechanism was based upon the direction of the motor. Figure 33 shows the position of the sliding gear when the motor running in a counter-clockwise direction where as Figure 34 shows the position of the sliding gear when the motor is running in the clockwise direction (please also refer to Figure 5 for an overall view of the transmission box set-up and motor position).

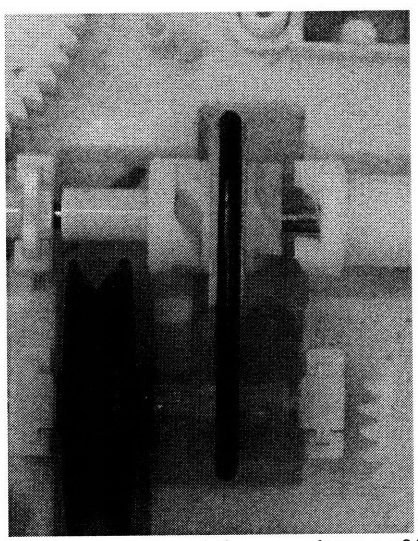

Figure 33: Shows the sliding gear in one of its bi-stable positions.

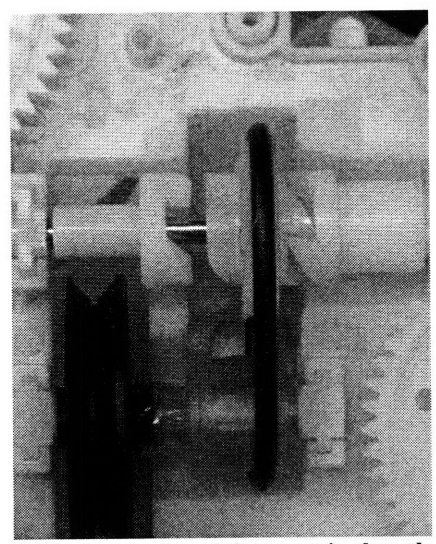

Figure 34: Shows the sliding gear in the other bi-stable positions.

The way in which the wide v-belt pulley worked was that it was able to accommodate two stable positions based upon the drive direction of the motor. The v-belt drive system was retrofitted into the current transmission box by machining out space for the v-belt. Refer to Figure 35 and Figure 36 for images of the transmission box shell before and after machining.

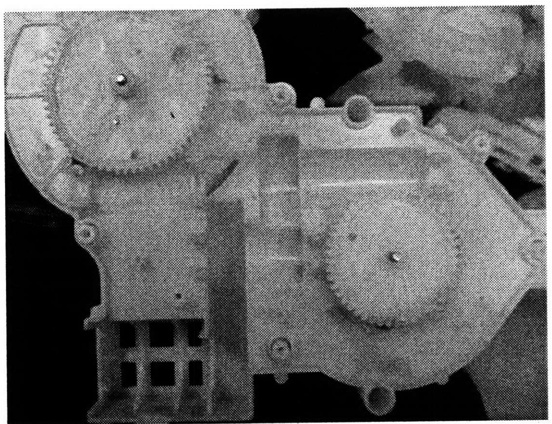

Figure 35: Transmission box shell before machining for v-belt integration.

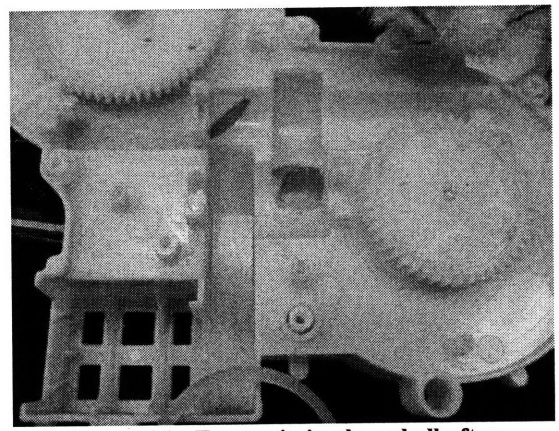

Figure 36: Transmission box shell after machining.

The clamshell holding the gears in place was modified in order to accommodate the belt of the v-belt drive. This retrofit was able to accurately demonstrate the of the v-belt drive concept.

3.2.4.3. Feasibility

Hasbro® used a v-belt to link the motor to a drive shaft, shown in Figure 37, for smooth power transfer from the DC motor directly to a larger sheave.

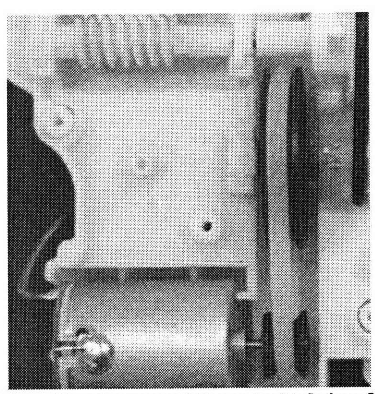

Figure 37: Image of the client's use of the v-belt drive for actuation.

This was done to reduce the noise output from this first stage of the gear reduction. Unfortunately, while much of the noise issues stemmed from the DC motor and the clattering plastic spur gears entering in and out of mesh when transmitting power, using v-belt drives did not eliminate the noise of concern. The noise produced by this v-belt modified transmission box was indistinguishable from the sound produced by the hard geared transmission box bringing the v-belt technology to its termination as a plausible alternative. The client uses v-belts for the first stage of the gear down since v-belts rely on friction and not forces for power transmission. Since the v-belts are quieter in that regard, they are the method of choice when transmitting power directly from the motor to the first sheave. However, during later stages in the speed reduction the acoustical benefits of using v-belts were less perceptible, ultimately eliminating v-belts as a method for quieter toy actuation.

3.2.5. Acoustical Enclosures

The original idea for the use of acoustical enclosures was to cover the toy with a viscoelastic bag to absorb the unwanted acoustical mechanical vibrations produced by the toy. Acoustical enclosures are coverings that provide acoustical attenuation to the source born sound produced by the enclosed object and to reduce sound produced by vibrating adjacent surfaces [4]. They are oftentimes used in industry to limit the excessive noise produced by machinery and other harmfully audible factory elements. An ideation sketch of acoustical enclosure concept can be seen in Figure 38:

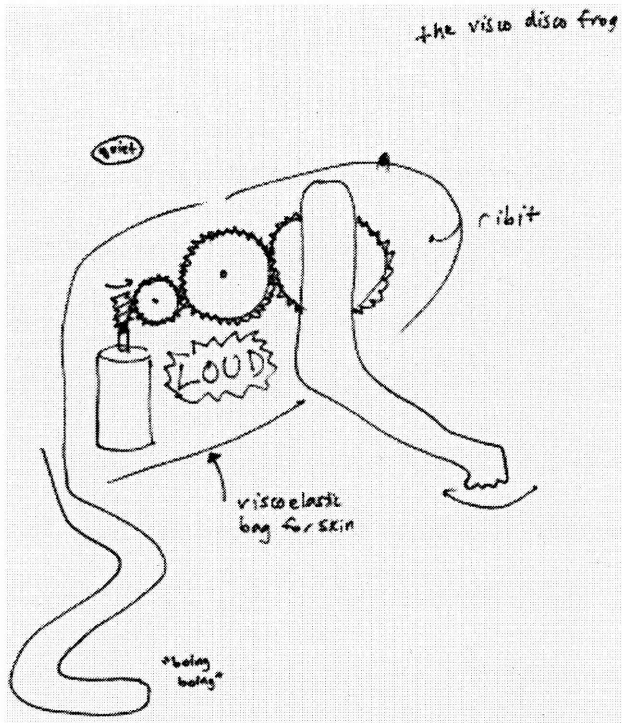

Figure 38: Image of the Visco Disco Frog, a concept illustrating the effects of using an acoustical enclosure to attenuate undesired sounds produced by the animatronic toy.

They can come in the form of sprays, fabrics, composite fabrics, matrixes, or viscoelastic bags.

Hasbro® was essentially looking for a way to make their animatronic toys quieter during actuation which did not necessarily mean that new actuators were needed. The acoustical enclosure seemed to be more promising both financially speaking and as a result of current practice in engineering environments. This notion brought forth the idea of creating a universally applicable acoustical attenuation enclosure.

3.2.5.1. Theory and Technology

Before the design of an acoustical enclosure could begin, it was important to ground the research with some theoretical background on acoustical enclosures. The main source used for the theoretical core of this research came from Miller and Montone [4], a handbook on the theory behind acoustical enclosures. It was most important to support the attempt in creating an acoustical enclosure with significant theoretical backing to avoid inefficiencies in aimless attempts to create acoustical enclosures based purely on speculation and thoughts as to what would make for an effective acoustical enclosure. .

In general, as the sound energy transfers from the source to the receiver, it looses energy as it propagates through porous acoustic deadening materials because the air molecules loose energy in the pores of the materials from viscous friction for higher frequency sounds [9]. Sound dampening materials such as foams, ceramic based paints, fiberglass, or felts, have a very high porosity in their structure giving them this sound dampening capabilities. The acoustical performance of these materials is frequency dependent and also dependent on the thickness of the material used, not the density of the material [4]. Since the DC motors used to actuate the various components of the animatronic toys were all around the same frequency, the materials that we selected could be used for the majority of the animatronic toy line manufactured by the client; ultimately satisfying the universally applicability of the acoustical enclosures to attenuate the undesired sound the toys produce.

Considering that direct user's interactions with the toy would be the main way in which the product would be used would eliminate the use of an acoustical barrier to eliminate the unwanted noises it produced. The best way to isolate the sounds it produced was through the use of sound absorptive materials which essentially reduce the transmitted sound energy from surfaces and ambient air and decrease sound reverberation due to energy losses in the acoustical waves produced by the source [4]. The best way to execute this is with the use of an acoustical enclosure around the toy without covering up any animal façades. Since the target consumer would want full-sensory access when using the toy, the first and the last alternative were deemed unreasonable. This initiated the development of an enclosure that would cover the sound source.

When creating an acoustical enclosure for the transmission box of the animatronic toy, it was important to consider what affects various openings or cracks might have in the enclosures ability to dampen sound. To provide the highest amount of acoustical attenuation for a given attenuating enclosure, it was best for the enclosure to have no leaks or openings of any kind; optimally they should be air tight according to Miller and Montone [4]. Some ways to control the gaps and leaks in the enclosures could be done by using adhesives like urethane foam or fiberglass, lead laminations, vinyl laminations, or sealings (butyls, polysulfides, elastomerics, or profiled extruded butyl tapes) [4].

Then the design of the particular enclosure began with the assessments of the three varieties they come in: 1.) localized enclosures; 2.) partial enclosures; 3.) complete enclosures, [4].

1.) Localized Enclosures: in the case of the animatronic toy, the majority of the noise came directly from a few elements, namely: the gears and the DC motor. Thus it was more efficient, in terms of both cost and time, to just enclosure the main source instead of the entire machine. In the case of the smaller versus larger animatronic toys, it might be more feasible to enclose the entire body of the small toys but just the transmission boxes of the larger ones.

2.) Partial Enclosures: this form of acoustical attenuating enclosures includes walls obstructing the line of action between the noise source and the receiver (the consumer) [4]. This application of acoustical attenuation would not be effective given the close proximity and multi-sensory interaction the end-user is with the product.

3.) Complete Enclosures: these would require the complete enclosure of the entire toy instead of just an element within the toy responsible for the disruptive noise production. This greatly reduces the reverberant sound field [4] existing between the noise source and the receiver but was the least cost efficient overall since it requires additional material in places that acoustical attenuation was not explicitly needed let alone completely shielding the toy from the child.

The best of these three options proved to be a combination of localized enclosures around the sources and complete enclosures around some of the smaller toys. In the larger line of the animatronic toys, namely Butterscotch, actual transmission boxes should be covered but in the smaller end of the line, namely: the kitten, puppy, lion, cat, et cetera, the entire toy should be covered since no modular transmission box existed in the toy.

Mechanical vibrations are prone to be issues in mechanical systems and can easily propagate to adjacent "hard" surfaces. Using softer rubber or felt isolator washers between these adjacent hard surfaces can greatly dampen these vibrations [4]. These hard clicking sounds, and other low frequency noises, can be eliminated from the principles of vibration isolation by putting sound absorptive felt pads in areas where two hard surfaces collide. This can help to mitigate the propagation of these low-frequency sounds that would not be stopped by some of the materials selected for the acoustical attenuating enclosure since these sounds would be outside the range of the effective acoustical dampening properties of the enclosure materials.

3.2.5.2. Sketch Model

The sketch model of the acoustical enclosure concept was created by covering the transmission box with a layer of black felt, which provided no additional sound dampening, and then spraying the polyurethane based spray foam to cover the black felt layer. Since different materials worked better at different frequencies, it was important to test a variety of materials designed for acoustical attenuation, however, this sketch model was able to successfully demonstrate the feasibility of the concept. Figure 39 shows an image of the sketch model of the acoustical enclosure created from a spray urethane foam.

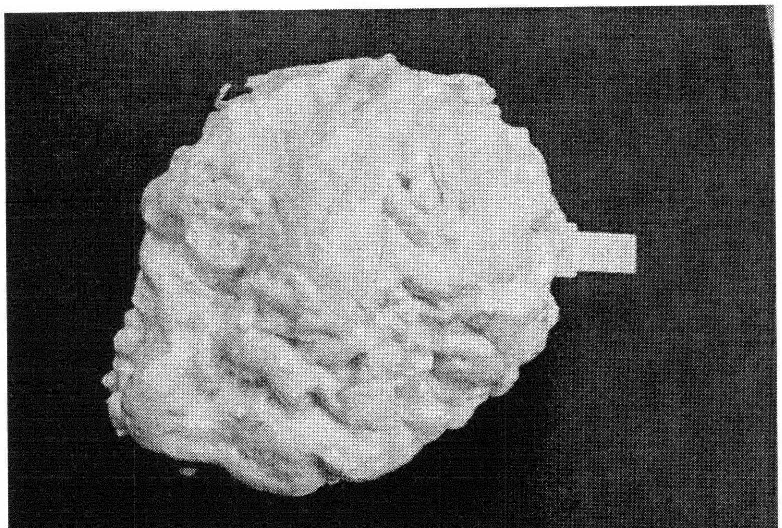

Figure 39: Sketch model created using GREAT STUFF as an acoustical enclosure [14].

The foam was sprayed in a two step process, a first coat for a general covering, and a second coat for more filling any cracks or gaps. Since the foam expanded as it dried, it was important to not be excessively liberal during the first coating. The first coat was left to dry for an hour and then the second coating was applied. While this sketch model was not the most promising, the idea of using acoustical enclosures was, and it was one of the few alternatives that adequately satisfied the client's needs. This idea is explored in more detail in later sections.

3.2.5.3. Feasibility

Of all the alternatives that were evaluated during the ideation process, the acoustical enclosure seemed to satisfy the client's needs the best. Coming up with new and more advanced modes of actuation were also a plausible solution, however, unlike the acoustical enclosures, significant capital would be required to implement the new types of actuators into the architecture and layout of the arsenal of animatronic toys produced by the client. Mould costs, revamping product architecture, et cetera would all have to be reevaluated where as with acoustically attenuating enclosures, implementation would be immediate.

While the GREAT STUFF Spray Foam did demonstrate the concept of an acoustical enclosure, the polyurethane foam spray did not perform particularly well for acoustical insulation. Regardless, GREAT STUFF was not intended to be used for acoustical attenuation, and performance was low. This notion goes back to the Theory and Technology, section 3.2.5.1, of the report, that the sound dampening properties of the material are dependent upon the sound frequency.

Some of the sounds produced by Butterscotch, such as the tail hitting a hard stop when it sways back and forth, produced low frequency clicks. This sound would not be able to be reduced using acoustical foam enclosures but rather by using vibration isolation materials like felt. Using mechanical vibration isolators can greatly lessen the vibration propagation and can provide substantial mitigation of the 'clicking' sound produced by the tail and other parts of the toy horse. Low frequency sounds that are below 125Hz [9] are very difficult to stop and eliminate with traditional lightweight acoustical enclosures like the ones used to attenuate the sound produced by the transmission box, adding heavy damping materials is not a viable option in most toys. To prevent sounds produced by hard stops of two rigid bodies, usually a viscoelastic isolator is used so that the two rigid bodies can collide with something soft and supple, absorbing the energy that would have been mostly converted to sound energy. Furthermore, to enclose the aforementioned sounds, traditionally a rigid enclosure would be required with an air space separating the source and the inside of the enclosure, along with a lining of a this heavy layer of fiberglass material to effectively reduce the sound energy of lower frequency sounds. This was by far the most promising of the methods evaluated for reducing the sound of the transmission box of the animatronic horse, Butterscotch.

3.2.6. Vibratory Flexure Driven (VFD) Actuator

The VFD actuator method of actuation was one that uses three or more skewed strips located radially about a plate that converts linear motion to rotary motion [3]. This mechanism was an economical way to convert motion from one form to another through the use of flexures.

3.2.6.1. Theory and Technology

VFD actuator flexures, in this particular application, converted linear oscillation strokes of a voice coil (speaker diaphragm) to discrete rotary steps of the flexure plate. A schematic of this can be seen in Figure 40. This device requires two components, the speaker diaphragm, to produce the linear strokes, and the flexure plate, to convert the linear strokes to rotation by means of the three or more evenly spaced flexures. The force produced by the voice coil (speaker) is defined by Equation 5:

$$\vec{F}_y = \vec{I} \times \vec{B} \qquad \text{[Equation 5]}$$

Where:

$\vec{F}_y$ = vertical force vector

$\vec{B}$ = magnetic field

$\vec{I}$ = current through the wire

Since equilibrium is observed, an expression for the output torque can be derived from equilibrium from the applied force due to the linearly oscillating speaker diaphragm, derived from first principles. The result of the derivation can be seen in Equation 6:

$$T_o = \frac{F_y \cdot r}{\tan(\theta)}$$ [Equation 6]

Where:

T_o = the output torque

r = radial distance of flexure to center of flexure plate

θ = rest angle between the flexure and the speaker diaphragm.

As Figure 40 depicts, as the speaker diaphragm translates in a linear oscillatory fashion, the flexure plate rotates thus converting linear motion to angular motion.

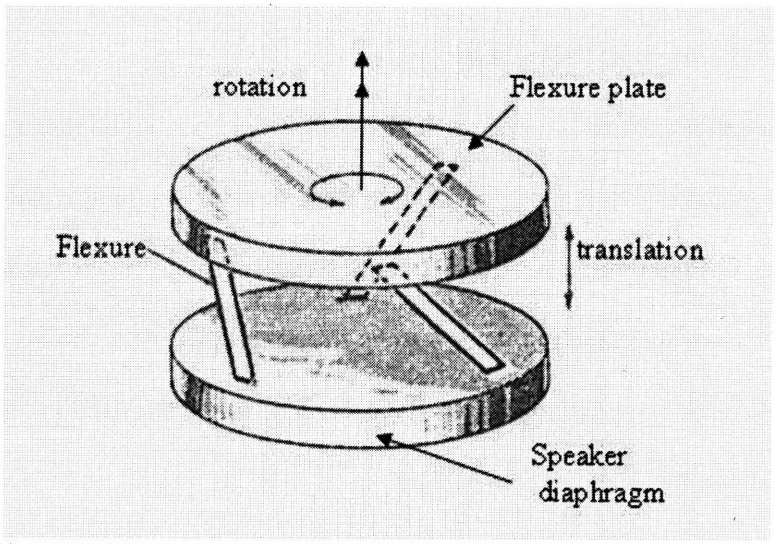

Figure 40: Schematic diagram of the flexures skewed strips converting linaer motion to rotational motion [3].

They key component behind the successful operation of the VFD actuator was to drive the speaker at sub-human hearing frequencies. This way, large amplitudes can be produced however, the resulting sound pressure waves would not be able to be detected by human hearing and thus quiet actuation can potentially be realized.

To attain a graphical understanding of the potential of this technology, equal-loudness curves, or Fletcher-Munson curves, helped to theoretically ground the concept. An example of such curve used to qualitatively compare the results can be seen in Figure 41. Since human hearing is more sensitive to some frequency of sounds than others, within the human hearing frequency spectrum (20Hz to 20kHz) [University of Salford 10], this concept can take great advantage of some frequencies of sound that are less sensitive to human hearing.

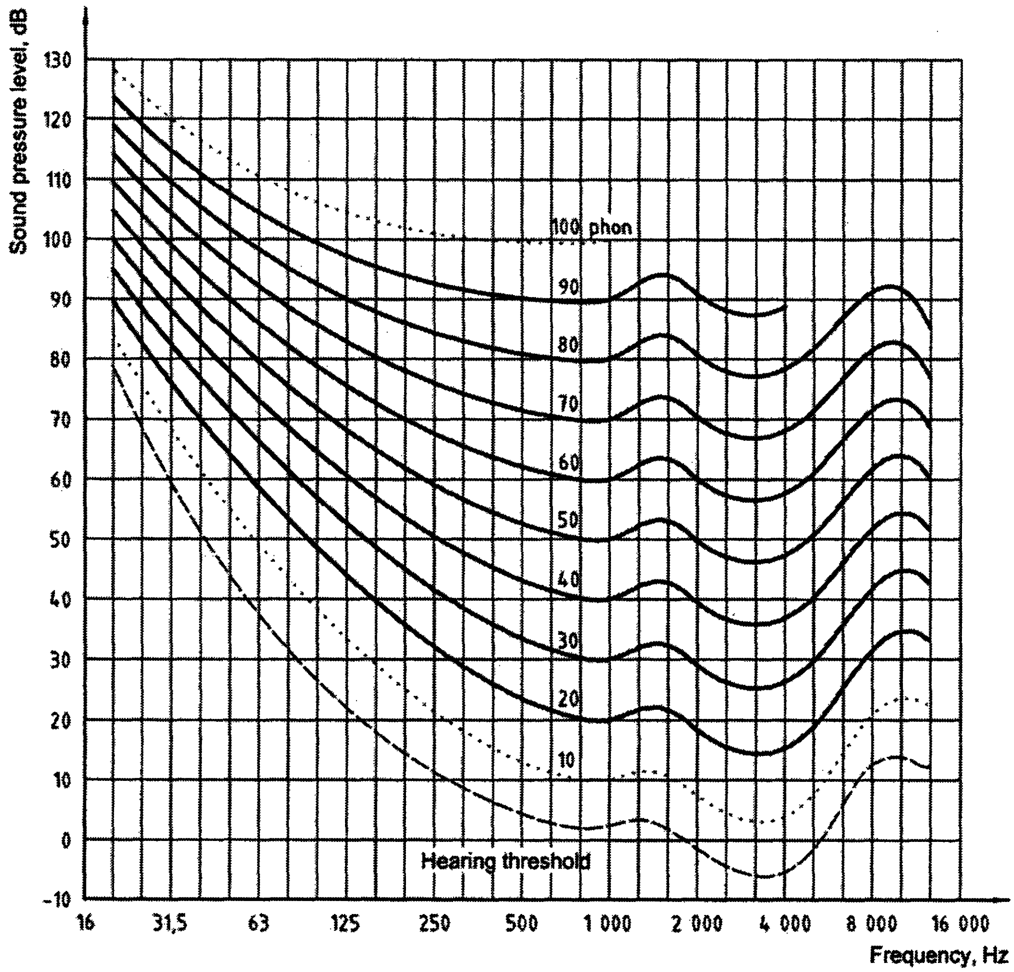

Figure 41: Numal equal-loudness-level (Fletcher-Munson) contours for tones [10].

The numbers under each curve in the Fletcher-Munson curves is the Phon level. For example, the contour that passes through the 1kHz tone at 40dB describes the 40 Phon Loudness Level contour [10]. Any other tone along that curve is of equal loudness to the 1kHz tone at 40dB. This notion of equal-loudness gives an understanding of the great potential of the VFD actuator technology.

3.2.6.2. Sketch Model

The first first-generation sketch model created was made out of a 3' length of 1.5in diameter PVC pipe, two 1in sections of 4in diameter foam tubes (water noodles [20]), and four wood coffee stirrers. The second first-generation sketch model was made from similar materials just did not require the use of the PVC pipe and was made out two 1in sections of 2.5in diameter foam tubes (water noodle) and four plastic zip tie ends as the flexures. Please refer to Figure 42 and Figure 43 for an image of the VFD actuator sketch model.

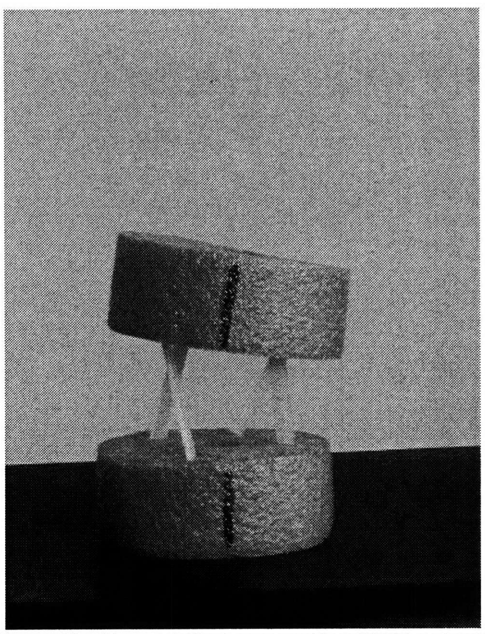

Figure 42: Second first-generation VFD actuator sketch model with no vertical load.

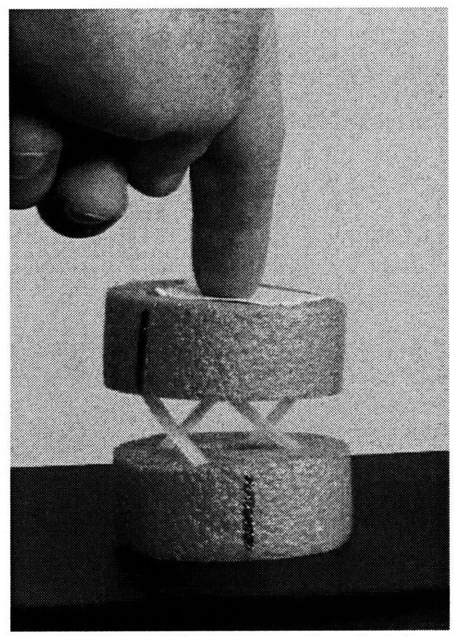

Figure 43: Second first-generation sketch model with vertical load showing the conversion of linear motion to rotational motion.

While this model was crude, it was able to illustrate the VFD actuator concept by converting the continuous linear reciprocating motion to discrete rotational motion. Furthermore, this model showed what basic mechanical elements were needed in order to create such a mechanism.

3.2.6.3. Feasibility

The sketch model indicated that this mode of actuation was promising as both quiet and effective on a very primitive level. A lot of improvements would need to be made to the concept before possible implementation. Each element making up the VFD actuator from the diaphragm to the flexures would need to be more carefully evaluated before its application into the animatronic toy line can be realized.

The first generation prototype, created by James Penn, was a friction based flexure. See Figure 44 for an image of the first generation VFD actuator prototype.

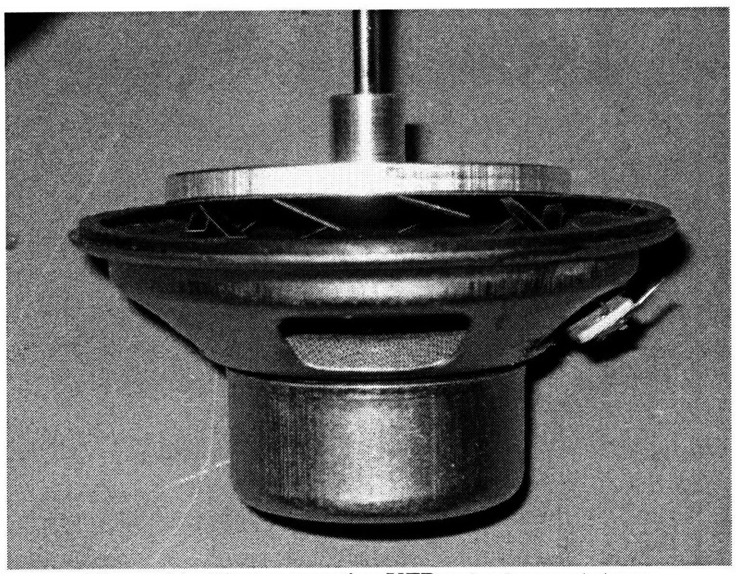

Figure 44: First generation VFD actuator prototype.

This prototype had a number of issues. First, the friction dependence of this system resulted in wear and other noise issues that might eliminate the VFD actuator as a method to quietly actuate animatronic toys. This system works by actuating the friction based flexures through the reciprocating linear strokes of the diaphragm of a speaker, so some concerns including wear and durability were also brought to attention. Due to some of the concerns in the first generation prototype, a second generation was created.

The development of the second generation prototype, also created by James Penn, while more costly, it eliminated a lot of the issues that arose in the first generation prototype. While the second generation prototype still used the speaker diaphragm to create the oscillating linear strokes, it was based on a fixed-interface instead of a friction-interface. Please refer to Figure 45 for an image of the second generation VFD actuator prototype.

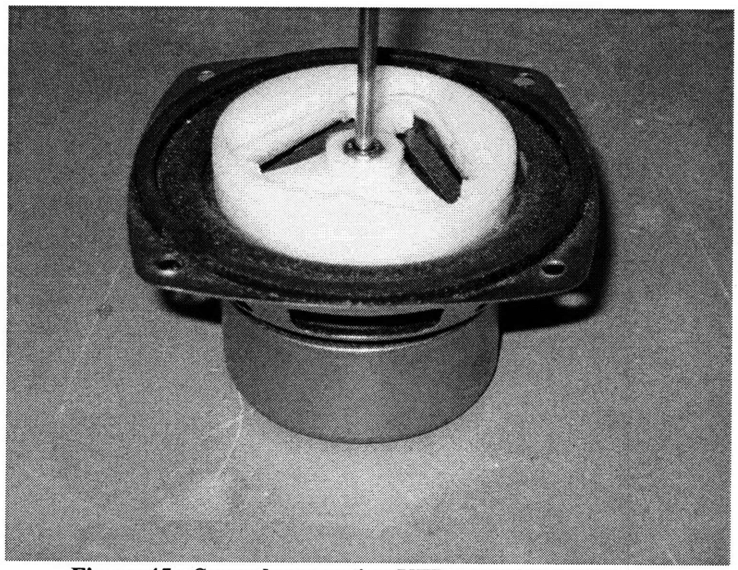

Figure 45: Second generation VFD actuator prototype.

Furthermore, the second generation had two one-way bearings which added substantial cost to the actuation system. However, the second generation model eliminated the friction dependent nature of the first generation prototype; a limiting factor on the torque output from the first generation prototype. Also, possible further complications in the first generation prototype such as wear and chatter during impact were also eliminated.

It was still early to make speculations by drawing hard conclusions on the true feasibility of the VFD actuator. However, since it was and still is being worked on and improved, it indicates that there was still substantial promise in the system. More will be discussed on future work on the VFD actuator actuation system.

3.3. Concept Selection

Each alternative in the ideation process provided a unique benefit be it low cost, performance, size, or universal compatibility. For example, the SMA actuators seemed to be the most promising initially with how they were marketed and how they initially performed, however were immediately eliminated once it was determined that they were infamous with a very poor shelf life and a limited range of performance. Bimetallic strips also had benefits and many potential applications, however the temperature the bimetallic strip needed to be raised to was well outside the safe zone considering these actuators were being used for children's toys. Some of the concepts, namely the v-belt drives and the FDS shafts did not eliminate the main contributors to the undesired noise produced by the animatronic toys: the DC motor and gear box. The v-belt drive eliminated very little if any of the sound of the gear teeth moving in and out of mesh but not the sound produced by the DC motor. Similarly, the FDSs were able to eliminate some of the potential hard clicking sounds produced by some of the linkages in the toy horse especially; however, it too did not eliminate the fact that the toy was still producing the undesired sounds from the DC motor and the gear box.

The most promising concept seemed to be the acoustical enclosures and the VFD actuator system. While the VFD actuator was still in its development stages, it had great promise. Converting linear motion from a voice-coil to rotational motion at sub-human hearing frequencies to actuate various linkages and appendages of the toys would completely eliminate the use of hard gearing and DC motors in the animatronic toys and, furthermore, it required relatively inexpensive elements, except the one way bearings, to make up the system. It is still being worked on as PhD research by James Penn [21]. In regards to the acoustical enclosures, they seem to be able to provide the client with quiet actuation without the added cost of new moulds, dies, and other re-tooling costs involved with integrating the new actuation modes with the toy line.

3.4. Summary

This portion of the research was dedicated to investigating the possible ways in which Hasbro®, the client, could realize quiet actuation for their line of animatronic toys. The explored possibilities included shape memory alloy (SMA) wires, flexible drive shafts (FDS), bimetal strips, v-belt drive, acoustical enclosures, and a VFD actuator. Each of these methods posed great potential, however some were self-eliminated due to the nature of their application and the target user. The bimetal strips were truly silent actuators however for appreciable displacements of the bimetal strips there needed to reach too high of a temperature for them to have been a safe alternative for quiet actuation. The SMA wire actuators were also silent however they had too poor a shelf live and were still a pre-mature technology for effective implementation. Out of all the alternatives, the most promising seemed to be the acoustical enclosures and the VFD actuator. However, the rest of the research done was dedicated to the advancement of the use of acoustical enclosures to achieve quiet actuation in the client's line of animatronic toys.

4. Selected Alternative: Acoustical Enclosures

4.1. Acoustical Enclosures

Of all the alternatives that have been evaluated during this research, the acoustical enclosure concept was the most promising. Once the sketch model was prepared, a number of different materials were selected that had the best sound absorptive properties for the frequencies of sound produced by the toy. The types of enclosures used were partly off-the-shelf materials, paints, and an in-house conglomerate created purely from experimentation.

Great Stuff Spray Foam:

Description and Installation: This insulating material was a low-pressure expanding spray foam caulk that is polyurethane based. It had a much lower porosity than the polyurethane open-cell foam sheets. Its most common use was for filling gaps and exposures in places where thermal insulation insulated ducts and pipes. Once sprayed, it was tacky to touch but was tack-free after roughly twenty minutes and it fully cured after eight hours [14]. An image of the application of Great Stuff Spray Foam as an acoustical enclosure can be seen in Figure 46.

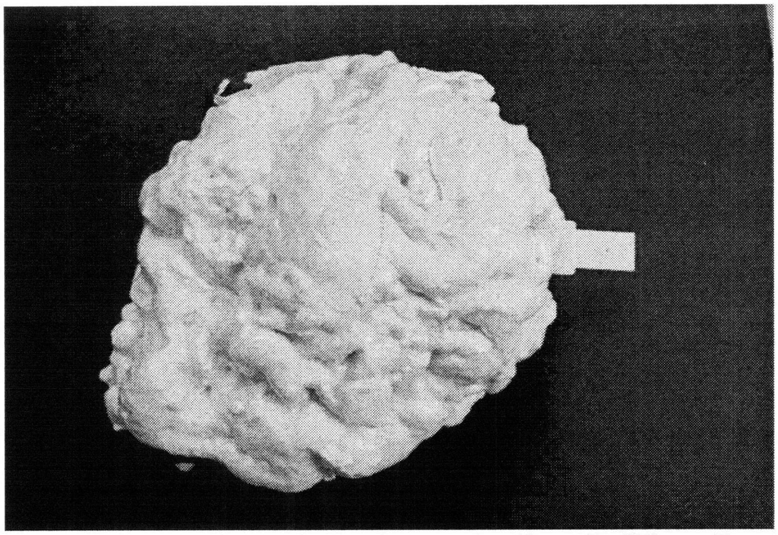
Figure 46: Images of acoustical enclosure using Great Stuff Spray Foam.

The application of this spray foam required minimal preparation; only the surface of the transmission box was needed to be covered with a layer of felt, which provided no acoustical absorption at the sound frequency produced by the transmission box. Once the transmission box was covered with the felt layer, the foam was sprayed and allowed to expand and dry for the recommended eight hours. Once the foam dried, a second layer was put on to cover any gaps and fill in any of the missed spots from the first covering. Some holes and gaps were intentionally left unfilled to allow some of the external linkages to freely move without the obstruction of the hard foam enclosure.

Dynamat:

Description and Installation: Dynamat [13] was one of the several materials selected as an acoustical enclosure that was specifically designed to limit sound and mechanical vibration propagation. It was a light-weight, elastomeric, butyl and aluminum multi-layered mat that could be cut into any shape and stuck only a variety of materials, including plastics. The optimal temperature performance range of this material is between -10°C to +60°C and can withstand temperature extremes between -54°C to +149°C [13]. It costs roughly $12.00 per square foot. This material can be die cut, at the factory, into any shape making its integration into the client's toy line quite smooth. For installation on the plastic toy body under the fur façade, clean the plastic with an alcohol swab, peel back the release liner, and adhere it to the desired location as shown in Figure 47:

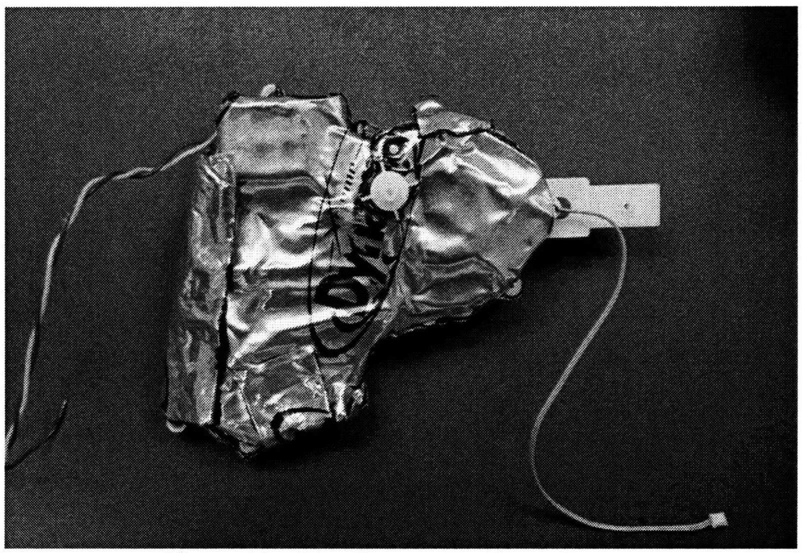

Figure 47: Using Dynamat as the enclosure.

Due to the materials tacky nature, it was difficult to peal the layer off once it has been applied. Furthermore, reducing any air pockets was also critical in maximizing the materials sound dampening capacity [13].

Neoprene Foam Sheets:

Description and Installation: Neoprene open-cell waffle textured foam sheets were used as another permutation in creating acoustical enclosures. This material selection surpassed the acoustic insulation performance of the other tested materials. Under this layer a layer of extra soft polyurethane foam sheets were used to reduce friction of the moving parts in contact with the enclosure since the neoprene sheets were tacky to touch. The enclosure can be seen in Figure 48 and Figure 49:

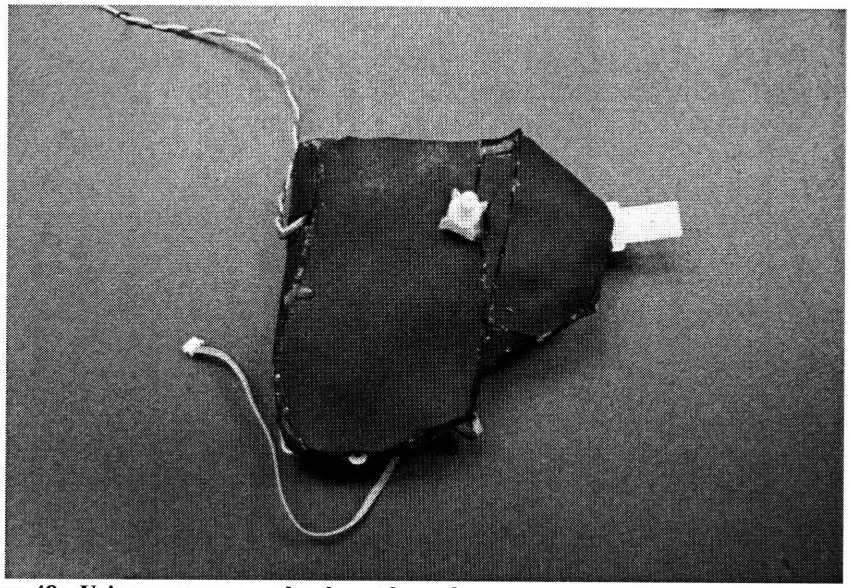

Figure 48: Using neoprene and polyurethane foam as a composite acoustical enclosure.

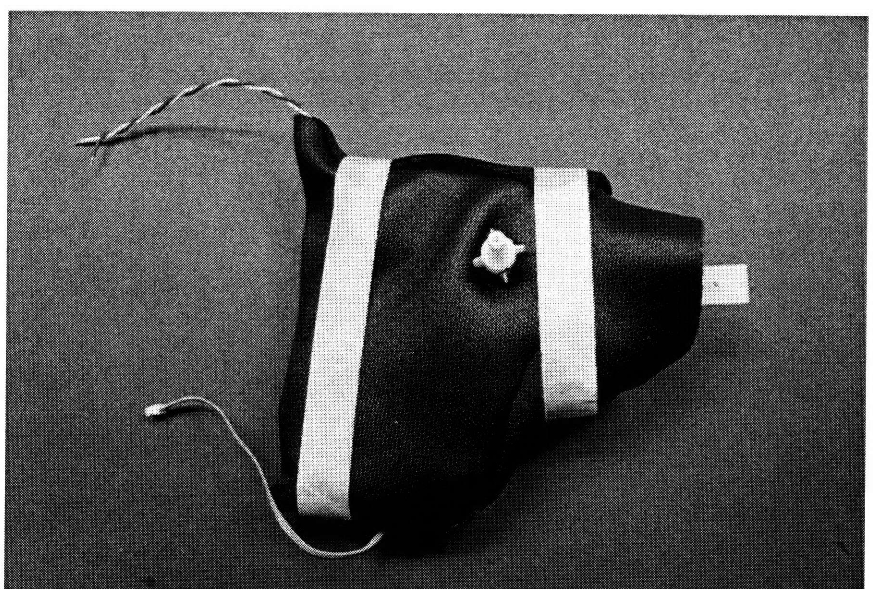

Figure 49: Using two layers of neoprene and one layer of polyurethane foam as a composite enclosure.

Some of the other beneficial properties of neoprene foam was that it was oil and abrasion resistant, impact resistant, weather resistant, and flame resistant which can add great durability and robustness to the animatronic toy that it would not have normally had in the absence of this layer [8].

Installing this enclosure was done by cutting a sheet of the neoprene foam and then using a hot gluing adhesive to bond it to the sheet of polyurethane foam. The sheet of polyurethane foam acted as a low-friction layer that served to prevent linkages inside the transmission box from getting stuck on the tacky surface of the neoprene foam sheets. Access holes were cut into the neoprene sheets prior to installation to allow for key points of location and motion transfer to be accessible to maintain functionality of the transmission box.

Acousti-Coat Paint:

Description and Installation: Acousti-Coat [15] was a flat latex water based paint that was saturated with ceramic micro-beads (~63% by volume), soft pigment fillers, and vacuum centers made by Hy-Tech [15]. This heavy-bodied, high viscosity, paint absorbs sounds and reduces its transmission power by up to 30% at sound frequencies in the 500Hz range (mid-range for human voice) [15]. Refer to Figure 50 for reference.

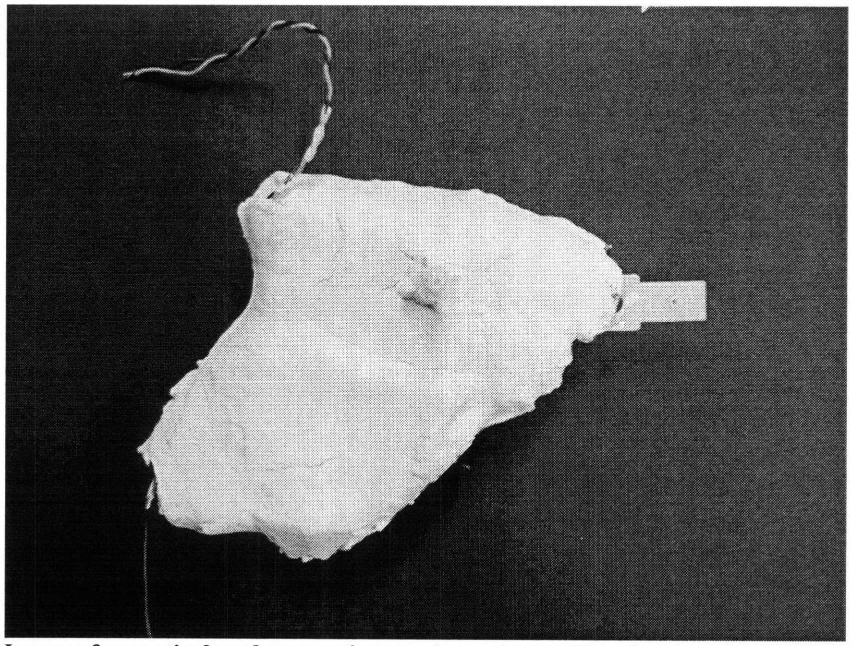

Figure 50: Image of acoustical enclosure using a polyurethane under-layer and ceramic Acousti-Coat acoustical insulating paint.

The paint can be used on a myriad of surfaces from porous cloth, drywall, plaster, metal, and wood. The paint provides a very high sound and heat insulation as well as being highly reflective and non-toxic. Primers are recommended for application and installation; however they were not used in this research. The suggested and practiced application called for two full generous coats applied by either a brush or a spray gun. If a spray gun is to be used, the manufacturer recommended using a thinning agent, namely water, to improve sprayer's effectiveness and to reduce the viscosity of the paint. The first coat should be allowed to dry overnight before the application of the second coat to allow for proper adhesion and crack filling of the second coat [15]. Once the paint dried, it was very brittle and fragments could easily break off if painted enclosure was not handled with care.

4.2. Comparing the Acoustical Enclosures

Once all the permutations of the various acoustical enclosure materials were prototyped, they were evaluated by comparing their sound dampening performance to the control, the naked transmission box, in a control box which isolated the experiment from the unwanted sounds produced by the ambient surroundings. A schematic diagram of the control box can be seen in Figure 51.

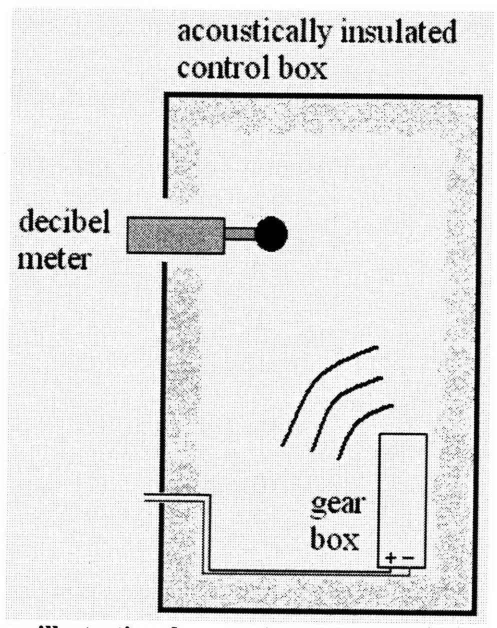

Figure 51: Schematic diagram illustrating the experimental set up of the control when comparing the materials used for the acoustical enclosures.

The sound pressure level, in decibels [dB], was measured using a decibel meter made by EXTECH Instruments, model #407730. It has a 40 to 130dB measuring range ±2dB as specified by the manufacturer, EXTECH [16]. The transmission boxes were placed inside the control box and then the output sound pressure level was measured. See Figure 51 for reference. Since the decibel meter was very sensitive to changes in distance towards and away from it was from the sound source, using the control box also provided great consistency, from test to test. The distance the decibel meter was from the gear box enclosure configuration being tested kept constant, at 12inches, for the purpose of comparison.

Once the comparisons were made, the data was tabulated and a metric was created to directly compare each enclosure. This parameter, the acoustical effectiveness, α_e, has units $[dB - \$/dB - ft^2]$ and describes the cost of the acoustical performance as a quantitative comparison tool which took into consideration the cost of the material per square foot, CPSF, and its acoustical performance characterized by the power reduction ratio, PR. The acoustical effectiveness equation can be found in Equation 5 and the power reduction equation in Equation 6 from the transmission loss equation in Equation 7 from Miller and Montone [4]:

$$\alpha_e = PR \cdot CPSF \qquad \text{[Equation 5]}$$

$$PR = \frac{P_1}{P_0} = \frac{1}{10^{\frac{D}{10}}} \qquad \text{[Equation 6]}$$

$$TL = 10\log\left(\frac{w_0}{w_1}\right) \qquad \text{[Equation 7]}$$

Where P_0 is the initial sound power, P_1 is the damped sound power, TL is the transmission loss, and D is the decibel difference between the incident sound power, w_0, and the transmitted sound power, w_1. The acoustical effectiveness, in tandem with the power reduction, enabled conclusions to be drawn, quantitatively, on the different enclosure materials and their permutations. The power reduction enabled the acoustically attenuating performance of each alternative to be compared to each other directly purely based on acoustical performance. Please refer to Table 1 for a list of the acoustical performance of each enclosure material:

Table 1: Tabulated data from the acoustical enclosure material alternatives (NOTE: naked- bare transmission box; PU- 1/8" polyurethane foam sheet; NE- 1/8" neoprene sheet; SF- spray foam; CAP- ceramic Acousti-coat paint; DM- Dynamat Xtreme).

	naked	1PU+1NE	1PU+2NE	2in SF	1 layer CAP	2 layer CAP	DM
dB reading (dB)	57	50	47	55	51	48	54
D=dB difference (dB)	0	7	10	2	6	9	3
thickness (in)	0.000	0.250	0.375	2.000	0.125	0.250	0.067
P1(damped sound power)	57.00	11.37	5.70	35.96	14.32	7.18	28.57
P0=initial sound power (dB naked)	57.00	57.00	57.00	57.00	57.00	57.00	57.00
PR=power ratio= P1/P0	1.00	0.20	0.10	0.63	0.25	0.13	0.50
cost per dB reduction	DNE	$0.74	$0.95	$0.59	$0.17	$0.22	$4.80
CPSF: cost per square foot	$0.00	$5.15	$9.50	$1.19	$1.00	$2.00	$14.40
α_e=PR*CPSF	$0.00	$1.03	$0.95	$0.75	$0.25	$0.25	$7.22
sound pressure reduction (%)	0.00%	80.05%	90.00%	36.90%	74.88%	87.41%	49.88%

The top two performing acoustical enclosures were the polyurethane-neoprene based composite layering and the ceramic water-based Acousti-coat paint with power reductions of 0.10 and 0.13 and with acoustical effectiveness of 0.95dB-$/dB-ft^2 and 0.75 dB-$/dB-ft^2 respectively. The main difference between the two best performing acoustical enclosures was the fact that the polyurethane-neoprene based composite layering provided a great deal of elasticity and shock absorption where as the ceramic Acousti-coat paint was rigid and brittle.

The other enclosures tested did not perform nearly as well as the two aforementioned high performing enclosures. The Dynamat Xtreme sheets were costly and since the frequency of sound that the transmission box produced was not in the optimal range for the material to perform at its greatest potential eliminated it from the array of materials used. The Great Stuff spray foam also did not perform as well as the other materials and was also messy to apply. Overall, the polyurethane-neoprene based composite layering and the ceramic Acousti-coat paint were the best materials.

The polyurethane-neoprene based composite layering and the ceramic water-based Acousti-coat paint solutions provide acoustically attenuating performance for the higher frequency sounds produced by the toys and transmission boxes. Since the acoustical enclosures that were designed for the transmission box had an optimal frequency performance range, some of the 'clicking' sounds produced by the animatronic toys were not able to be stopped, thus a further investigation into mechanical vibration isolators would needed to eliminate the low frequency clicking sounds.

5. Conclusion

5.1. Summary

In the beginning of this research project, toys from the client and project sponsor were provided for a further understanding of the design problem they posed. The animatronic toys, especially the toy horse Butterscotch, were producing a lot of noise from the gear boxes and transmissions and were ultimately taking away from the end-users experience with the toy. Hasbro® was interested in a way to actuate the toys quieter without taking away the life-like nature of the toys.

Brainstorming sessions were held in order to evaluate the problem further and try to establish new technologies, or combinations of old technologies that would allow the design team to establish a firm foundation to build the research on. Some of the technologies that came from the brainstorming sessions that were materialized included: shape memory alloy wire actuators, flexible drive shafts, bimetallic strip actuators, v-belt drive implementation, and acoustical enclosures. An additional concept that was evaluated was the VFD actuator actuation system; however that was not conjured from the brainstorming session. Each concept was evaluated by assessing the performance of the respective sketch models in the direction that the sponsor desired. A concept reduction was then performed and the two standing concepts that showed great promise and merited further evaluation were the acoustical enclosures and the VFD actuator system.

The remaining research was devoted to mostly the application of the acoustical enclosure concept to reduce the noise the receiver observes from the transmission box of the animatronic horse Butterscotch. Background research on the application of acoustical enclosures was conducted to understand the use of acoustical enclosures and proper material selection. Once the theory was understood, several different types of materials were evaluated based upon their sound dampening capabilities through the use of a control box, a control transmission box, and a decibel meter. The most promising of the materials included Acousti-Coat paint and a polyurethane-neoprene based composite layering. While the ceramic based sound dampening paint was effective and inexpensive, it did not provide the flexibility and the sound dampening performance that the polyurethane-neoprene based layering provided. To stop the other undesired sounds produced by the linkages and other hard stopping elements in the toys, the use of mechanical vibration isolators should be used in order to dampen the propagation of these low frequency sounds. Please refer to the following sections on recommendations for the use of Acoustical Enclosures and the VFD actuator system.

5.1.1. Acoustical Enclosures

After several acoustical enclosures were created using several different types of sound absorptive materials, the use of neoprene sheets and separately the use of the Acousti-coat ceramic paint were superior to any other material used. While the double neoprene sheets were not the least costly materials experimented with, at $4.35 per square foot, it provided the best sound dampening performance, reducing the observed sound pressure level by roughly 90% of its original amount in the transmission gear box of the animatronic horse, Butterscotch. It also provided flexibility and great shock absorption as well as its intended sound absorption. The ceramic based Acousti-coat paint also had high performance, with a power ratio of 0.13, it was a bit less flexible but costs only $1.00 per square foot (before dilution). In conclusion, the use of acoustical enclosures can be implemented immediately into the line of animatronic toys. Forming the neoprene sheets and applying the Acousti-coat paint may differ from toy to toy, however, these materials would be both extremely effective in eliminating the sounds produced by the DC motors and multiple gear reduction stages but neither were effective in eliminating the hard clicking sounds produced by tail swaying and head motions. This might eliminate, all together, the use of acoustical enclosures for a lack of cost efficiency since they are not effective in attenuating unwanted sounds at all frequencies with a single enclosure in the lesser expensive line of animatronic toys.

5.1.2. Vibratory Flexure Driven (VFD) Actuator

The VFD actuator is still in process, being continued by another student; however it may have the most potential of all actuation methods evaluated. It does not require the use of any spur gears or DC motors and the premise upon which it functions requires sub-human hearing oscillations of a speaker to drive the flexures, converting linear motion from the speaker to rotational steps of the flexure plate. In conclusion, there is much work needed to be done in order to begin implementation of the VFD actuator into the line of animatronic toys in the form of an alpha-prototype.

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