Programmable Force Feedback Keyboard

Team 15

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Executive Summary

Musical synthesizer keyboards today have the capability to very accurately reproduce the sounds of their acoustic counterparts, as well as the sounds of a wide variety of other instruments. However, they cannot reproduce the feel or “touch response” of the acoustic instruments that they emulate. We have been asked to design a force reflecting keyboard with adjustable touch response ranging from a synthesizer keyboard to a grand piano. This will allow a user to adjust not only the sound output, but also the feel of the instrument with the push of a button. Our sponsor wishes to conduct research using our product for the possibility of eventual commercialization.

The most important design specification of our product is the above mentioned adjustable range of force feedback. Due to the fact that the action of depressing a piano key occurs on the order of milliseconds, our system must have an appropriately fast response time in order to accurately adjust the force response. Our design must also be totally programmable and will be interfaced with a computer that will act as a controller. A successful design will also have a robust power source so that it can sufficiently power a large number of depressed keys at the same time. Additionally, the mechanical components of our system must have negligible noise and vibration so that they do not interfere with a musician’s ability to play the instrument. Finally, the design must be reliable, repeatable, and safe to operate.

Our project involves several mathematical and technical challenges. First of all, some of our candidate designs rely on physical processes such as eddy currents and electromagnetic fields. We conducted research on these topics in order to learn how they can apply to our specific designs. We selected the eddy current brake system as our alpha design through a quantitative analysis, which compares the candidate designs and how they met engineering specifications.

Upon completion of our theoretical analysis, we designed and built our prototype. The role of our prototype was to verify our mathematical model through experimentation. We were able to use the results of our initial experimentation to further refine our design in preparation for the design expo. The final purpose of our prototype is to provide Professor Gillespie with an experimental research apparatus with which he can further explore our theoretical model of an eddy current braking system.

Introduction

Revised Abstract

Electronic instrument interfaces exist in a wide variety of forms today, and many have the capability to accurately reproduce the sounds of their acoustic counterparts. They all exhibit one major fault however; an inability to precisely reproduce the touch response that characterizes the mechanical interaction between user and acoustic instrument. We were asked to design a haptic feedback system for an electronic keyboard that can produce a programmable touch response, ranging from a synthesizer to a grand piano. We decided to use an eddy current braking system in order to accomplish this goal. The advantage of using such a system is that it allows for the production of a programmable force by the addition of inertia to the system without any additional weight on the key.

Problem Description

While there are numerous methods for electronically synthesizing music, there are presently only a few simple sensors in current electronic musical instruments at the musician's disposal for controlling the sounds achieved while playing. Several existing electronic keyboards accurately capture the physics of sound-production by translating readings from switches, potentiometers, and pressure transducers into synthesizing algorithms [1]. Though this is true, no currently existing keyboard can accurately capture the mechanical interactions between the musician and the acoustic instrument. This lack of connection with the instrument introduces difficulties in musical expression for the user. Our sponsor, Professor Brent Gillespie, has assigned us the task of creating a device that would allow for research in the haptic response of electronic keyboards.

Background

Professor Gillespie has been working on this project for some time. In his dissertation toward the degree of Doctor of Philosophy, he developed and applied haptic interface technology to a synthesizer keyboard [2]. This is an extremely valuable resource which provides us with the insight in the history of this project. The prototype developed by Professor Gillespie for this dissertation was successful for the purpose he intended – simulating the dynamic model of a piano. However, the design had an extremely complicated transmission and was difficult to maintain. His prototype design used a capstan drive, a design which gives haptic feedback through the action of a low-inertia motor. Photographs of the design can be seen in Figures 1.a and 1.b, showing a view of the front and a side view that shows the complex packing of the components. It is easy to see in these figures that the complexity of the design creates a problem with stable operation and assembly. The dissertation also includes a breakdown of the dynamics of the grand piano action, which will help us model it and give us a better idea of how to simplify the model and accurately re-create it. Additionally, the dissertation and its associated prototype will be quantitatively analyzed in order to determine which aspects of the design are effective and which areas can be improved upon. This includes the maximum force output, the packing efficiency, system complexity, and system responsiveness among other mechanical properties.

Figure 1.a: Front view of prototype [2]

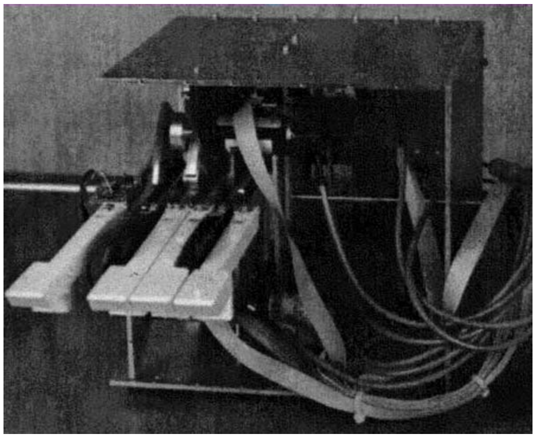
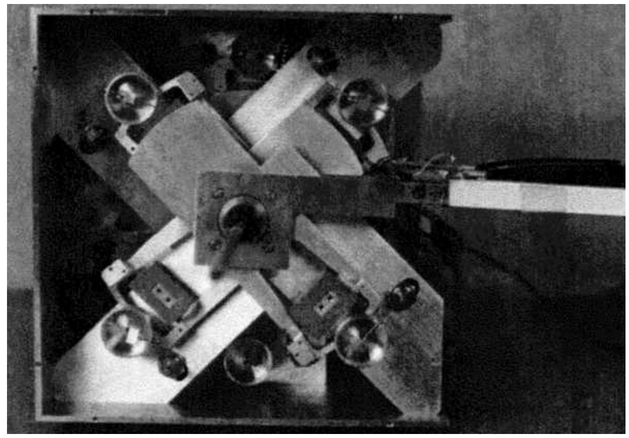
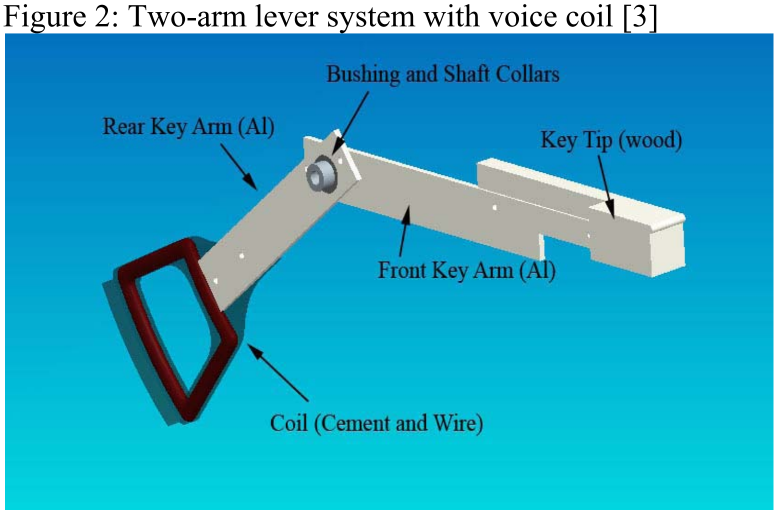


Figure 1.b: Side view showing complexity of packing [2]



During the winter 2006 semester, in the Mechanical Engineering 450 class here at the University of Michigan, a student group was assigned the task of creating a haptic interface for a keyboard. In their design, each key consisted of a two lever-arm system with a voice coil incorporated into one end, as seen in Figure 2 [3]. When the key was pressed, the voice coil passed through a magnetic field, producing an output force. The final prototype for the project did not meet its functionality goals because the product exhibited two major shortcomings. First, the magnitude of the achieved output force was not sufficient to provide a noticeable touch response for a user. Second, the bearings used could not adequately restrict lateral motion of the keys and as a result the voice coils could touch the magnets and the keys were allowed to overlap each other As with professor Gillespie's dissertation, this engineering group's final report has been quantitatively analyzed to determine the prototype's effective and ineffective design components.

Figure 2: Two-arm lever system with voice coil [3]



Project Goals

In order to solve the problem at hand, we will design and prototype a motorized electronic musical instrument controller which utilizes actuators and sensors to recreate the mechanical response of an acoustic instrument when played by a musician. The prototype will also be programmable for active adjustment of mechanical response, allowing the musician to choose which instrument he or she would like to emulate using the keyboard. This prototype will be used to quantify the value of incorporating actuators into the musician-instrument interface and to help with further research. If the final prototype is successful, it may eventually be commercialized.

Information Sources

We have found the following information sources valuable when researching for this project. Bob Grijalva, the Director of Piano Technology at the University of Michigan, provided us with information on the specific concerns of the pianist in terms of physical interaction with the instrument, as well as other related information. We met with him on February 13, 2009. Professor Brent Gillespie, our sponsor, has provided us with pertinent information including requirements as a customer, as well as linking us to other resources. IEEE Xplore has also proven to be a valuable tool, allowing us to explore the details of preliminary design ideas and also to further investigate the reasons for the failure of the previous Mechanical Engineering 450 group's prototype design [3]. We have also researched existing patents using Google Patents. While no patents exist on our specific project, several involving haptic interfaces have been found, and we will need to remain aware of their existence throughout the course to ensure that we do not copy any patented designs [4]. Additional resources include journals and dissertations found on Jstor [5].

Project Requirements

Creating a device that can produce an effective active force feedback response to imitate a wide range of different acoustic keyboard instruments is our main goal, so any requirements relating to this were considered the most important. The force response must be programmable using a computer so that different force responses can be programmed for any instrument. The system must appropriately balance the passive inertia and the virtual or "active" inertia supplied by the actuator. Additionally, the system must be stable enough for reliable and repeatable use. We also determined requirements that need to be considered for our ultimate goal of commercializing our device. These are important in the long run, but not as much for the scope of our project. These can be found in the bottom portion of the list below, and they are minimal noise and vibration, ease of operation, minimal weight and tolerable pricing.

Project Requirements (in order of importance)

1. Wide range of programmable force response with adequate force profile
2. Optimize passive/active inertia ratio
3. Safe to operate
4. Reliable/Robust to environment change
5. Negligible noise/vibration
6. Easy to operate
7. Affordable

Engineering Specifications

This section will outline the engineering specifications we obtained by constructing a QFD, which can be found in Appendix B. Engineering analysis also provided several performance balances that serve as engineering specifications that we must meet while constructing our prototype design.

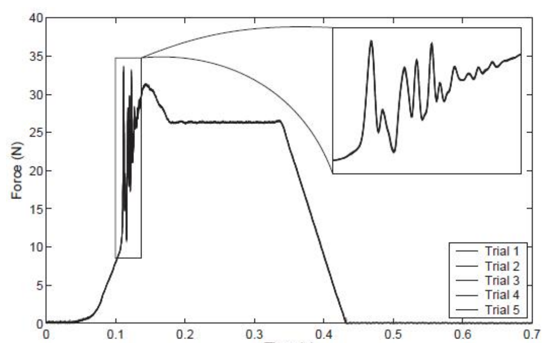
Total Inertia of System at Pivot: We found that the requirement target for the total inertia is 0.015 kg*m^2. We set the target for this inertia as the same as the inertia of a typical grand piano action system as determined by Professor Gillespie's research notebook. He determined this by first modeling the piano action components with only the key and hammer, neglecting the whippen assembly by assuming that the inertia of these components to be negligible. By performing simple pendulum experiments on the hammer and key by measuring the period of their swing, he determined the inertia of both of these components. He then determined the total inertia of the system by factoring in the mechanical advantage that the key has over the hammer, which is typically a ratio of 1:5. This mechanical advantage factor was also confirmed by Bob Grijalva. By following this approximation, the total inertia of the system can be expressed as:

$$J_{total} = J_{key} + 5^2 \cdot J_{hammer} \qquad \text{Eq.1}$$

Here, J_{total} represents the total inertia of the system, and J_{key} and J_{hammer} are the inertias of the key and hammer, respectively. The 5^2 term represents the mechanical advantage of the hammer, and this result was confirmed in Professor Gillespie's notebook [25].

Response Time: We defined the system response time to be the duration of time required for our system to receive an input, adjust the command current appropriately, and produce an output force. The total response time is affected by parameters including resolution of sensors, speed of the controller, and current rise time. Although the actual response time of our system will be determined experimentally, we chose a target requirement for the system response time to be 10ms.We determined this response time by analyzing the force profile plots (force magnitude vs. time) of various types of blows of the piano key measured by Hirschkorn [6], an example of which can be found in figure 3. We felt that 10 ms was sufficiently fast to reproduce the various force profiles without significant loss of accuracy.

Figure 3: An example Force vs. Time profile for a *forte* blow [6]



Force Output: We determined the target requirement for the force response to be 35N. We determined this value from observing the maximum force reached from the force profile shown in figure 3 [6]. We found that the maximum force measured by a very loud *forte* blow reached approximately 35N, and a very soft *piano* blow barely reached 2.5N. In order to effectively imitate the appropriate feel of similar keyboarded instruments, we must be able to produce reaction forces between these upper and lower limits of finger forces.

Noise: We chose the sound requirement of the actuating portion of the system to be approximately 0 dB (relative to the threshold of human hearing) [7]. Any sounds generated by the mechanical components of the system must not be perceivable, so that the user will not be distracted.

Vibration: We set the target requirement for vibration of the device to have a target of -20 dB (relative to a 1 μm displacement) of vibration felt at the finger tip of the user, with an upper limit of -10 dB . We determined these values from a vibration sensation threshold contour on a displacement vs. frequency plot in Askenfelt and Jansson [8]. Similar to the sound specification, this vibration specification must be as close as possible to the target value in order to deliver the intended feel to the user.

Maximum heat generation: We determined the limit of heat generation by modeling the coil's heat transfer as thermal buoyant flow from a cylinder exposed in air, given a certain length of the coil and room conditions [9]. We determined that the maximum temperature the coil could reach is about 120^0C, because at this point the wooden key would begin to slowly char [21]. For example, for a coil of length 300m (about 1500 turns) in room temperature, the allowed maximum heat generation is 185W, which is generated by a current of 6.2 Amps. Although this seems like a very low current, it should be sufficient for our project. If issues are met regarding heat generation, this analysis will be revisited and conduction will then be introduced. Small fins could potentially be attached to the toroid in order to help with heat dissipation.

Engineering specifications as equation balances: We have other engineering specifications for the device in terms of equation balances. Some examples include the heat generation and force output balance or the total system inertia vs. force output balance. These balances will allow us to determine aspects of the design such as material selection and the geometry in such a way that will meet all the above mentioned engineering specifications as well as the other project requirements.

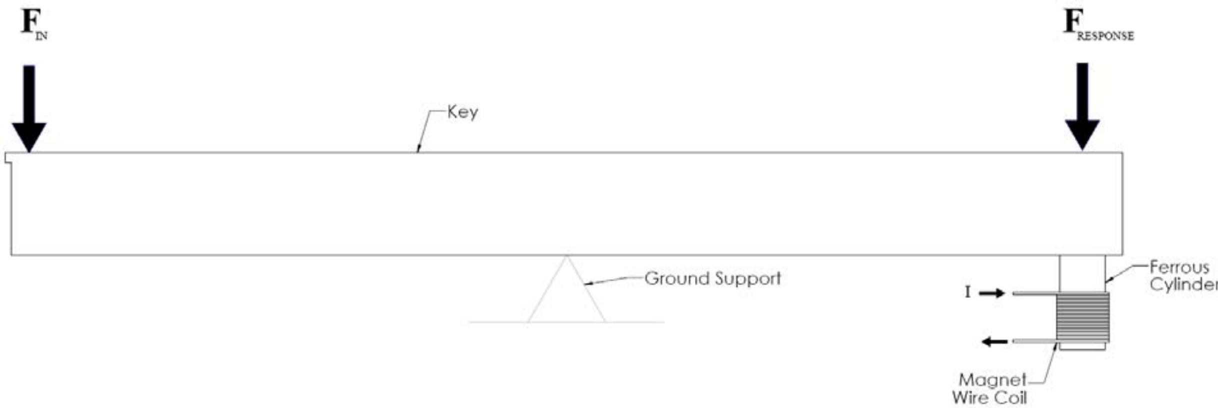
Concept Generation

In order to generate an alpha design, we first brainstormed to generate several possible concepts. The ideas we came up with use electromagnetic forces to achieve force feedback, which gives us a high amount of active control and allows us to add passive controls. Following is a breakdown of the different concepts and how they work. The concept designs below focus only on the active portion of each, since the passive portion will be designed for the chosen alpha design in order to maximize the system and achieve the most effective active-passive control ratio. Additionally, infeasible concepts driven by a motor coupled to the key by belts, gears, or a capstan drive were not included here as they are too complex, add unnecessary friction, and have a narrower range of programmability.

Solenoid Design

This design relies on a solenoid attached to the key in order to generate force feedback. A simple sketch of a solenoid attached to a key can be seen in Figure 4.

Figure 4: Solenoid Concept Sketch

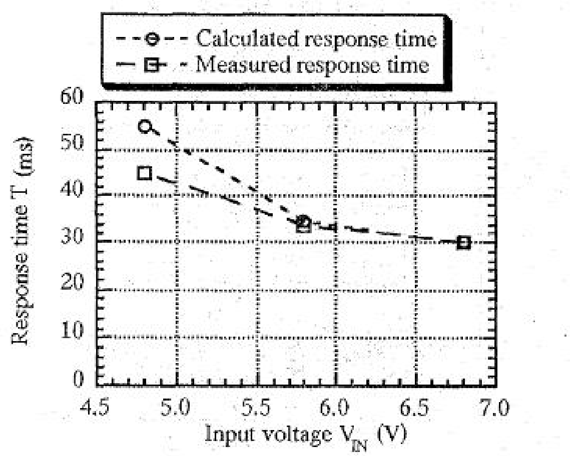


Where F_{IN} is the force input by the user, $F_{RESPONSE}$ is the force response of the solenoid, and I is the current running through the wire coil. The solenoid's force response can be approximated using Equation 2, though a more accurate force equation would be required for more complex geometry.

$$F_{RESPONSE} = \frac{\pi}{2\mu_0}\left(\frac{rNI}{stroke}\right)^2 \qquad \text{Eq. 2 [10]}$$

Here r is the radius of the ferrous cylindrical plunger, N is the number of turns in the coil, μ_0 is the magnetic permeability of the ferrous cylinder, I is the current, and *stroke* is the measure of how far out of position the plunger is. One concern we have with this design is its slow response time relative to other designs. At the voltages at which our prototype will operate, the response time for this design falls within a range of approximately 30 to 50 ms, as seen in Figure 5 [11]. This is too large to generate the complex force response curve of the grand piano, among other acoustic keyboard instruments [6]. Also, as is apparent from equation 2, the force output is dependent on the position of the plunger and therefore is not actually linear. This could present difficulty in accurately controlling the solenoid.

Figure 5: Typical response time of a linear solenoid actuator.



Voice Coil Design

This design utilizes voice coils attached to the end of the key as shown in Figure 6, in which one magnet pair has been removed in order to show the inside. When a current is applied to the wire coil, a force is produced in the wire according to Lorentz's Equation (Equation 3.) The simplest example of this type of force can be seen in Figure 7.

Figure 6: Existing voice coil

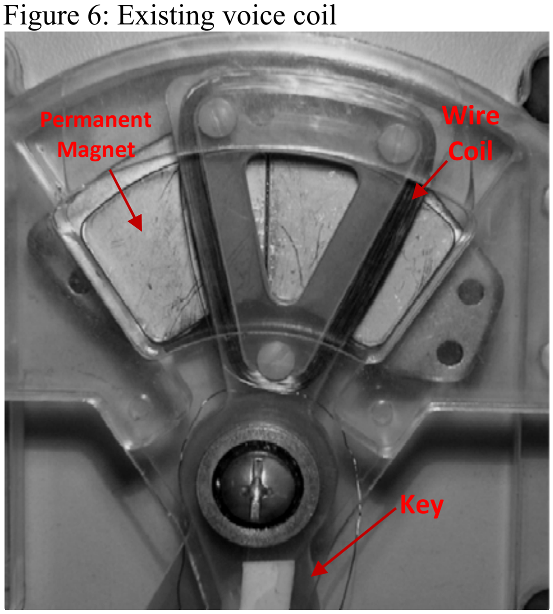
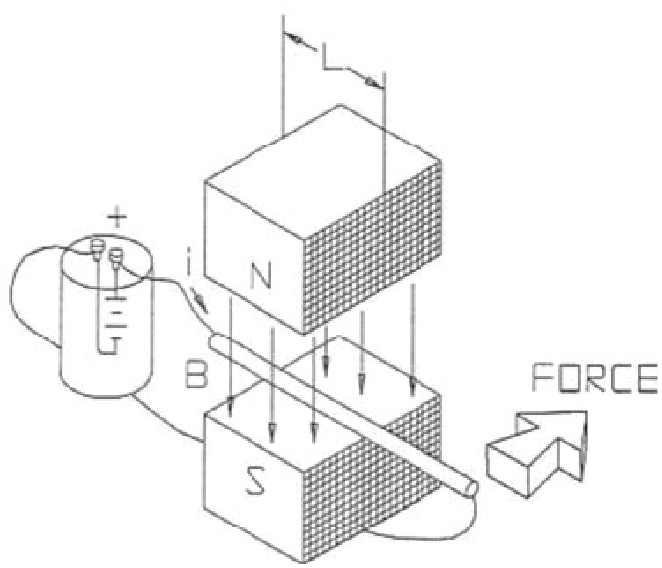


Figure 7: Force applied to wire [12]



$$F_{out} = iL \times B \qquad \text{(Eq. 3) [12]}$$

Where F is the force produced, L is the length of wire passing through the magnetic field, and B is the magnetic flux density. Although this design is simple, it was proven by the previous ME 450 group that it is difficult to generate the required force output using voice coils. Their alpha design failed largely due to the lack of numerical analysis of the system and minor mechanical design flaws. This will be discussed later in Concept Selection. Below, in Table 1, is a set of parameters that the team used to calculate the output torque of their final design. Upon completion of their prototype, these calculated values turned out to be insufficient to provide an acceptable force response at the key tip.

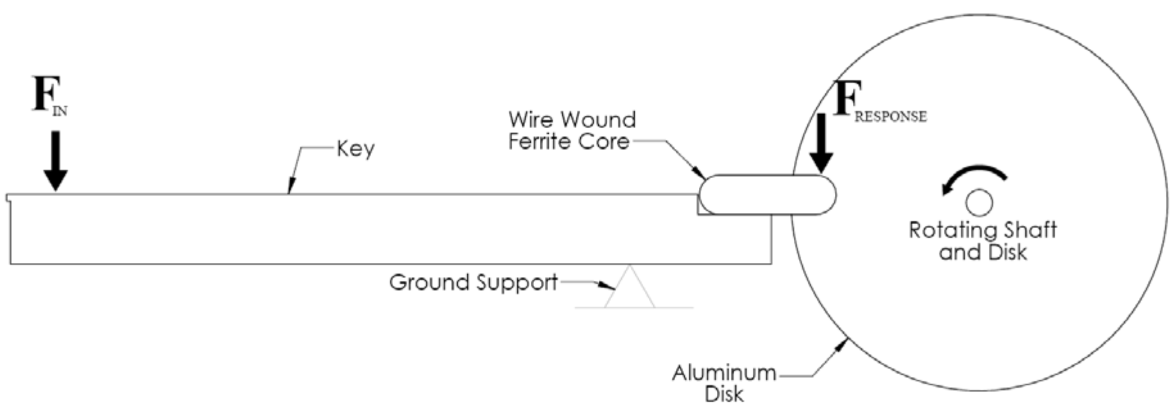
Table 1: Torque output analysis from previous ME 450 group [3]

Parameter	Design 1	Design 2	Design 3
B [T]	0.5	0.5	1
I [A]	5	5	5
L [m]	0.02	0.02	0.02
L_a [m]	0.2	0.2	0.2
n [#]	25	50	50
Torque [N-m]	0.5	1.0	2.0

Eddy Current Brake

The eddy current brake design consists of an electromagnet with a gap in it, through which an aluminum disk rotates. Although the disk is nonferrous, the motion through the magnetic field induces a current within the aluminum, which in turn reacts with magnetic field and produces a reaction force. In this design the disk is rotating on a shaft whose location is fixed, so the force produced acts on the piano key attached to the electromagnet. A sketch of this design can be seen in Figure 8.

Figure 8: Eddy Current Sketch



In the figure above, F_{IN} is the force input by the user and $F_{RESPONSE}$ is the force exerted back on the key by the eddy current brake. This design generates a force governed by a complex model, which is analyzed in Engineering Analysis. The force response of eddy current breaking is linear with respect to the rotational speed of the disc only at low speeds, so it may not be a possible to generate the desired output force [13].

Concept Selection

As mentioned in the Concept Generation section, we generated three conceptual designs as the candidate designs for our force actuator. In the Engineering Specification section, we used a QFD chart to determine the rank of our technical requirements in terms of their relative importance. Then, we gave each candidate design a subjective score in those specifications, as shown in Table 2. In this section, we will use these scores to assess the competence of each candidate design and choose the best design as the "alpha design" for our following work.

Technical Performance Rank and Metric

As discussed in the Engineering Specification section, we used the weight of customer requirements to rank the technical requirements in order of their relative importance, and we did relevant research to determine the target value for each of the technical requirements. For some of these requirements, such as the vibration magnitude, we could only find a range of target value. Subjectively, we gave each of our conceptual designs a score measuring its ability to achieve these requirements. Greater relative weight is given to more important technical requirements. We expect our design to achieve values within the target range, or near the target value, of the most important technical requirements.

Table 2: Eddy current brake is the optimal conceptual design

Ranked Technical Requirements	Relative Weight	Target Value	Score of Candidate		
			VC	ECB	Solenoid
1 .Total Inertial of System (kg.m^2)	0.18	< 0.015	3	2	3
2 .Controllability on Force (#)	0.13	N/A	3	5	1
3. Response Time (ms)	0.10	10	5	5	1
3. Maximum Force Produced (N)	0.10	35	1	5	3
3. Resolution of Motion Detection (mm)	0.10	2.5	5	5	5
3. Average Damping Coefficient (N.s/m)	0.10	N/A	N/A	N/A	N/A
7. Average Friction Coefficient (g)	0.08	8.5	5	5	5
8. Vibration Magnitude (dB)	0.08	< -10	5	4	5
9. Fatigue Cycles (#)	0.04	N/A	N/A	N/A	N/A
10. Maximum Heat Generation (W)	0.03	30	5	5	5
11. Total Volume (for 88 keys) (m^3)	0.02	< 1.5	5	5	5
12. Total Weight (for 88 keys) (kg)	0.02	< 10	5	3	5
13. Maximum Noise (dB)	0.01	< 0	5	3	5
13. Manufacture Cost ($)	0.01	< 1000	3	4	5
Total Score	1.00		3.33	3.68	2.90

Note: A technical requirement's relative weight is determined by QFD chart.
Total Score is the summations of the relative weights.
Controllability is currently a subjective metric with 5 maximum.

Analysis of Each Candidate

All three candidate designs will utilize similar components, such as bearings, sensors, and data acquisition equipment. For the purpose of this analysis, we will mostly be concerned with the force response of each design, and will design the rest of the system later.

Voice Coil: The voice coil design has advantages in total volume and weight, because its components are small and lightweight, as discussed in the Concept Generation section. However, its maximum force output is small compared to the other two candidates. Using Equation 3, with wire current 1.5 Amps and 100 turns will produce a force of approximately 4N. In this case we approximated the magnetic field strength to be 0.5 Tesla based on the analysis of the previous ME 450 group [3]. Although this value is not a maximum output, it is still far less than the target force output.

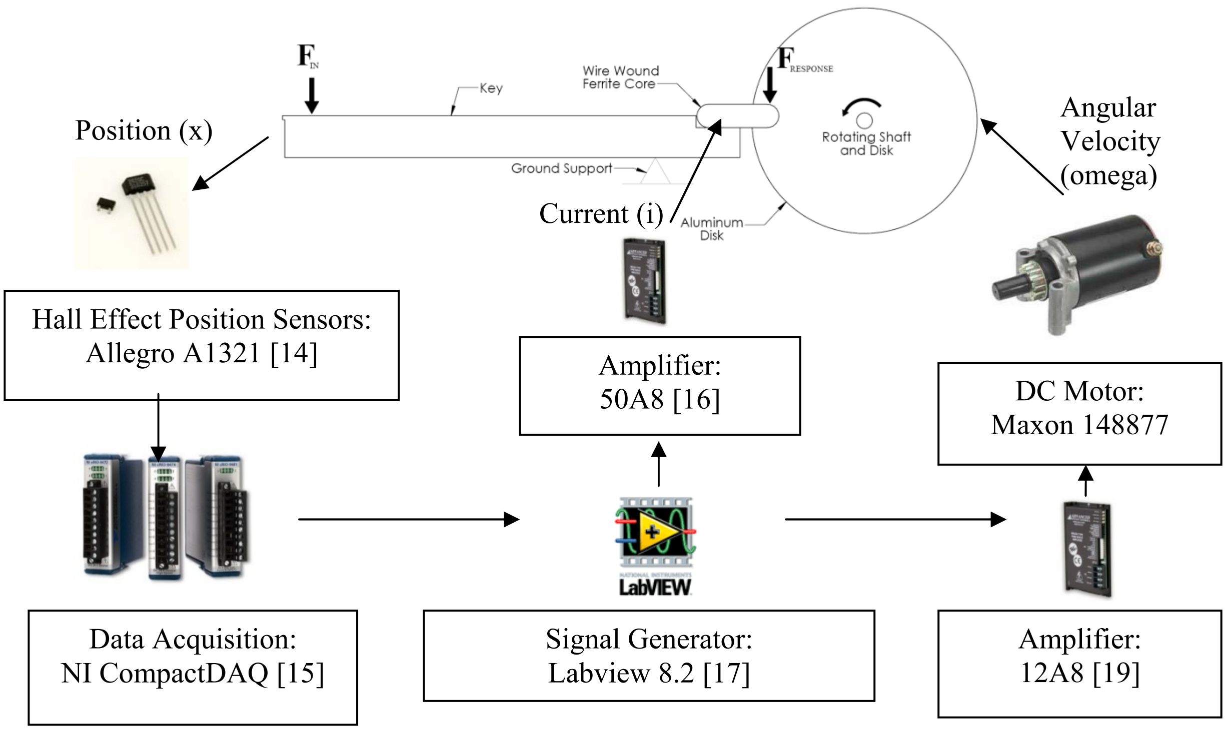
Eddy Current Brake: Compared to the voice coil design, the eddy current brake has greater overall inertia due to the attachment of the electromagnet on the end of the key, as shown in Figure 8. This system also has the potential to produce a larger output force by increasing the rotational speed of the spinning disc. For a typical eddy current brake setup using a ferrite core, it can generate more than 10 N if it has 1000 coils and 1.5 A current (eq. 9). Additionally, this design has a high range of force output and controllability. The wide variety of options in material properties makes it even more controllable. However, an eddy current brake may encounter some problems due to noise production generated from rotating components. It also weighs more and costs more to manufacture.

Solenoid: Subjective ratings of the solenoid design are between voice coil and eddy current brake in almost every category. One of the biggest advantages of solenoid is that it has very simple components and therefore is easy to assemble, as shown in Figure 5. As a result, a solenoid key can be designed to occupy less space and weigh less. The biggest problem, however, is that the solenoid has a very slow response time [11], which makes the dynamic modeling difficult, lowering system controllability.

Alpha Design

As discussed in the Concept Selection section, we used the rank and weight of technical requirements to assess each candidate design, and determined the eddy current brake to be the optimal design for the force actuator. According to its mechanical and electronic requirements, we selected competent devices to support its functionality and rendered the overall system. The overall system includes a key model with an electromagnet, a DC motor, a speed controller, an aluminum disc, multiple sensors, a signal generator and two amplifiers, as shown in Figure 9.

Figure 9: Detail Rendering of Alpha Design



Key Model

We measured the geometry of a key, and reproduced its shape in Solidworks. The position of the joint and the length of the lever are designed so that it can simulate the kinematics of a real piano key. In other words, the key end can travel the same distance a real piano travels (approximately 9.5 mm). We attached a ferrite core at one end of the key and aligned the aluminum disc within the air gap, with a clearance of 0.75 mm on both sides. This can be seen in Figure 9.

DC Motor

The dynamic model of a linear eddy current brake, Equation 9, is valid only if the disc's rotational speed is low [13]. We will test the validity of our theoretical model at high speeds, to be discussed later in the Engineering Analysis section. In order to generate and maintain 35N force output at the key end, our DC motor should take on as much as 4 N-m of torque without a significant loss in RPM. A typical DC motor, Maxon 148877 DC will be sufficient in this respect [18].

Aluminum Disc

Aluminum is the best material available right now in terms of its permeability and conductivity. The only parameter we need to consider is the thickness of the aluminum disc. Previous experiments have shown that thin discs have a better ratio between torque and inertia [13]. Currently, we have an aluminum disc with a thickness of 3.2mm.

Sensors
We need to use high resolution sensors to detect the position of the key. Hall Effect sensors have a great advantage over digital sensors in term of resolution and accuracy. For the intended purpose, a resolution on the order of tenths of millimeters is required. An Allegro A1321 Linear Hall Effect Sensor has a sensitivity of 50 mV/ mT, which will be more than sufficient [14].

Data Acquisition, Signal Generator and Amplifiers
The NI CompactDAQ [15] is used to collect the position information of key from the Hall Effect sensor. LabView 8.2 [17] is then used to translate the force output and send a current to the coil. The 50A8 amplifier [16] is used to amplify the signal and send amplified current to the coil. Labview will also be used as a the motor speed controller, commanding voltage to the 12A8 amplifier [19].

Engineering Analysis

This section outlines our method of developing a model which allowed us to predict the force output of our eddy current braking system. This analysis involved mostly principles from the physics of electromagnetism, a concept that is a major cornerstone of our design. We approximated our design to follow the example setup presented in [13], in which a circular disc rotates through a magnetic field created by a toroidal magnetic core. This setup is shown in Figure 10. In this case, the braking torque (τ_{diss}) induced by the rotating disc is given by Equation 3[13] below.

$$\tau_{diss} = \frac{\pi\sigma}{4} D^2 d B^2 R^2 \omega \qquad \text{(Eq. 4)}$$

Here σ represents the specific conductivity of the disc material (1/Ωm), d is the disc thickness (m), R is the effective radius (m) (meaning the distance from the center of the disc to the center of the core cross section), and ω is the angular velocity of the disc (rad/sec). In order to allow the equation to accommodate a magnetic core of any cross sectional shape, we replaced $\pi/4D^2$ (cross sectional area of circle) with a general cross sectional area term A_c. The only remaining parameter that required further investigation was the magnitude of the magnetic field (B). Magnetic field is defined by Equation 4[20] as following:

$$B = \frac{\Phi}{A_c} \qquad \text{(Eq. 5)}$$

Where A_c is the cross sectional area of the core, and Φ is the magnetic flux. Using the equation of magnetic flux in Gillespie’s course material [20], we extracted three relevant equations to define the magnitude of the magnetic flux, as shown in Equations 6, 7 and 8 below:

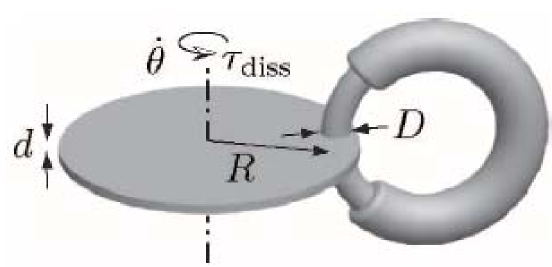
$\Phi = Ni / \mathbf{R}_{tot}$ (Eq.6) $\mathbf{R} = \frac{l}{\mu A_c}$ (Eq.7) $\mathbf{R}_{tot} = 2\mathbf{R}_{gap} + \mathbf{R}_{core} + \mathbf{R}_{disc}$ (Eq.8)

In this case, N is the number of windings of wire around the core, *i* is the current through the windings (Amps), and $\mathbf{R}_{tot}$ is the total reluctance of the system (Amp-turns/Wb). Reluctance of a single component of the system is defined in terms of the length the magnetic field travels l (m), the magnetic permeability of the material μ (N/A^2), and A_c (m^2), as shown in Equation 7. The total reluctance of a system may be found in a similar way as the total resistance is found in an electrical circuit; the components that are in series may simply be added together. In this application, the total reluctance is the sum of the reluctances of the core, the disc, and two air gaps (one on each side of the disc), which is shown in Equation 8. All of Equations 6 through 8 can be combined algebraically to produce an expression for the magnetic field B. In the final step of the process we used the fact that $\tau_{diss} = R*F_{out}$ in order to find a master equation for the force out F_{out} (N) produced by the eddy current brake, as shown in Equation 9:

$$F_{out} = \frac{\sigma_{disc} d R \omega N^2 i^2 A_c}{\left(\frac{2l_{gap}}{\mu_{air}} + \frac{l_{core}}{\mu_{core}} + \frac{d}{\mu_{disc}}\right)^2} \quad \text{(Eq.9)}$$

This equation not only provided us with a way to obtain a reasonable estimate of the force output of the system, but it also allowed us to decide which parameters should be minimized and maximized. For example, in order to maximize the force output we can clearly see that it is desirable to maximize both cross sectional area and specific conductivity of the disc, while minimizing the size of the air gaps.

Figure 10: Eddy Current Brake Schematic



Parameter Analysis

Our force output equation (eq. 9) involves several controllable parameters that we can either minimize or maximize in order to obtain the largest possible output force. This section examines the ways in which the parameters of each key component will influence the output force.

Ferrite Toroid: We chose to use toroidal shaped cores made of ferrite for several important reasons. The most important parameter that the use of ferrite maximizes is the magnetic permeability of the core (μ_{core}). Our ferrite core has an initial magnetic permeability of 2,500 (relative to the permeability of air) which will increase as the core temperature increases [22]. Due to the fact that each piano key will have its own core, it was also important to examine the trade-off between the core length (l_{core}) and the number of turns (N) that can be wound around the core. As the core length increases, the number of possible turns will also increase, but eventually the difficulty in packing the cores together outweighs the benefit of using a larger core. Thus, we decided to use a core with a length of 0.177m [22] and a cross sectional area of $2.175x10^{-4}$ m^2 [22].

Since ferrite is generally difficult to machine, our cores will require the use of a water jet cutter to machine the slots. This will allow a much greater degree of accuracy during machining, and will therefore make the task of minimizing the air gap (l_{gap}) much easier. As a result, we decided on a target total air gap size of no more than 1.5 mm. We felt that although it may be possible to machine the part to an even smaller tolerance, it is unrealistic to assume that there will be no lateral movement in the keys, so it is therefore necessary to include a small gap.

Aluminum Disk: We chose to construct our rotating disc out of aluminum because it was the most cost effective and readily available material. The specific conductivity of aluminum (σ_{disc}) is approximately $30x10^6$ S/m [23], which comparatively is not an exceptional value. For example, had we made our disc out of pure silver we could expect a specific conductivity of nearly double aluminum ($63x10^6$ S/m) [24]. We decided to use aluminum because it best fits into a realistic budget.

Aluminum was also chosen because of its ease of manufacturability. We were able to choose our preferred effective radius (R) and disc thickness (d), and then machine accordingly. We felt that an effective radius of 0.875m would be sufficient given the constraints of our experimental setup. We also felt that 0.003175m (1/8th inch) would be an acceptably small disc thickness and would in turn eliminate the necessity of extra machining. Selecting a slightly higher thickness than what is actually achievable will also allow for the possibility of reducing the thickness in the future if it were deemed necessary.

Magnet Wire: The chosen diameter of our magnet wire has important implications on the performance of our system. A smaller diameter wire allows for more turns (N) around the ferrite core, but also has a high resistance and therefore allows less current (i) to flow through it. In addition, a high resistance leads to a higher amount of generated heat. Conversely, a larger diameter wire will have much lower resistance and therefore allow for more current and lower heat generation. The drawback to using a larger diameter wire is that the potential number of turns around the core will decrease.

DC Brushed Motor: Professor Gillespie provided us with a Maxon 148877 DC brush type motor to drive the aluminum disc in our experimental apparatus, and eventually our prototype. The motor has a smooth 6mm diameter shaft which we will attach our disc to using a keyless bushing. This solved some previous shaft coupling issues that we were experiencing with other DC motors. The Maxon motor has a "no load speed" of 7580 RPM and a stall torque of 2.5 Nm [18]. These speed and torque constraints coupled with the inertia of the rotating disc should allow us to reach and maintain any desired ω value within realistic constraints for the purposes of our design.

Piano Key Length: The positioning of the toroid on the end of the key and the length of the key will effectively determine the force felt by user given a specific force output. We will mount our toroid at a distance of 0.15m from the central key pivot, and use a key length (from pivot to key tip) of 0.33m. These dimensions can be clearly seen in Appendix C (Prototype layout drawings). An in-depth analysis of how we arrived at this setup including inertia and torque balances can be found in more detail in our inertia analysis section.

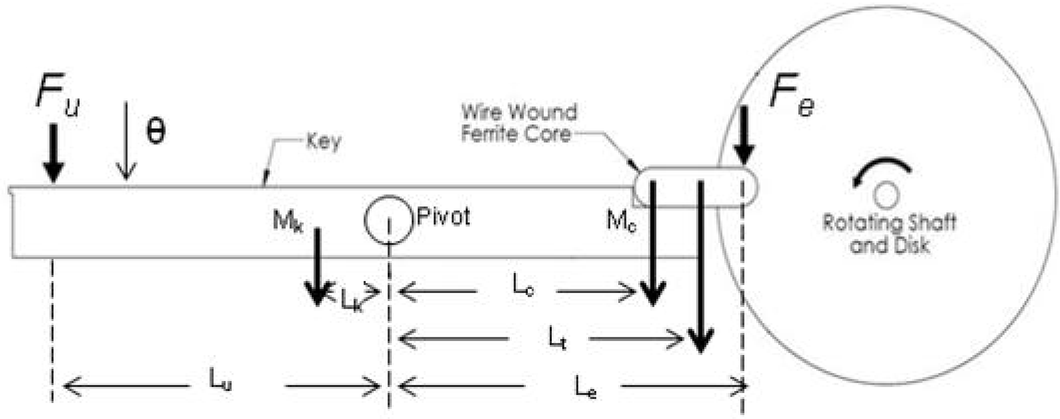
NOTE: In eq. 9, the only parameter that is completely out of our control is the permeability of air (μ_{air}), and as a result we will did not address it in this section.

Dynamic Analysis

In this section we will concentrate on the other end of the key, the position where user will impose a force. We will start from the dynamic equation of a piano key, and then design our controller so that our system can reproduce the force response of a typical piano key.

The typical assembly of a key design with an eddy current brake is shown in Figure 11. The user imposes a force at the key tip, and the eddy current brake then generates a responding force. There are three major gravity forces in the system: the weight of the key, the weight of the coil, and the weight of the toroid. All forces are positioned at each object's center of gravity. After taking the moment balance about the pivot and taking into the consideration of system's dynamic response, we have a governing second order differential equation for our system, shown in equation 10.

Figure 11: The schematic of a prototype key and its force diagram



$$F_u L_u - F_e L_e + (\underbrace{M_k g L_k - M_c g L_c - M_t g L_t}_{G}) = (\underbrace{M_k L_k^2 + M_c L_c^2 + M_t L_t^2}_{I})\ddot{\theta} + \underbrace{b\dot{\theta}}_{\text{Friction}}$$

$$\ddot{\theta} + \frac{b}{I}\dot{\theta} + F_e \frac{L_e}{I} = F_u \frac{L_u}{I} + \frac{G}{I} \qquad \text{Equation 10}$$

Our system is governed by the second order differential equation of $\boldsymbol{\theta}$ with an input force $\boldsymbol{F_u}$ (eq. 10). This input force is dynamic and a function of time. To simplify the problem, we assume that our system is a quasi-static process. For a second order system, this assumption is only valid when the settling time of the system is fast. In order to follow this assumption, and also make the force response of the system follow a prescribed profile, we designed our control law to be a derivative control with several correction terms, as shown in equation 11.

$$F_e = K_d \dot{\theta} + f(\theta)\frac{L_u}{L_e} + \frac{G}{L_e} \qquad \text{Equation 11}$$

The first order term $\boldsymbol{K_d}$ makes the system respond faster. The term $\boldsymbol{G}$ is to balance the gravitational force on the right hand side of equation 11. The prescribed function $f(\theta)$ is a relationship between the force response and the rotation angle of a real piano key, which is similar to those determined by experimental results from Hirschkorn's related piano project [6]. Using this controller design, when the steady state is reached ($\ddot{\theta} = \dot{\theta} = 0$), our system allows users to experience the exact amount of force feedback as one will do with a real piano ($F_u = f(\theta)$).

We want our key to have low rotational inertia, because as shown in equation 10, our system is slowed down by a factor of $\boldsymbol{I}$. The effort to design a low-inertia key will be explained in detail in Final Product Description section.

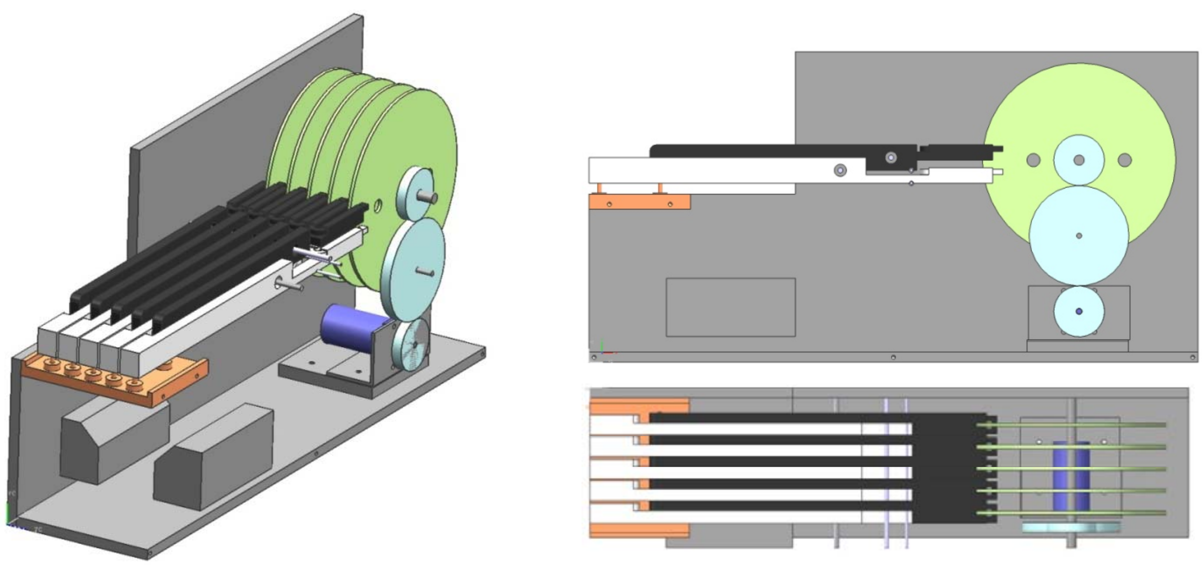
Final Product Description

As discussed in the parameter analysis section, we analyzed the effect of each eddy current brake system's parameter on the system's force response and established the guidelines of our engineering approach. Following these guidelines, we designed each component to optimize these parameters and therefore our final product.

We designed our final product according to the technical requirements that were previously analyzed. These requirements include the total inertia, the force output controllability, and the force output magnitude. When assembled, each key's lateral position should be constrained so that the clearance between the toroid and the disc can be maintained. The spacing between keys should also be taken into consideration.

For the convenience of this discussion, only 10 keys are shown. If one wants to expand the assembly to include more keys, the same design can be used to form any keyboard length. As a direct result however, the motor's power requirement may need to be redesigned, and the effect of increasing the amount of keys on the dynamics of the discs may need to be researched and validated. Figure 11 shows the trimetric view, top view and side view of the system.

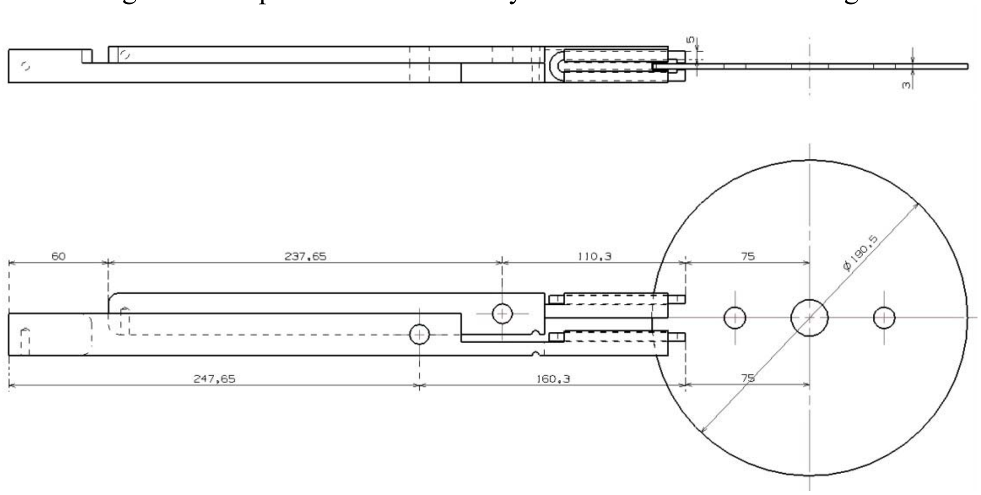
Figure 11: Trimetric, top, and side views of the final design



Key Body and Bearings

We designed the geometry of white keys and black keys, as shown in Figure 12. The black key (shorter key) is elevated and its toroid position is 15 mm above that of white key. The spacing allows the white key to rotate without hitting the black key. The toroids of both keys are perfectly aligned vertically to avoid obstruction from neighboring key couples. The detail drawings of both keys are shown in Appendix D.

Figure 12: Top and side view of keys and actuators in final design

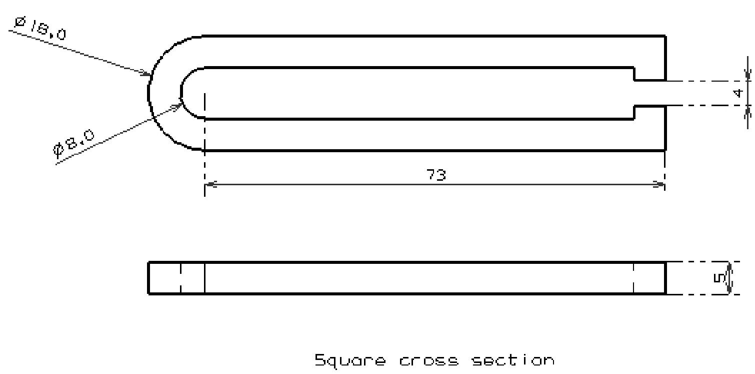


For each key, we will use two bearings to connect the key with the shaft, so that keys' lateral motion will be restricted. The bearings will also be thin enough to be placed side-by-side inside the key. For both the white and the black keys, the bearing position on the key is designed so that they can potentially reproduce the kinematics of the grand piano keys.

Core

At the end of the key a coil-wound ferrite core will be attached, as shown in Figure 13. The U-shape core allows the majority of the coil windings to be at the circular section, which will be very close to the rotation joint of the key. This will reduce the total inertia of the key. The straight part of the U-shape core then directs the current-induced magnetic flux to its tip and interacts with the disc. According to equation 9, the force output is inversely proportionally to the air gap. As a result, we designed the clearance between the toroid and the disc to be no more than 1 mm; a mechanical limit we feel is feasible.

Figure 13: Top and side view of U-shaped ferrite core



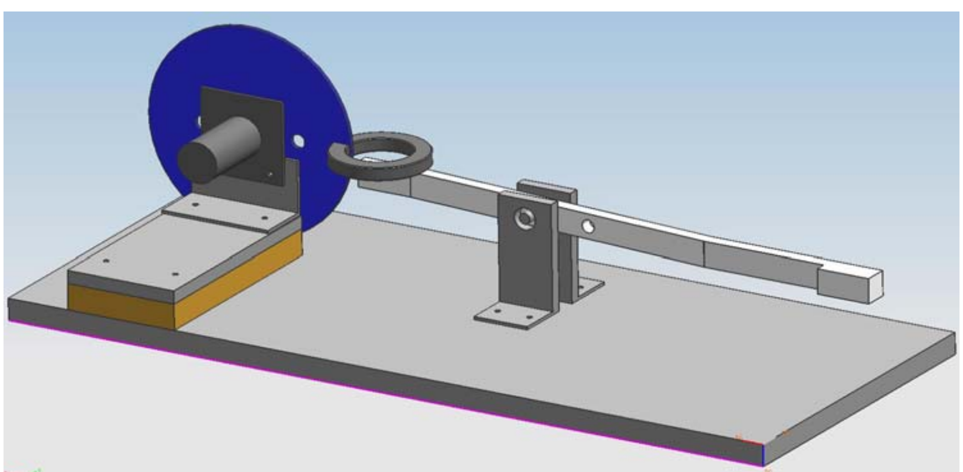
Motor and Gear
A motor must be specially chosen based on its maximum pulse torque output and continuous torque output. The maximum pulse torque must be sufficient to power several discs through a sudden blow on several piano keys, while the continuous torque is related to normal play on all the keys and its resulting average load. These requirements will change depending on the number of keys in the system, and thus it is necessary to obtain a specific motor for a given set of constraints.

We decided to use gears to deliver motor's power to the shaft. The advantage of gear series over a chain is that gears can safely deliver the torque under condition that there is a velocity difference between the disc and motor.

Prototype Description

Our prototype differs from our final design in that it will only consist of a single key, not a full keyboard with multiple keys. Our prototype will still prove the most important aspect of the device's functionality in that it will be able to create a wide range of programmable feedback force when the piano key is pressed. The inertia of the key and toroid combination will be minimized as much as possible in order to allow for better system performance. A major difference between the prototype and the final design is that the final design will have a different pivot system to prevent unwanted lateral in the keys. For our prototype lateral movement is less of a concern because the key is mounted rigidly on the shaft, which is attached to ground via a two bearing system. The prototype assembly can be seen in figure 14. The layout drawings for each component can be found in Appendix C.

Figure 14: Prototype Assembly



Wooden key: The wooden key was taken from a real piano, and has a maximum length of 501.4mm, a maximum height of 23mm, and a thickness of 11.8mm. A wooden key was chosen for its low density to minimize inertia. The key will be rigidly mounted on the metal shaft.

Metal shaft for key: The shaft has a diameter of 10mm and a length of 40mm. The shaft will be mounted on two ball bearings which are press fitted into pillow blocks.

Shaft clamps: Two sizes of shaft clamps will be used, one to clamp either side of the piano key and hold it perpendicular to the shaft, and a smaller size to hold the shaft in place.

Pillow blocks: The key shaft will be supported by two pillow blocks, one at either end. Each pillow block will house a bearing that holds the shaft and allows it to rotate.

Wooden blocks: The two pillow blocks will be supported by two wooden blocks. The blocks will be very simple, and their only features will be two holes that allow the pillow blocks to be bolted to the wooden base.

Ferrite toroid: A ferrite circular toroid with an outer radius of 85mm, an inner radius of 55mm, a thickness of 12mm and a slot opening of 5mm will be mounted on the end of the piano key rigidly. The toroid has a very high magnetic permeability of 2500 (relative to the permeability of air) [22] to maximize the force output between the spinning aluminum disk, when current is passed through the magnet wires wrapped around it.

Magnet wire: Magnet wire will be wound around the core in two coils of gauge 14 and 24, with 761 turns and 902 turns, respectively. These wire gauges were chosen because they fall within our limits to minimize heat generation with a large current, while allowing a large number of turns which will ensure a large force output from the actuator. The magnet wire will be connected to a 50A8 servo drive amplifier, which will be interfaced to a National Instruments Compact DAQ.

50A8 Servo Motor amplifier: This amplifier will supply the large current necessary to the magnet wires for the actuator to produce a large force output to the key structures. The input current signal will come from the interfaced National Instruments Compact DAQ, which will be interfaced to Labview 8.2. The desired force profile output at the actuator will be achieved from the programmable input signal from Labview 8.2. The amplifier will be powered by a compatible DC power supply. A similar amplifier, the 12A8, will be used to control the DC Motor as well.

Maxon DC brushed motor: The DC motor will be mounted on a square steel plate with 76mm sides with 4 screws. This plate will be used to mount the motor on an L-bracket with two screws of 5mm diameter 52mm apart. The DC motor has a specification that can be found in appendix E. This motor was chosen because it can produce the required angular velocity for the aluminum disk necessary to produce the desired force output from the actuator, while having enough torque output to make sure the reflective force from the actuator does not stop the spinning aluminum disk. The DC motor will be interfaced to Labview 8.2 with the National Instruments Compact DAQ and another 12A8 servo driver amplifier so that it can be controlled by a computer.

L-bracket for DC motor: This L-bracket will mount the DC motor onto the motor base, which will be mounted on the full base plate. The L-bracket has a height of 50mm, width of 100mm and a base length of 50mm.

Aluminum disk: An aluminum disk with a radius of 190.5mm and 3.2mm thickness and an electrical conductivity of approximately $30x10^6$ S/m will be coupled to the shaft of the DC motor with a keyless bushing, so that the outer rim of the disk will be able to spin through the slot opening of the toroid. The toroid and the aluminum disk will experience a force between them by eddy currents through electromagnetic induction when current is passed through the magnet wire and the disk is rotating.

Table 3: Chosen parameter values for prototype

Parameter	Value	Unit
Disc Conductivity (σ_{disc})	2E06	1/(Ωm) or S/m
Disc thickness (d)	0.003175	m
Effective radius (R)	0.0875	m
Disc Speed (ω)	Varies	rad/sec
Coil # (N)	902	N/A
Coil current (i)	Varies	amps
Core cross section (A_c)	0.0002175	m^2
Air gap size (l_{air})	0.001	m
Core circular length (l_{core})	0.177	m
Air permeability (μ_{air})	1.2566E-06	Newtons/amp^2 (or H/m)
Core permeability (μ_{core})	2500	Newtons/amp^2 (or H/m)
Disc permeability (μ_{disc})	1.2567E-06	Newtons/amp^2 (or H/m)

Fabrication Plan

This section includes a breakdown of our prototype into a plan to manufacture each component and a brief summary of the required assembly process. The descriptions below do not include those external to our prototype, such as amplifiers, DAQ, LabView, or a computer. Additionally, tolerances that are critical include all drilled hole locations, as they need to be accurately drilled for the prototype to properly fit together. More specific tolerances are noted within the manufacturing description of the associated component.

Base: The base will be constructed out of particle board. If for some reason the board is not flat, it may be properly balanced by adding some type of rubber shims to each corner of the board. This will also dampen vibrations caused by the motor. We chose particle board mostly because it would suit our needs and was available in the machine shop. After selecting a board, the base must be cut to the appropriate size using a band saw. Then, several holes will be drilled and tapped using T-nuts in order to secure the motor and key assembly in place.

Motor Face Plate: Professor Gillespie provided us with a previously manufactured plate onto which the supplied motor fits. This plate will be bolted to both the motor face and to and angle bracket which will support it. To do this, several holes will be drilled into it with the drill press.

Wooden Blocks: The key will be supported by two pillow blocks, which will in turn be supported by wooden blocks. These wooden blocks need only be cut to size with the band saw, and then drilled through to allow bolts to pass through them.

Aluminum disk: The aluminum disk is to be machined from 1/8" thick electrical grade Aluminum flat bar stock. The disk will be machined using a rotary table in a mill. The approximate center and radii will be marked using a compass, a scribe, and a center punch. Then, two thru holes will be drilled into the disc at an approximate 1" radius. Two bolts will secure the plate to the rotary table through these holes. After centering the mill to the rotary table, the plate will be machined to the appropriate radius.

Key: This component is being taken directly from an old piano action supplied by Bob Grijalva. We will use a band saw to cut the end to our specifications. Then, we will use a drill press to drill a hole into the key in order to fit the shaft upon which the key will pivot. The drill press will also be used to drill holes into the top of the key at the end where the toroid will be secured so that the metal clamp may be screwed in.

Toroidal Core: The toroid to be used in the prototype will require the machining of a single 0.13" wide slot. Because the core is made from ferrite (MnZn alloy), it is extremely hard and difficult to machine. After some investigation, we determined that a water jet will be capable of cutting the cores. The machined dimension of the toroid's slot is critical to the functionality and assembly of our prototype. If the slot is inaccurately machined it may contact the aluminum plate during operation or create too large of an air gap. Specifically, it is critical that the slot have two parallel sides of the appropriate dimension apart.

Key bed: The key bed which supports the key is made from a steel bracket and bent to the appropriate height simply by using a hammer and vice. We will press fit a metal pin and felt from an actual piano key action into the hole which is already in the bracket.

Toroid support: Similar to the key bed, this is simply a steel bracket bent to the appropriate height which will support the weight of the toroid at the end nearest the disk.

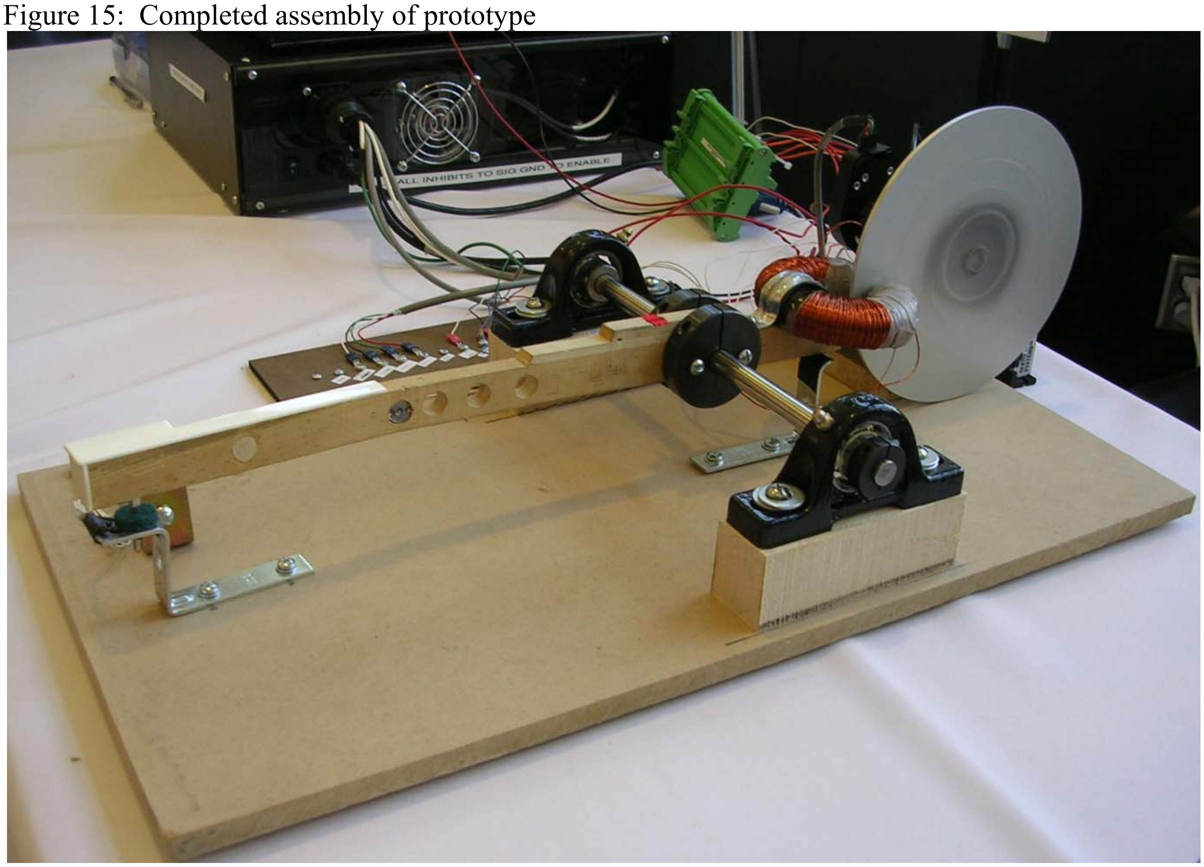
Prebuilt Components: The prebuilt components in our prototype include fasteners, a shaft, a keyless bushing, an electric motor, a metal clamp, magnet wire, and pillow blocks.

Assembly: Following the manufacturing of each component as described above, the assembly process will begin as follows:

1. The key will be secured to the shaft by tightening the large shaft clamps to the shaft and onto the key.
2. The key bed and toroid support are then screwed into the base.
3. The key and shaft will then be positioned between two pillow blocks which will then be bolted to the base.

4. The small shaft clamps must then be attached and secured to the ends of the shaft to hold it in place.
5. The toroid will be wound with magnet wire and secured onto the key by screwing the pipe clamp into the key.
6. The motor will be bolted to its face plate and angle bracket, which will then be bolted to the base.
7. The aluminum disc will be fitted to the keyless bushing, which will then be mounted onto the electric motor shaft, positioning the disc in the center of the toroid slot.
8. Finally, the key's motion will be briefly tested to ensure that the toroid does not contact the disc at any point along its travel. If the toroid does contact the disc, the keyless bushing can be adjusted accordingly.
9. A complete wiring diagram of the system we used to interface the various prototype components to the DAQ and their associated power supplies can be found in Appendix F. The LabView VI's that were used can be found in Appendix G. Also, a bill of materials can be found in Appendix H.

Figure 15: Completed assembly of prototype



Validation

Mechanically, our prototype functions as was intended. The mechanism of the key-shaft design successfully restricted the lateral motion of the key to less than 0.5mm. The motor shaft and the disc are aligned so that the wobbling of the disc is less than 1 mm. Both of these lateral restrictions successfully minimize the air gap between the disc and the toroid, which is crucial to our force output. The height of the pillow blocks is set to align the toroid with the center of the disc. The two key beds successfully allow a 9.5 mm vertical motion of the key, which is approximately the traveling length of a typical grand piano key.

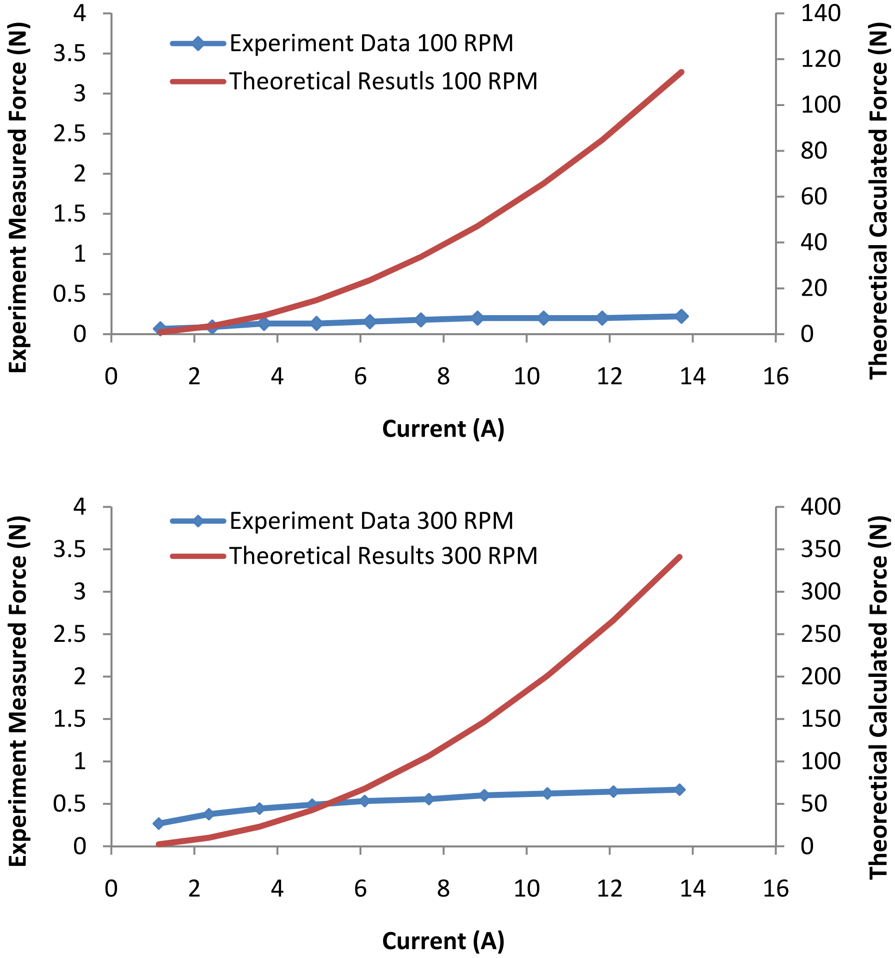
Secondly, our prototype is working electronically. Labview has complete control of all the devices through the DAQ interface. The resolution of the key position measurement (detected by Hall Effect sensor) is less than 0.01 mm. The coil current command has the range from 0 to 40 A with a resolution of less than 0.01A. The speed of the disc (detected by the encoder and controlled by the motor voltage) has an upper limit of 3000 RPM and lower limit of 50 RPM, with a resolution of 5 RPM. The delay of the Hall Effect sensor and coil current feedback control is negligible when compared to other system components. We determined by inspection that the delay of the motor feedback control is about 1.0 sec due to the dynamic response of the motor.

According to equation 9, our prototype can theoretically generate as much as 970 N (at 100 RPM and 40 A coil current, which reaches the low speed limit of our force model). We conducted several experiments on our prototype and evaluated its actual performance. The experiments include force output measurements, the motor response time evaluation, and the coil configuration evaluation.

***Force Output Model Validation*:** To verify the force model, we conducted validation experiments measuring the force output at the tip while varying the coil current and the disc speed. Labview 8.2 was used to control the motor and the coil current. An Advance Motion Control 12A8 amplifier, powered by a 24 Volt power supply, was used to magnify the voltage signal from Labview and power the motor. An Advance Motion Control 50A8 amplifier, powered by a 48 Volt power supply, was used to magnify the voltage signal from Labview and supply current into the coil. A digital scale was used to measure the torque generated at the key. The circuit diagram can be found in Appendix F. The Labview code is shown in Appendix F.

We varied coil current from 1 to 10 A (with step of 1 A) and kept the disc speed constant, recording the corresponding force output. We varied the disc speed from 100 to 1000 RPM (with step of 100 RPM) and kept the coil current constant, recording the corresponding force output. The resolution of the force measurements is 0.01 N. All other parameters' values are shown in Table 3. The results are shown in Figures 16 through 19.

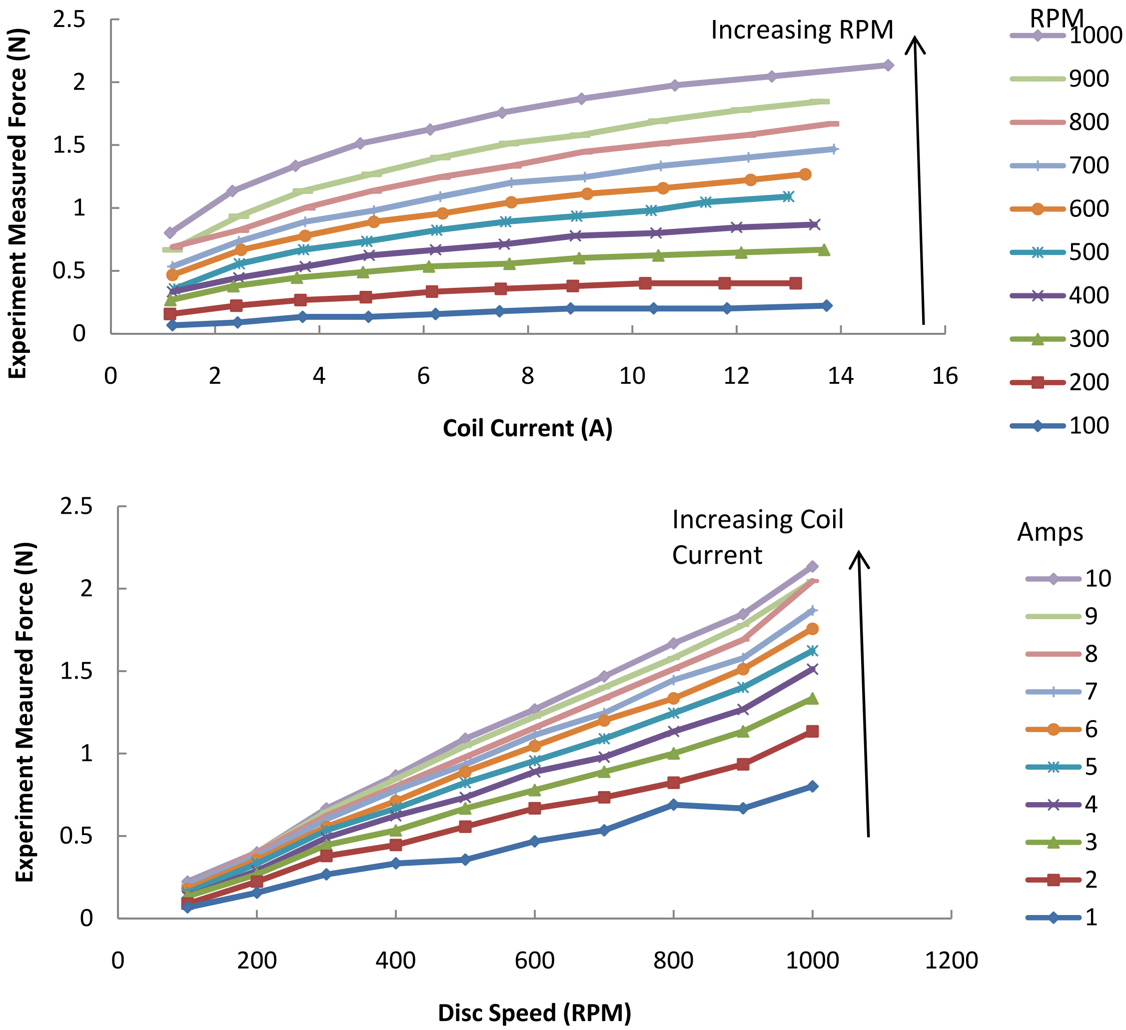
Figure 16: Comparison between experimental and theoretical force output at (a) 100 RPM (b) 300 RPM



There is large difference between the experiment results and theoretical model. The experimental results show much less force output than the theoretical model predicts. We found several possible reasons for this unexpected behavior. First, there may exist some magnetic loss at the sharp corner of the toroid cross-section. Next, the water-jet cutter did not make a perfectly smooth cut at the cross section, leaving a cross sectional area that was not uniform. The air gap was also larger than we had intended, and we did not accurately measure the exact value of the gap on either side of the toroid. Finally the wobbling of the disc made the air gaps vary with time.

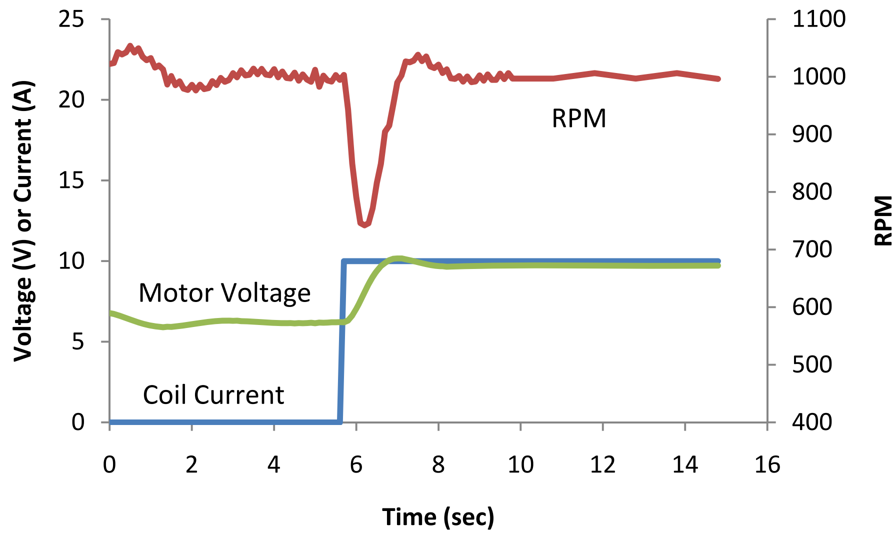
The experimental results do not show the trend that the theoretical model predicts. The results show that the force output increases almost linearly with the increase of the coil current. One possible reason that it does not follow the theoretical model is that coil's resistance increases as it is heated up. This allows less current to flow through the coil with increased temperature. Another possible reason for the discrepancy is that the upper limit of the disc speed where the theoretical model is valid is still unknown. There is a possibility that at 100 RPM or above, the theoretical model is no longer applicable. On the other hand, we were able to validate the relationship between the force output and the disc speed. Figure 17b shows that the experimental force output increases linearly as the disc speed increases. This is consistent with the prediction of the theoretical model.

Figure 17: Experiment measured force output increases (a) linearly as coil current increases. (b) linearly as disc speed increases.



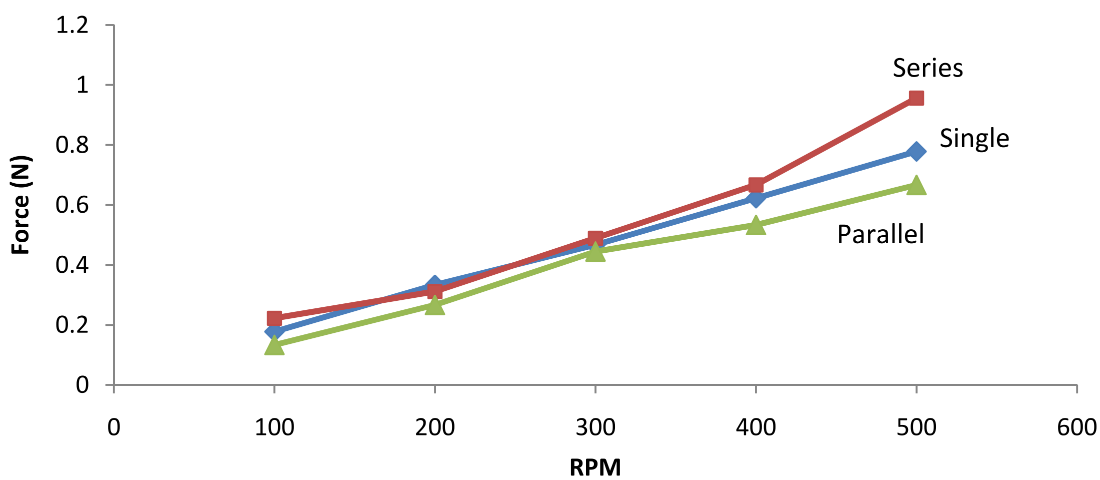
Response Time Evaluation: Our motor is feedback controlled by a proportional controller. It takes in the information of disc speed and outputs a corresponding motor voltage. In our experiments on the evaluation of the motor's response time we took measurements of the motor voltage, motor speed, and coil current. We then evaluated the time that the motor took to settle down to steady state. We assumed that there was no significant delay in our computer programs. The experimental results are shown in figure 18. Under a current control algorithm, the motor has approximately a 1.0 second delay.

Figure 18: 1.0 sec delay in motor dynamic response.



Coil Configuration Evaluation: As mentioned above in our prototype description, our ferrite core was wound with two separate coils: one with 761 turns and 4.0 ohms resistance, and the other with 902 turns and 2.4 ohms resistance. We conducted experiments to explore the advantages of the possible coil configurations. Three configurations were tested: one using a single coil (the one with 902 turns), one using two coils connected parallel, and one using two coils connected in series. We supplied 3 A to all these configurations and measured the force output, varying the disc speed from 100 RPM to 500 RPM. The results are shown in Figure 19.

Figure 19: System performance with different coil configurations



The series configuration had the best performance, likely because it has double the turns at the same current. The advantage of this configuration shows itself at high RPM. The parallel configuration had the lowest force output, which is because it doubles the coil number but at the same time splitting the current. Yet this configuration has its own advantage over other configurations because of its small resistance, which decreases the heat generation and also allows larger maximum current.

Design Critique

During and after construction of our prototype, several problem areas were brought to our attention. A major problem area of our design was the difficulty in both winding the wire around the toroid core and maintaining the wire's position on the core after it was wound. The toroid required constant adjustment in order to prevent the wires and the tape from sliding off into the air gap. If we were to construct another one, we would devise a new way to keep the wire on the toroid and possibly a faster method of winding it. Heat generation also proved to be much more of a factor than we had originally considered. There was a sufficient amount of excess heat to melt some of the electrical tape on the toroid, and in some cases the core itself became hot enough to be hazardous to touch. In addition, we did not consider the fact that the performance of the system decreases with an increase in wire temperature. This is because the resistance of the wires increases as they heat up, therefore allowing less current to flow through. Had we been aware of these issues back in the design phase, we could have designed some sort of heat dissipation system.

The biggest strength of our design is that it delivered a force output that exceeded our initial expectations. After construction of our prototype, we were skeptical as to whether it would produce a large enough output force that could be felt by a user at the key tip. Our initial testing was somewhat disappointing, but after configuring the controllable parameters (current, angular velocity) correctly we were able to achieve much larger output forces by the design expo. Those who tested our prototype were generally able to feel the difference in force at the key tip as we adjusted the coil current.

One major weakness of our design was the fit of the disc inside the air gap. We were unable to perfectly balance the disc on the motor shaft, and as a result it wobbled slightly as it spun. This prevented us from minimizing the air gap to the smallest size we could, which in turn reduced the overall performance of the system. It also presented problems in combination with the core's wire issue discussed above. In some cases the disc would grind against the wire, electrical tape, and even the ferrite core itself. Another weakness was the total friction in the bearing system we used. The purpose of the bearing system was to restrict the lateral motion of the key while also providing a key pivot with as little friction as possible. Our key pivoted about a shaft that was anchored at each end by ball bearings which were press fitted into pillow blocks. When we first received the bearings, there was such a large amount of internal friction that we thought they were not usable. We were able to slightly reduce the friction by removing the shields on either side of the bearings, but they still required much more force to spin them than what was desirable. Our prototype was also very inefficient in its power consumption. Our toroid core used a dedicated 1000 Watt power supply to power it. The system also required two additional power supplies to run the other various components (amplifier, encoder, Hall Effect sensor, load cell). Since our design only involves a single piano key, it is not feasible to expand our design into an entire keyboard while powering it in this way.

All of these weaknesses could be improved upon during future iterations of refining our design. Firstly, the wobbling of the disc could be easily fixed by more precisely machining the disc. Our disc was made of scrap aluminum that had a few holes drilled in it and was likely not of exactly uniform thickness (down to the order of thousandths of an inch). Obtaining a perfectly circular and uniform disc would make the processes of balancing much easier if not eliminate it altogether. The keyless bushing that coupled to the disc was also easily yielded if over tightened, and it's possible that that it also contributed to the disc wobbling. This could be solved by simply using a higher quality and likely more expensive bushing.

The flaw in our bearing system did not lie in its design; it was the bearings themselves. Ordering nicer bearings would likely solve this problem, and no alterations to the design of the system would be necessary.

The power consumption issue is the most difficult to improve upon. Although correcting some of the issues in other areas of the design would make the prototype operate more efficiently and thus slightly reduce its power requirements, it is unlikely that there would be any substantial decrease. Since the functionality of an eddy current brake system is dependent on a large magnitude of electrical current, our design will always require a power supply that is capable of generating large currents (on the order of approximately 30 Amps). It is possible to use wire of smaller resistance (larger diameter) in order to reduce the voltage drop necessary to drive large currents through the core, but this in turn reduces the possible number of windings. This introduces a trade-off between the number of windings and wire resistance that is briefly examined in figure 19, but would benefit from further investigation. Other than using different wire, there is not an apparent way to drastically reduce the required power of the system.

In order to improve the heat dissipation around the core, it would be possible to design fins that fit onto the toroid. The fins could be designed to clamp onto the ferrite core before it was wrapped with wire, and then extend outward. This would not only help with heat dissipation, but it would also solve the issue of keeping the wire in place after winding it, as the fins could serve as "anchors" that would keep the wire from slipping off. A major drawback of this idea is that adding fins also adds weight to the system and therefore increases the required output force to maintain the same level of performance. Unless the fins were made of an extremely light material, it is doubtful that the added heat dissipation is worth the added weight. This is another design aspect that would be better examined in future iterations of this project.

Recommendations

Since this is most likely not the last time this project will be revisited, we have included below a list of recommendations that will allow for testing of the existing prototype and also assist in the construction improvements in the future.

Electromagnet: There are several things that we recommend for the creation of a new electromagnet. First, if a new electromagnet needs to be constructed, then a better core material should be selected. The material should have high magnetic permeability and be highly machinable to allow for custom core geometries. Second, it may be desirable to find a way to automate core winding in order to save time. Manually winding the core can be very time consuming; more than 6 hours were devoted to winding the core used in this prototype. Finally, wire management was a problem during prototype testing. When the electromagnet reached high temperatures, the wires loosened and the tape no longer adhered, allowing the wire to begin sliding and contacting with the disk. This could be solved by designing a small wall into the geometry of the core when building a new one. The wall would be near the core slot and would stop wires from sliding into the gap, thus restricting it from contacting the disk.

Heat generation: During testing, it was found that temperature changes were a very large problem. The danger of having hot coils near the user was not the largest problem as previously thought. As temperature increased, so did the resistance in the coil. This meant the maximum current flowing through the coil was decreased. Analyzing the heat generated in the coil would allow for the design of efficient fins that would dissipate heat. Using those fins could allow for maximizing heat dissipation, thus allowing a higher maximum current output and maximum force output. Additionally, the fins could be used as the small wall and be designed into the geometry of the core as described above.

Sensors and controllers: The encoder attached to the motor we used sent too many pulses per revolution to LabView. When operating at high speeds, LabView failed to read the data coming from the encoder. Instead, a Hall effect sensor could be used to read the rotational velocity of the disk. One small magnet could be attached to the disk, and each time it passed the Hall effect sensor it would generate a pulse. Logic can be used to convert this into one revolution of the disk. If this method is not high enough resolution, then multiple magnets can be placed on the disk to generate multiple pulses per revolution. This can also be used with LabView logic to determine rotational velocity. Another problem we had was making the disk rotate at constant velocities, which we solved using LabView. Using the tachometer speed control built into the amplifier instead of LabView as a speed controller may be preferred.

Hinging mechanism: The bearings and pillow blocks used in our prototype are infeasible for a final design, so a more advanced solution must be found. We used the bearings on a long shaft to restrict lateral motion because it was a major problem. This can be solved using a more compact design and we recommend using a compliant mechanism to do so. Such a compliant mechanism must simply allow for vertical motion but restrict lateral motion of the key.

In-depth analysis: Due to the inaccuracy of our theoretical model, a more in-depth analysis of the system is recommended. The model may need to simply be modified or perhaps a new model must be generated. There are several ways to do this, though the easiest may be to first acquire data using the existing prototype, then attempt to modify the model based off it. In order to improve the accuracy of such a model, we also recommend performing a finite element analysis on the system. Additionally, the model should be tested with a range of each variable. Since there are so many variables, there is much improvement to be made in the system.

Conclusion

In order to solve the problem with a musician's lack of physical connection to an electronic keyboard, we have designed and prototyped a single key haptic feedback system with the potential of simulating the force response of a variety of acoustic keyboard instruments. We chose the eddy current braking system as our actuator through the use of our QFD. Then, we constructed our prototype and performed the experiments described in the validation section to show that eddy current braking is a viable system for use with haptic response. Though the experimental data does not meet the expectations presented by the theoretical model, the system still looks promising. Our prototype can be used as a tool to adjust the existing theoretical model and find where improvements can be made in the system. This will allow for further design optimization, which will eventually lead to the next iteration of this project and perhaps even commercialization.

Acknowledgements

We would like to acknowledge the following people for assisting us in the design, manufacturing and testing of our prototype:
Professor Brent Gillespie – Helped with many aspects of the project
Bob Coury – Assistance with manufacturing in the machine shop
Marv Cressey– Assistance with manufacturing in the machine shop
Steve Erskine – Helped us cut our toroidal cores using the water jet in the ERC
Bob Grijalva – Provided us with information about the grand piano action model

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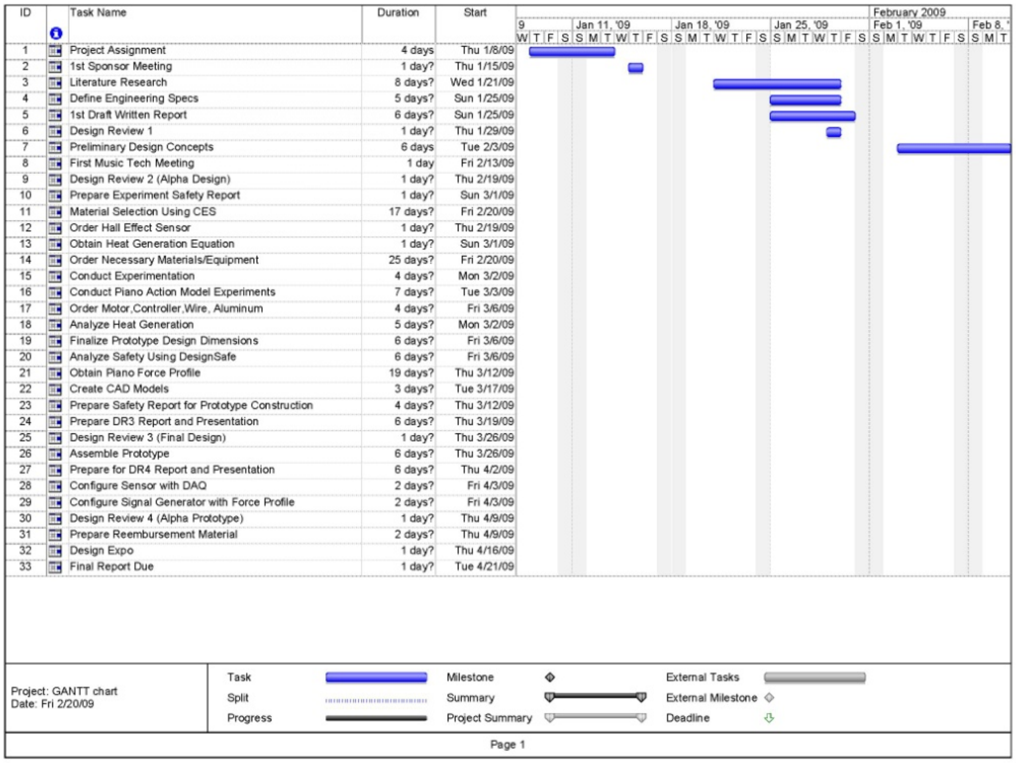
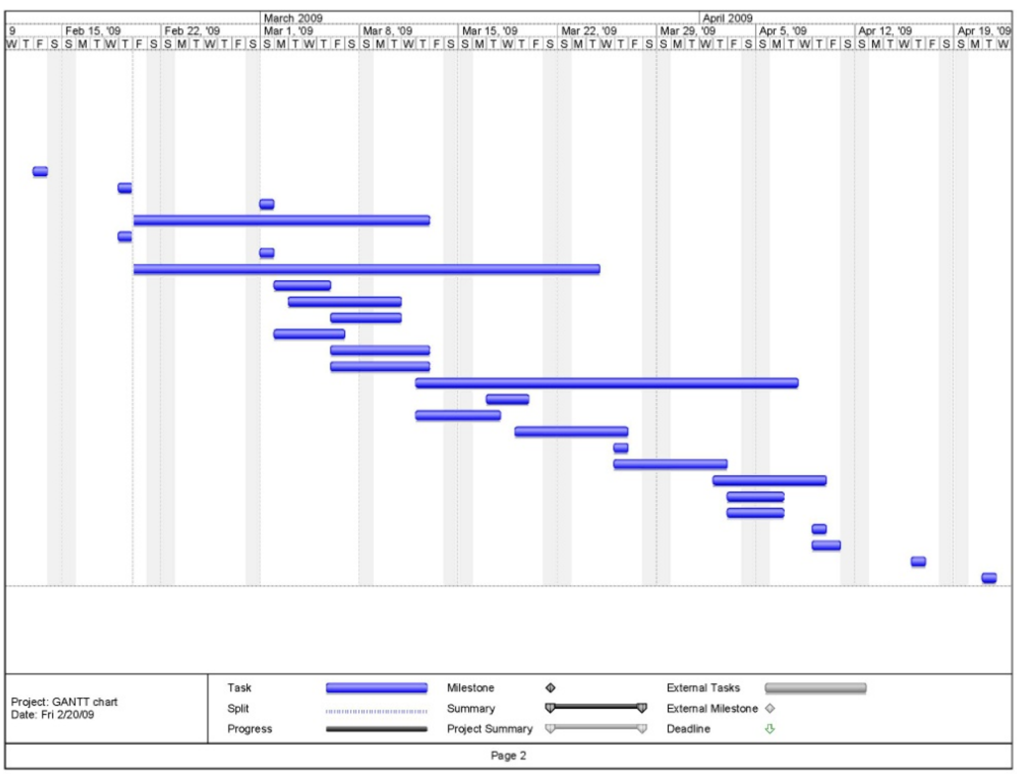
Appendix A

Gantt Chart



ID	Task Name	Duration	Start
1	Project Assignment	4 days	Thu 1/8/09
2	1st Sponsor Meeting	1 day?	Thu 1/15/09
3	Literature Research	8 days?	Wed 1/21/09
4	Define Engineering Specs	5 days?	Sun 1/25/09
5	1st Draft Written Report	6 days?	Sun 1/25/09
6	Design Review 1	1 day?	Thu 1/29/09
7	Preliminary Design Concepts	6 days	Tue 2/3/09
8	First Music Tech Meeting	1 day	Fri 2/13/09
9	Design Review 2 (Alpha Design)	1 day?	Thu 2/19/09
10	Prepare Experiment Safety Report	1 day?	Sun 3/1/09
11	Material Selection Using CES	17 days?	Fri 2/20/09
12	Order Hall Effect Sensor	1 day?	Thu 2/19/09
13	Obtain Heat Generation Equation	1 day?	Sun 3/1/09
14	Order Necessary Materials/Equipment	25 days?	Fri 2/20/09
15	Conduct Experimentation	4 days?	Mon 3/2/09
16	Conduct Piano Action Model Experiments	7 days?	Tue 3/3/09
17	Order Motor,Controller,Wire, Aluminum	4 days?	Fri 3/6/09
18	Analyze Heat Generation	5 days?	Mon 3/2/09
19	Finalize Prototype Design Dimensions	6 days?	Fri 3/6/09
20	Analyze Safety Using DesignSafe	6 days?	Fri 3/6/09
21	Obtain Piano Force Profile	19 days?	Thu 3/12/09
22	Create CAD Models	3 days?	Tue 3/17/09
23	Prepare Safety Report for Prototype Construction	4 days?	Thu 3/12/09
24	Prepare DR3 Report and Presentation	6 days?	Thu 3/19/09
25	Design Review 3 (Final Design)	1 day?	Thu 3/26/09
26	Assemble Prototype	6 days?	Thu 3/26/09
27	Prepare for DR4 Report and Presentation	6 days?	Thu 4/2/09
28	Configure Sensor with DAQ	2 days?	Fri 4/3/09
29	Configure Signal Generator with Force Profile	2 days?	Fri 4/3/09
30	Design Review 4 (Alpha Prototype)	1 day?	Thu 4/9/09
31	Prepare Reembursement Material	2 days?	Thu 4/9/09
32	Design Expo	1 day?	Thu 4/16/09
33	Final Report Due	1 day?	Tue 4/21/09



Appendix B

QFD

System QFD

Project:	Programmable Force Feedback Keyboard
Date:	2/20/09

#	Technical Requirement	1	2	3	4	5	6	7	8	9	10	11	12	13
1	Average Damping Coeffficent of System													
2	Average Rotation Friction Coefficient													
3	Total Inertial of System about the Rotation Pivot													
4	Response Time	3	3											
5	Maximum Force Produced	3	3		3									
6	Resolution of Key Postion Detection	3	3		3	3								
7	Heat Generation													
8	Noise		3											
9	Fatigue Cycles			3										
10	Total Weight (for 88 keys)	3	3							9				
11	Total Volumn (for 88 keys)		1											
12	Manufacture Cost		9									3		
13	Controllability on the Force Response												1	
14	Vibration													
15														
16														
17														
18														
19														
20														

Survey Legend

A	Current product
B	Competitor B
C	Competitor C

Technical Requirements / **Customer Opinion Survey**

#	Customer Needs	Customer Weights	Kano Type	Average Damping Coeffficent of System	Average Rotation Friction Coefficient	Total Inertial of System about the Rotation Pivot	Response Time	Maximum Force Produced	Resolution of Key Postion Detection	Heat Generation	Noise	Fatigue Cycles	Total Weight (for 88 keys)	Total Volumn (for 88 keys)	Manufacture Cost	Controllability on the Force Response	Vibration	1 Voice Coil	2 Eddy Current Brake	3 Solenoid	4	5
1	Similar Froce response to traditional piano	4		9	3	9	9	9	3							9	3	3	5	3		
2	Easy to program the force response	4		3	1	9	3	3	9							9		2	5	4		
3	Easy to operate	2											1	3		3		3	4	4		
4	Comfortable Touch Feeling	4		3	9	9	3	3	3							1	9	3	5	3		
5	Robust for enviroment change	2										3						3	4	4		
6	Safe to operate	2								9		9						4	3	4		
7	Small Volume	1												9				3	3	4		
8	Lightweigh	1											9					3	3	4		
9	Affordable	1													9			4	3	4		
10	Sound quality	1									9							3	4	4		
		Raw score		60	52	108	60	60	60	18	9	24	11	15	9	82	48	31	39	38	0	0
		Scaled		0.555556	0.481481	1	0.555556	0.555556	0.555556	0.166667	0.083333	0.222222	0.101852	0.138889	0.083333	0.759259	0.444444					
		Relative Weight		10%	8%	18%	10%	10%	10%	3%	1%	4%	2%	2%	1%	13%	8%					
		Rank		3	7	1	3	3	3	10	13	9	12	11	13	2	8	3	1	2		
	Requirement Benchmarking	Best in Class																				
		AVE																				
		Worst in Class																				
		Kano		L	L	L																
		Direction																				
	Technical Requirement Units			N*s/m	g	kg*m^2	ms	N	mm	W	dB	#	kg	m^3	$	#	dB					
	Technical Requriement Targets			N/A	9	0.015	10	35	2.5	30	0	N/A	0.02	0.02	1000	N/A	<-10					
	Technical Requriement USL							50									8					
	Technical Requriement LSL							0.5									-20					

Appendix C

Prototype Dimensioned Drawings

Figure C.1: Assembly of prototype

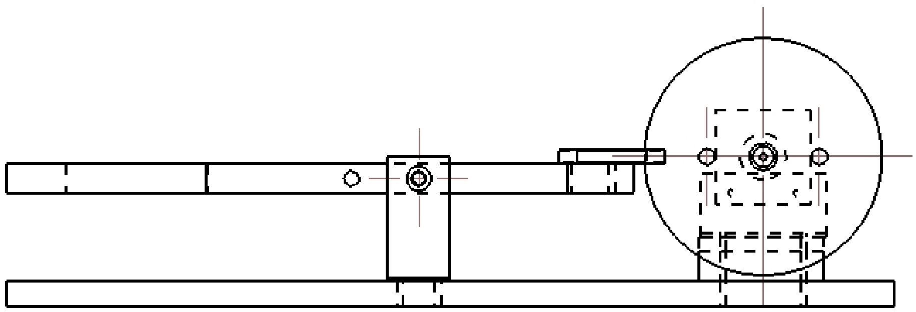


Figure C.2: L-bracket for key

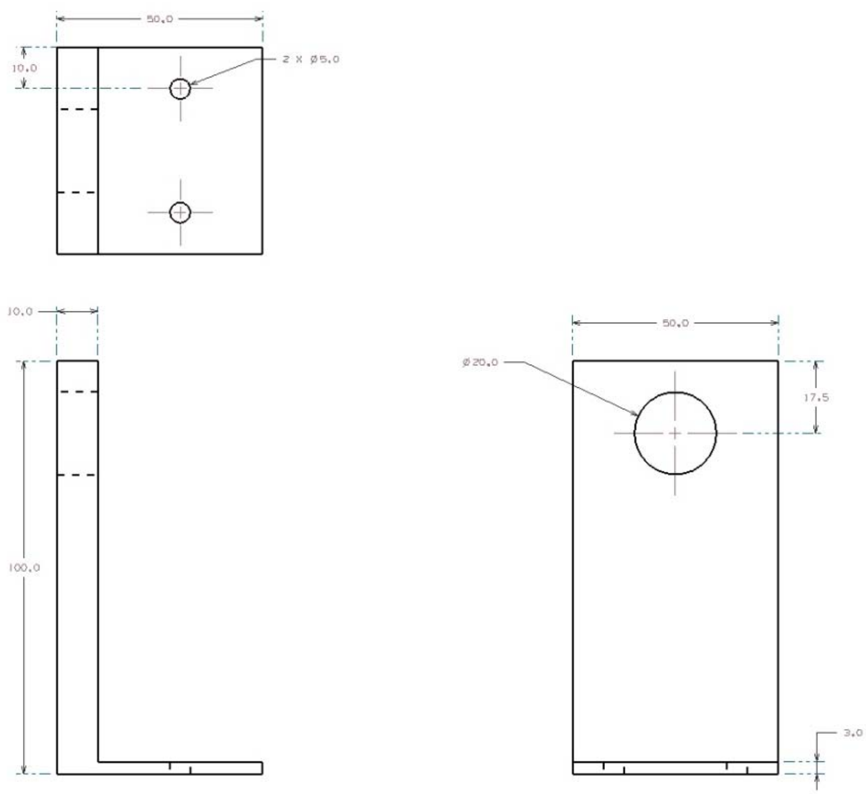


Figure C.3: Motor and face plate

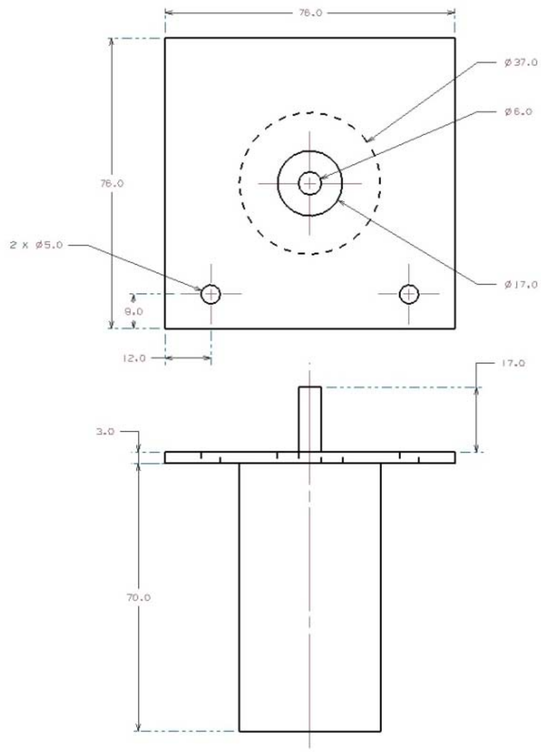


Figure C.4: Motor base

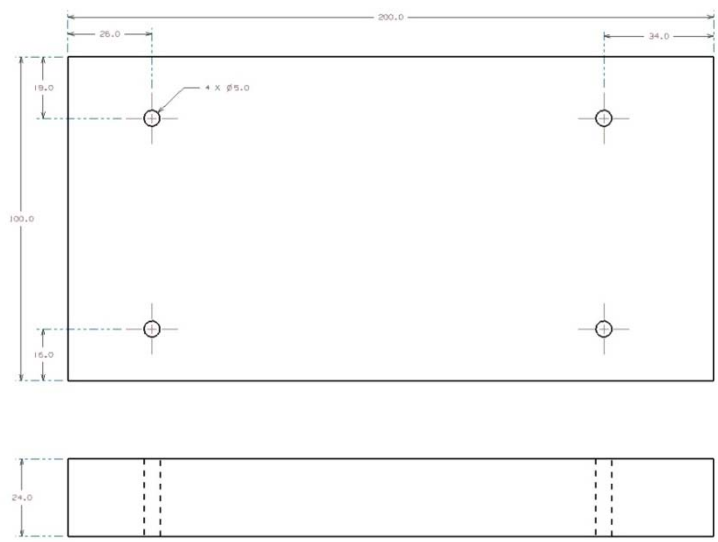


Figure C.5: L-bracket for motor

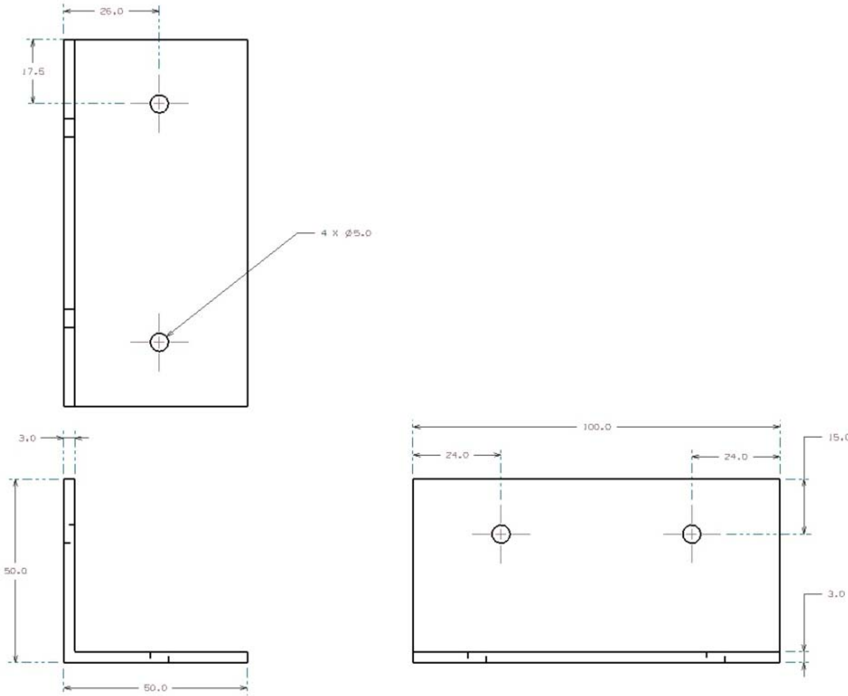


Figure C.6: Toroidal ferrite core with slot

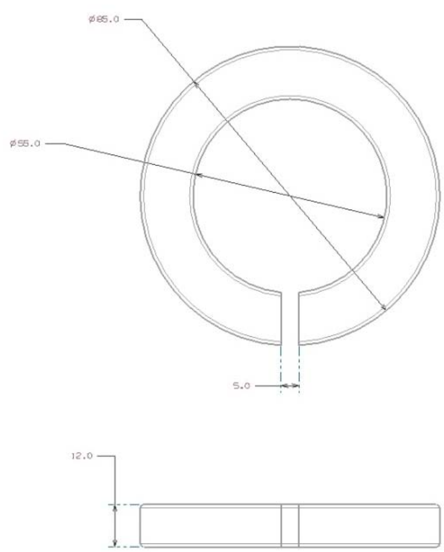


Figure C.7: Key shaft

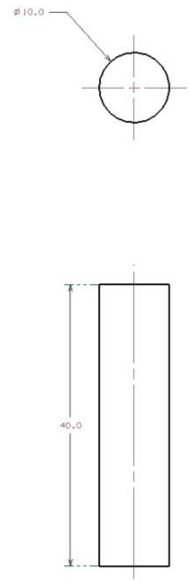


Figure C.8: Key

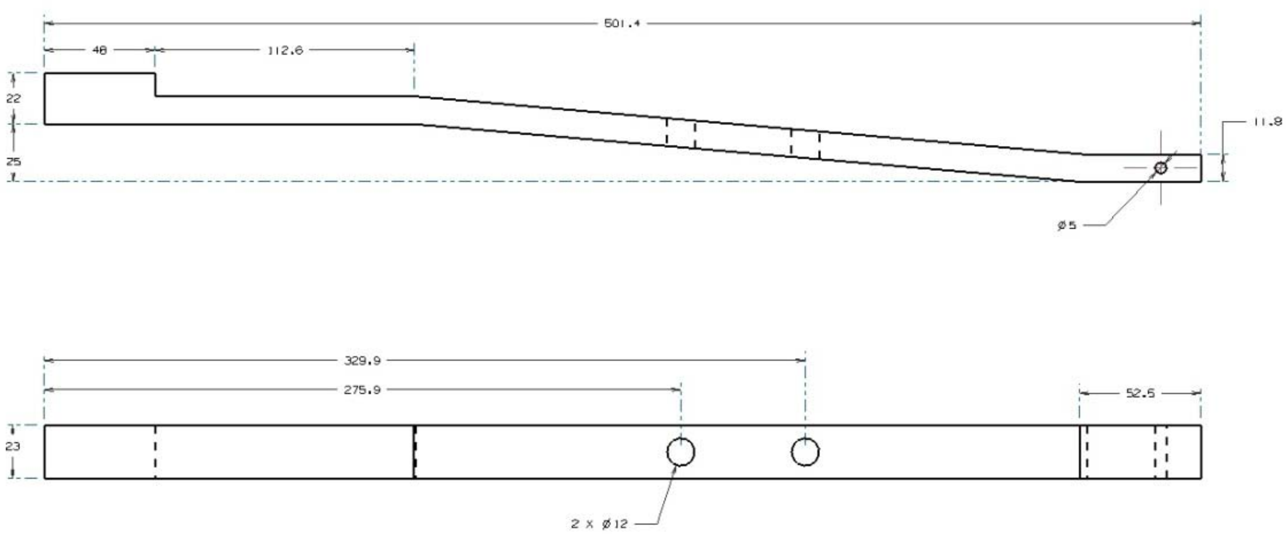


Figure C.9: Aluminum Disc

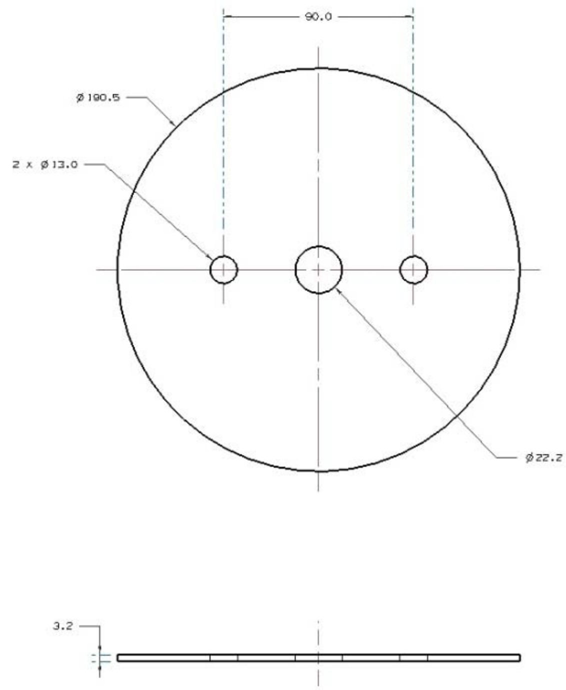
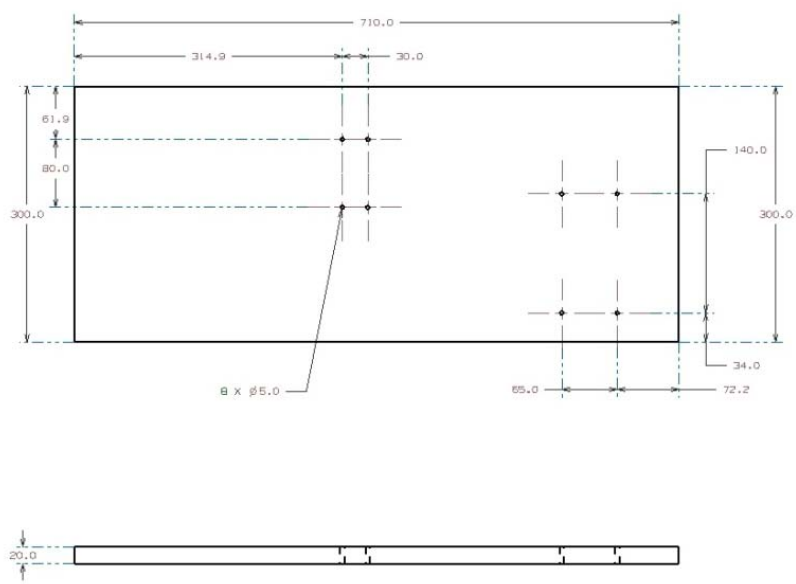


Figure C.10: Base



Appendix D

Figure D.1: Black Key

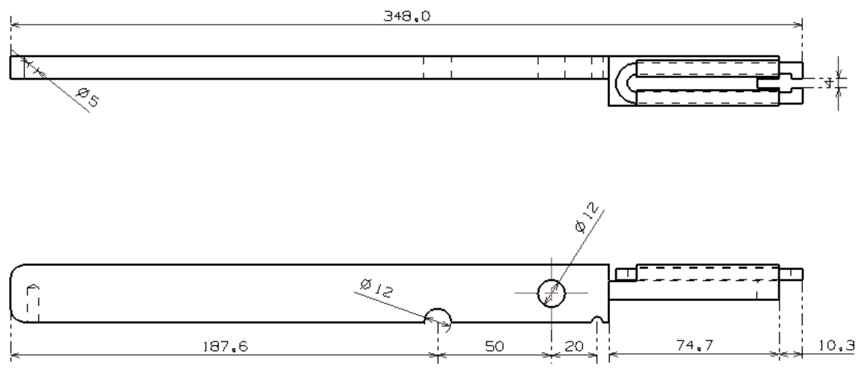


Figure D.2: White Key

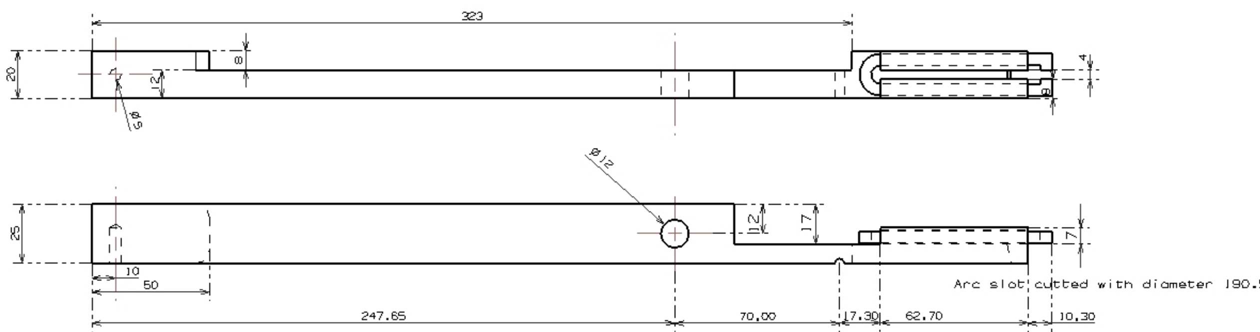


Figure D.3: Base Plate

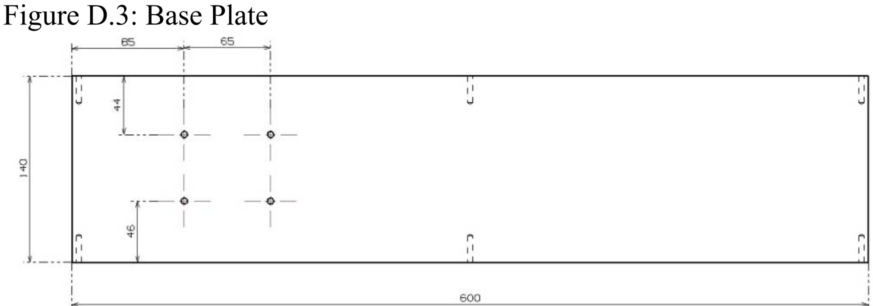


Figure D.4: Disc

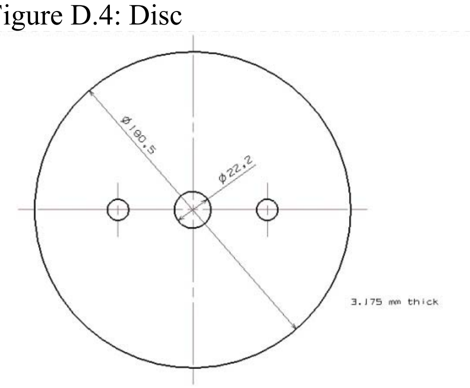


Figure D.5: Stand Plate

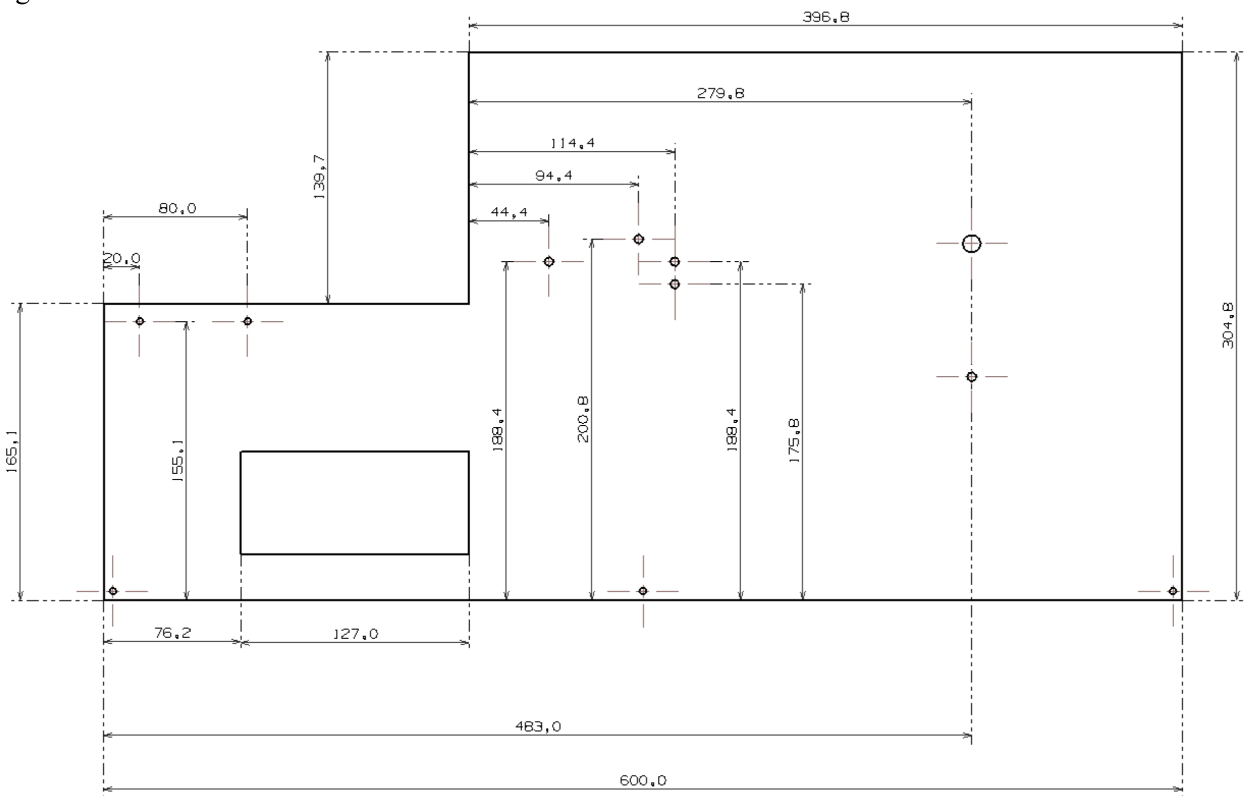


Figure D.6: Key Bed

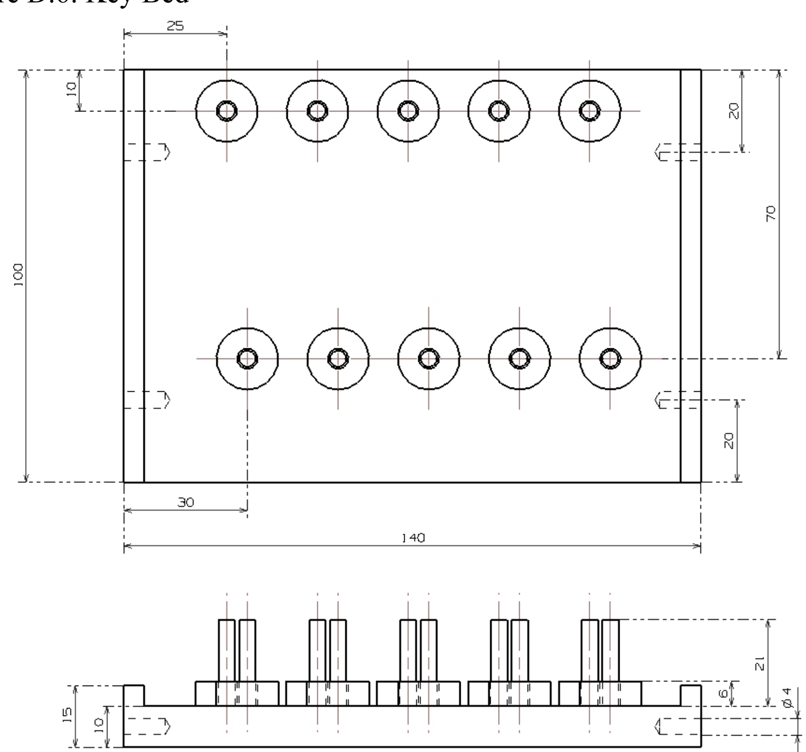


Figure D.7: Motor

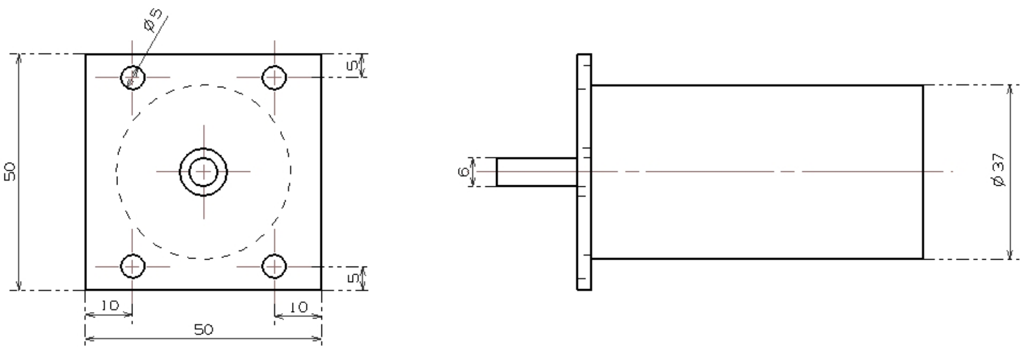


Figure D.8: Motor Bracket

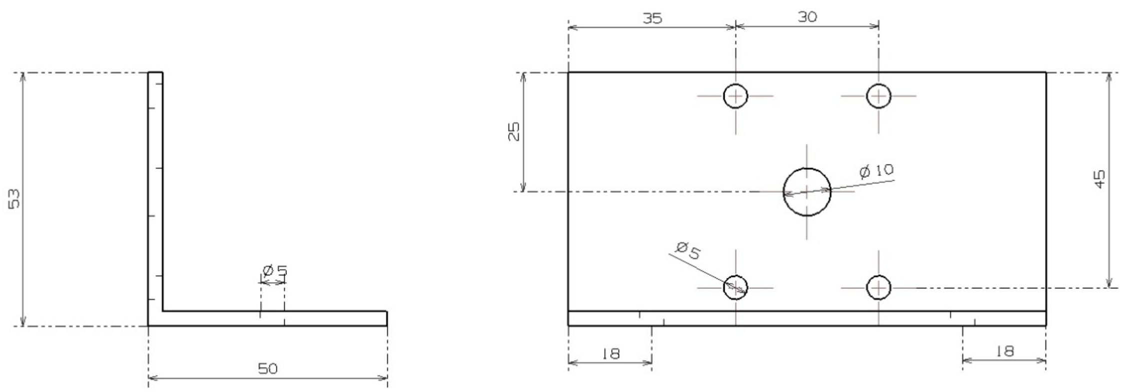


Figure D.9: Motor Base Plate

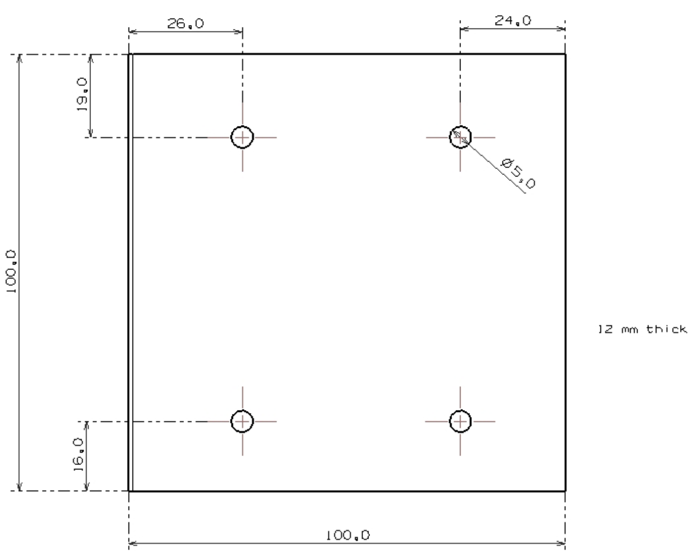
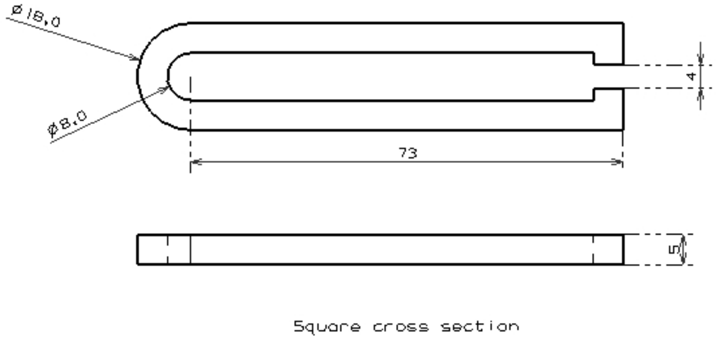


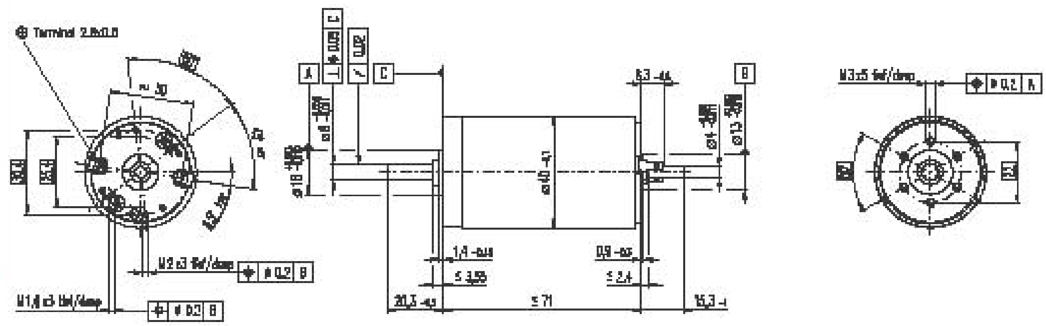
Figure D.10: U-shaped core



Appendix E

RE 40 ∅40 mm, Graphite Brushes, 150 Watt

maxon DC motor



M 1:2

Stock program
Standard program
Special program (on request)

Order Number

Motor Data		148866	148867	148877	218008	218009	218010	218011	218012	218013	218014	218015
Values at nominal voltage												
1 Nominal voltage	V	12.0	24.0	48.0	48.0	48.0	48.0	48.0	48.0	48.0	48.0	48.0
2 No load speed	rpm	6920	7580	7580	6420	5560	3330	2690	2130	1710	1420	987
3 No load current	mA	241	137	68.6	53.7	43.7	21.9	16.7	12.5	9.67	7.77	5.16
4 Nominal speed	rpm	6370	6930	7000	5810	4920	2700	2050	1500	1080	774	339
5 Nominal torque (max. continuous torque)	mNm	94.9	170	184	183	177	187	187	189	189	188	188
6 Nominal current (max. continuous current)	A	6.00	5.77	3.12	2.62	2.20	1.38	1.12	0.898	0.721	0.593	0.413
7 Stall torque	mNm	1680	2280	2500	1990	1580	995	796	641	512	415	289
8 Starting current	A	102	75.7	41.4	28.0	19.2	7.26	4.68	3.00	1.92	1.29	0.627
9 Max. efficiency	%	88	91	92	91	91	89	88	87	86	85	83
Characteristics												
10 Terminal resistance	Ω	0.117	0.317	1.16	1.72	2.50	6.61	10.2	16.0	24.9	37.1	76.6
11 Terminal inductance	mH	0.0245	0.0823	0.329	0.460	0.612	1.70	2.62	4.14	6.40	9.31	19.2
12 Torque constant	mNm / A	16.4	30.2	60.3	71.3	82.2	137	170	214	266	321	461
13 Speed constant	rpm / V	581	317	158	134	116	69.7	56.2	44.7	35.9	29.8	20.7
14 Speed / torque gradient	rpm / mNm	4.15	3.33	3.04	3.23	3.53	3.36	3.39	3.35	3.37	3.44	3.45
15 Mechanical time constant	ms	6.03	4.81	4.39	4.36	4.35	4.31	4.31	4.31	4.31	4.32	4.33
16 Rotor inertia	gcm²	139	138	138	129	118	123	121	123	122	120	120

Specifications

Thermal data

17 Thermal resistance housing-ambient 4.65 K / W
18 Thermal resistance winding-housing 1.93 K / W
19 Thermal time constant winding 41.6 s
20 Thermal time constant motor 1120 s
21 Ambient temperature -30 ... +100°C
22 Max. permissible winding temperature +155°C

Mechanical data (ball bearings)

23 Max. permissible speed 12000 rpm
24 Axial play 0.05 - 0.15 mm
25 Radial play 0.025 mm
26 Max. axial load (dynamic) 5.6 N
27 Max. force for press fits (static) 110 N
(static, shaft supported) 1200 N
28 Max. radial loading, 5 mm from flange 28 N

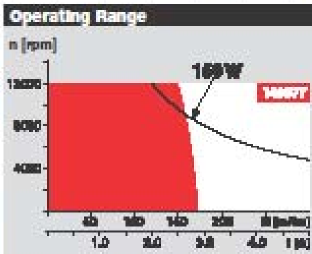
Other specifications

29 Number of pole pairs 1
30 Number of commutator segments 13
31 Weight of motor 480 g

Values listed in the table are nominal.
Explanation of the figures on page 49.

Option
Preloaded ball bearings

Operating Range



Comments

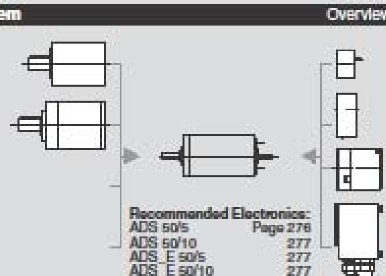
Continuous operation
In observation of above listed thermal resistance (lines 17 and 18) the maximum permissible winding temperature will be reached during continuous operation at 25°C ambient.
= Thermal limit.

Short term operation
The motor may be briefly overloaded (recurring).

Assigned power rating

maxon Modular System

Overview on page 16 - 21



Planetary Gearhead
∅42 mm
3 - 15 Nm
Page 244

Planetary Gearhead
∅52 mm
4 - 30 Nm
Page 247

Encoder MR
256 - 1024 CPT,
3 channels
Page 259

Encoder HED_ 5540
500 CPT,
3 channels
Page 262 / 264

Brake AB 28
∅45 mm
24 VDC, 0.4 Nm
Page 308

Industrial Version
Encoder HEDL 9140
Page 267
Brake AB 28
Page 309

Recommended Electronics:

ADS 50/5	Page 276
ADS 50/10	277
ADS_E 50/5	277
ADS_E 50/10	277
EPOS 24/5	294
EPOS2 50/5	295
EPOS 70/10	295
EPOS P 24/5	297
Notes	18

May 2008 edition / subject to change

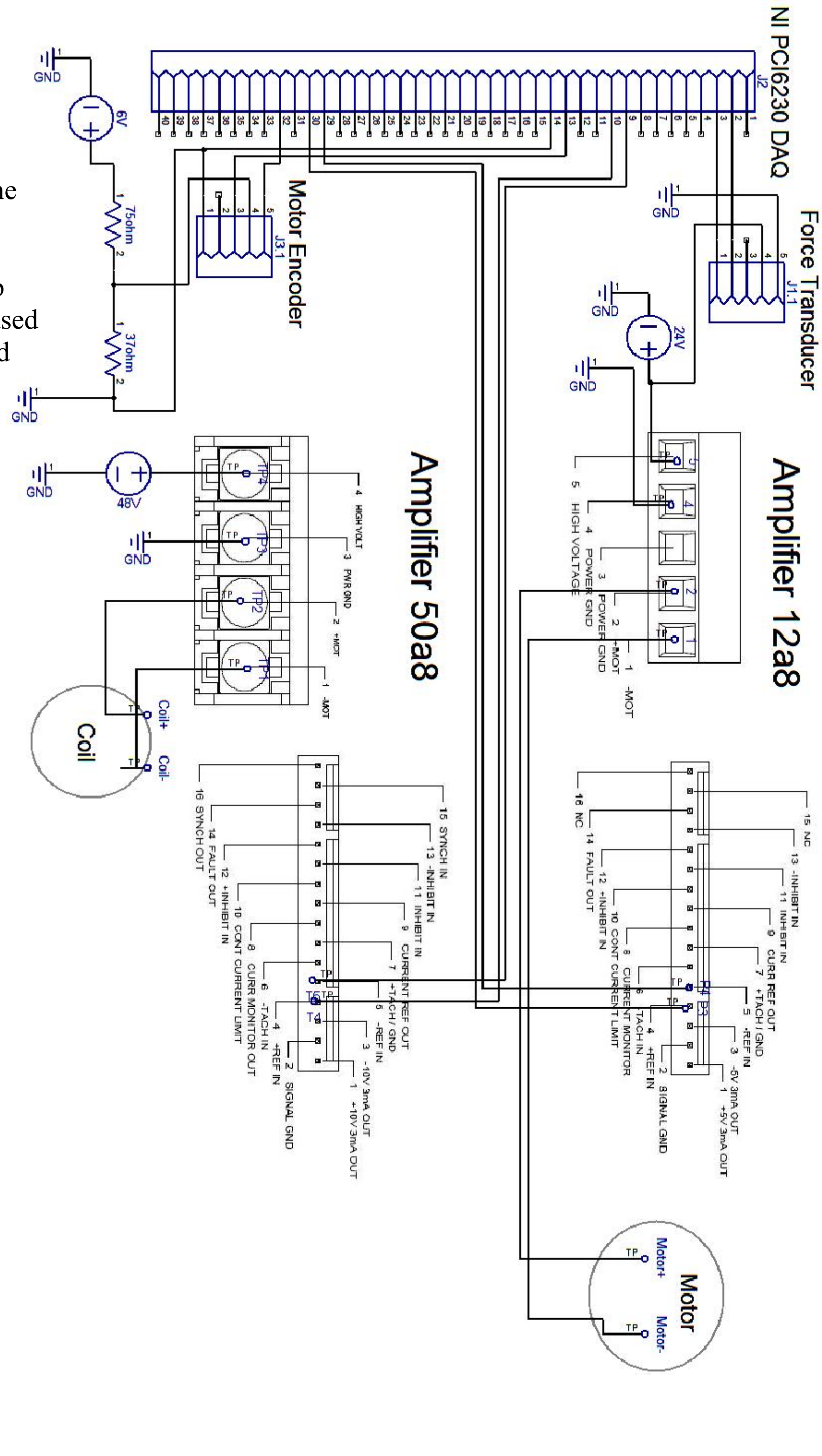
E

Appendix F

Circuit Diagram for the Experiments of force output measurements.

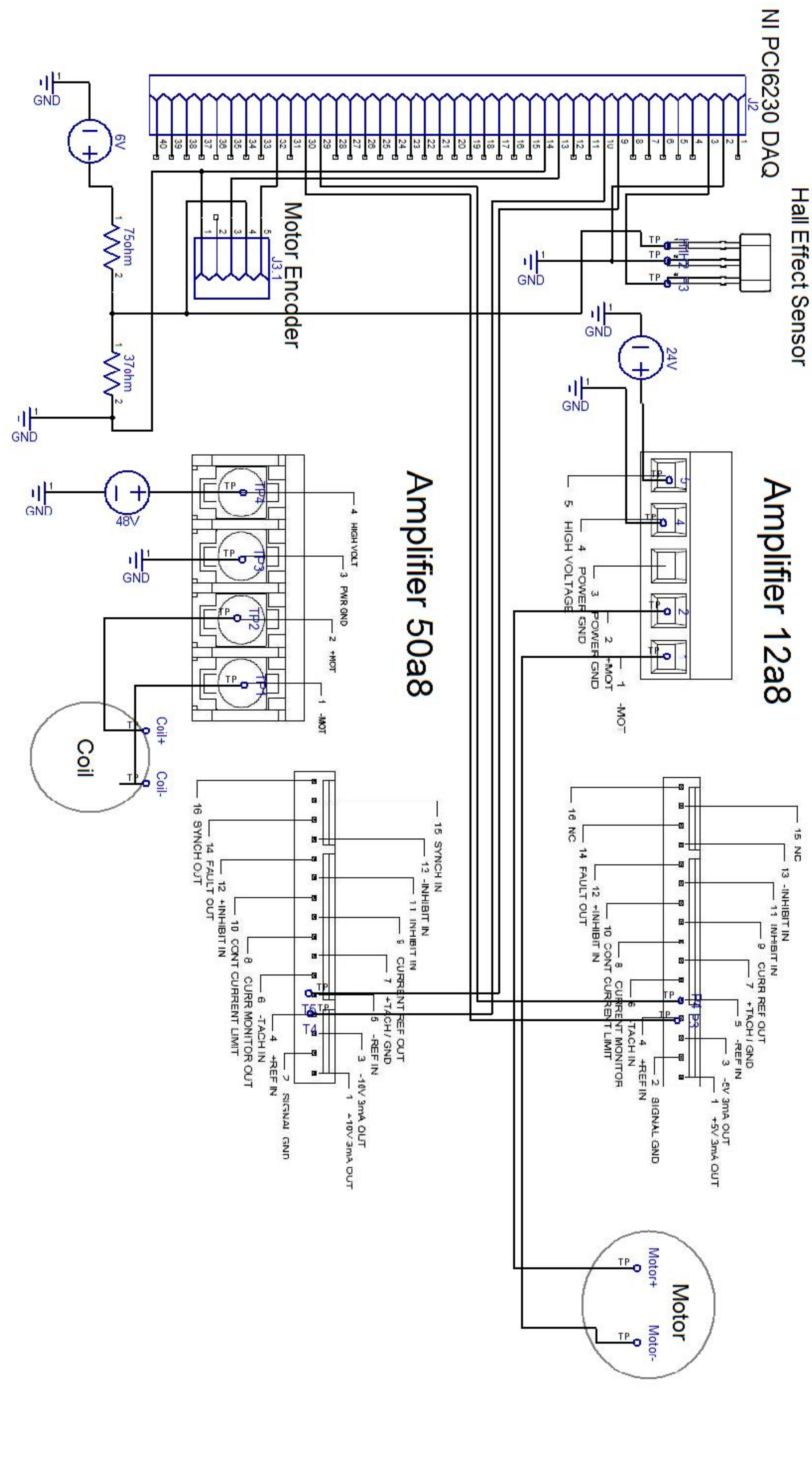
Two amplifiers are used, one for the motor and the other for the coil.

Encoder runs at 5V but in X50 Lab there is no 5V power supply. We used a voltage divider to get the required voltage.



Circuit Diagram for the coil feedback control

The only change here is we replace the force transducer with a hall-effect sensor, which is powered by 5V DC supply. We used same voltage source as encoder does.



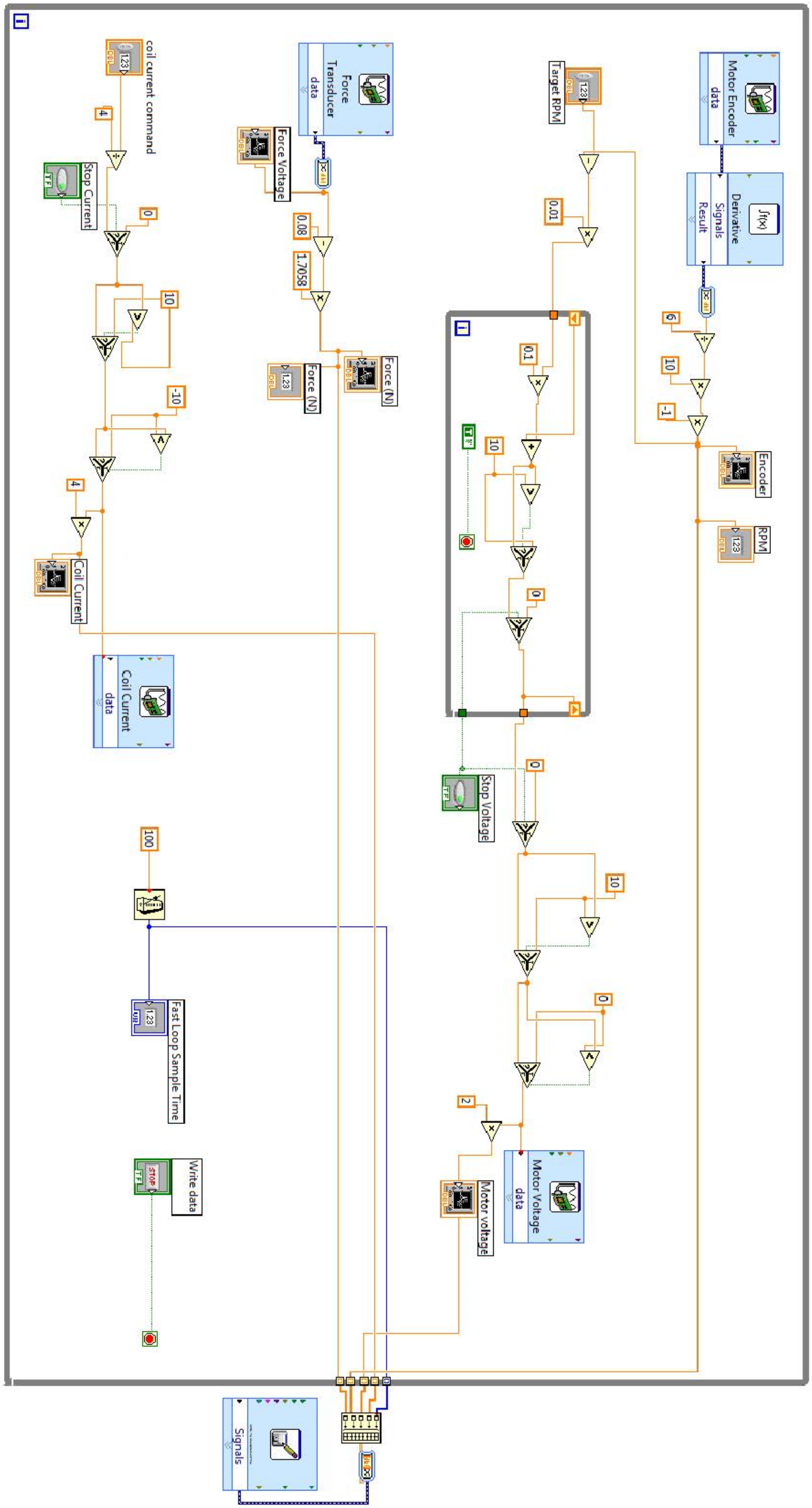
Appendix G

Labview code for the experiments of the force output measurements

Our Labview runs in a while loop and the sampling rate is 10Hz.

The motor is feedback controlled using integrator controller. It reads encoder's output and compares with the target RPM, and decides what amount of the motor voltage is needed to reach the target RPM.

Force transducer is calibrated before experiments and the calibration is included in VI. For every output to the DAQ assistance, there is upper limit 10 V and lower limit -10V constraints.

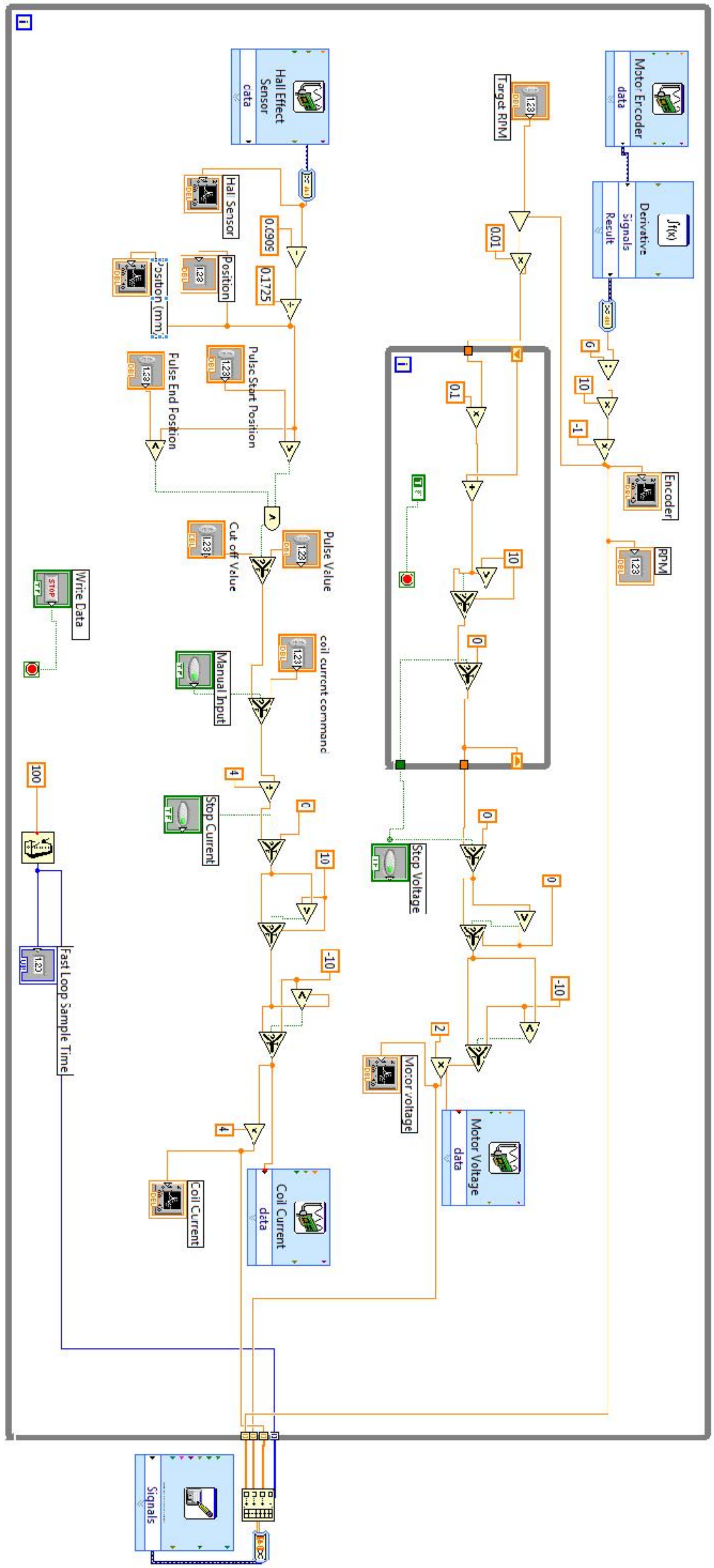


Labview code for coil feedback control

We used the data from the Hall Effect sensor to control the current running through the coil. The only difference between the demo VI and experimental VI is that the coil current is governed by the position of the key, which is measured by the Hall Effect sensor.

The code is designed to send a current pulse to the coil when the position of the key drops within a certain interval, say 2-8 mm.

The Hall Effect sensor was calibrated beforehand, and the calibration is included in VI.



Appendix H

Bill of Materials					
Item	Quantity	Source	Catalog Number	Cost	Contact
Large shaft clamps	2	McMaster-Carr	9964K12	27.64	mcmaster.com
Small shaft clamps	2	McMaster-Carr	6435K14	4.84	mcmaster.com
Teflon tape	1	McMaster-Carr	76475A31	4.49	mcmaster.com
Pillow block	2	McMaster-Carr	6244K51	67.34	mcmaster.com
Ferrite core (Small)	1	McMaster-Carr			mcmaster.com
1/4" Shaft	4	McMaster-Carr	6061K33	6.66	mcmaster.com
Pipe Clamp	4	Home Depot	-	0.93	homedepot.com
High Temp Electrical Tape	1	Home Depot	-	4.18	homedepot.com
3 x 30mm screw	4	Carpenter Hardware	-	1.27	-
3mm nut	4	Carpenter Hardware	-	0.72	-
1/4"-20 x 4"	4	Carpenter Hardware	-	2.12	-
Ferrite core (Large)	1	Magnetics Inc.	0P47313TC	no charge	mag-inc.com
Ferrite core (Medium)	1	Magnetics Inc.	0P48613TC	no charge	mag-inc.com
Wood blocks	3	Machine Shop	-	-	Bob Coury
Flat bar stock (Aluminum)	1	Machine Shop	-	-	Bob Coury
Angle stock	1	Machine Shop	-	-	Bob Coury
Flat bar stock (Steel)	1	Machine Shop	-	-	Bob Coury
Angle bracket	1	Machine Shop	-	-	Bob Coury
Particle Board	1	Machine Shop	-	-	Bob Coury
Misc. Nuts and Bolts	-	Machine Shop	-	-	Bob Coury

Appendix I

Description of engineering changes since design review 3:

Since design review 3, very few things have changed. Instead of using l-brackets to support the bearings that hold the shaft in place, we purchased pillow blocks that come pre-fitted with bearings in them, saving us machining time.

We also changed the size of wire gauge we were using. We initially wrapped the toroidal core with 24 gauge wire, but found that its resistance was too high and began a second coil of 18 gauge wire on top of it. This also changed the number of turns of wire on the coil from our estimated value of 1500 to 1663 turns.

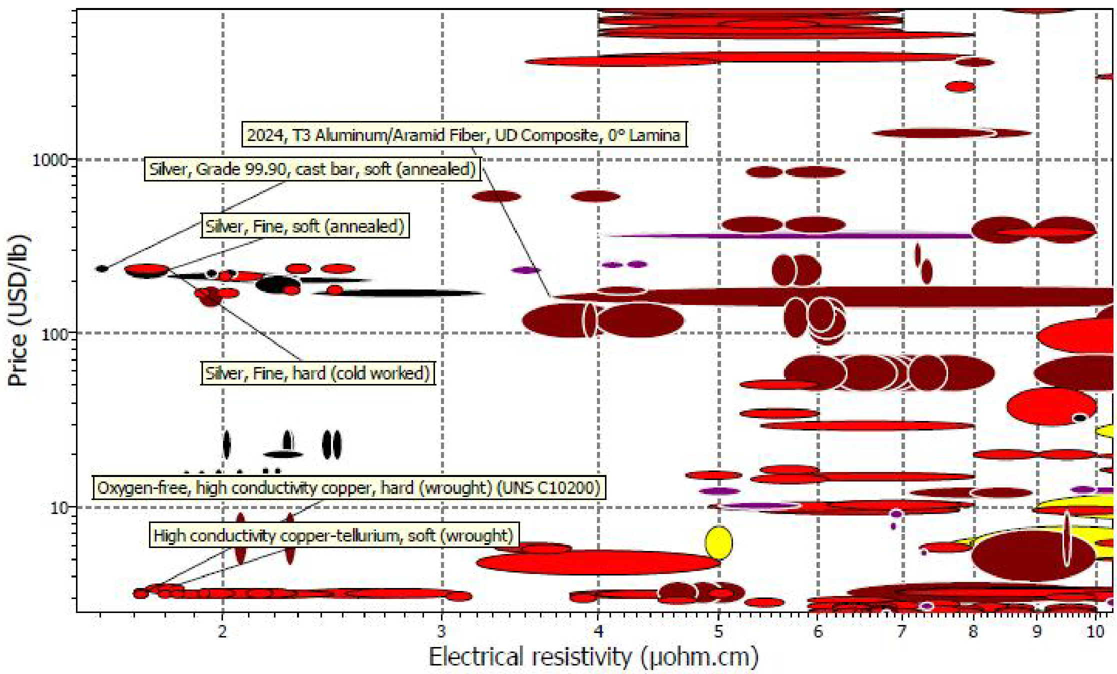
Additionally, we added a keybed at the end where the user inputs and a core support at the end where the toroid is located. Both are made from l-brackets and simply restrict the motion of the key to that of an actual piano action.

Appendix J

1. Material Selection (Functional Performance):

Spinning Disc for Eddy Current Brake

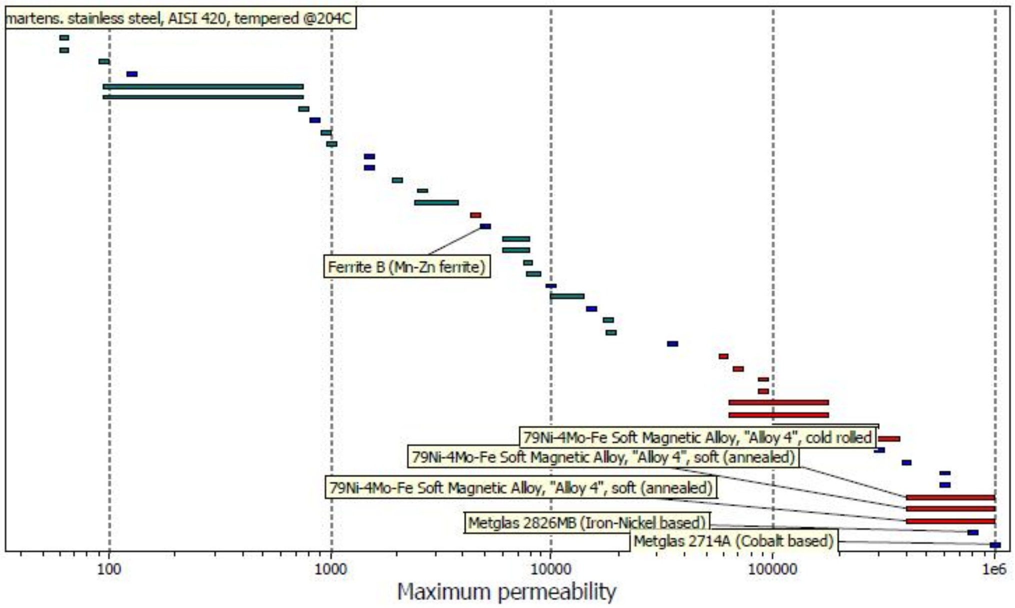
Function: To spin and generate force with eddy current
Objective: Maximize electrical conductivity
Constraint: Price
Matrial Index: Electrical Conductivity/Price σ/$



We needed to maximize the electrical conductivity of the spinning disc as much as possible to maximize the force output of the eddy current brake system. The top five choices we determined from CES to maximize electrical conductivity was silver grade 99.90 cast bar soft (annealed), silver fine soft (annealed), silver fine hard (cold worked), Oxygen-free high conductivity copper hard (wrought) (UNS C10200) , high conductivity copper-tellurium soft (wrought) . However, we did not choose any of these materials because of the high price or lack of availability, and because we could get the 2024 aluminum for free at the machine shop which has high enough conductivity for our purpose. Also, we chose aluminum because it is easy to machine with our available tools in the machine shop.

Toroidal Core for Eddy Current Brake

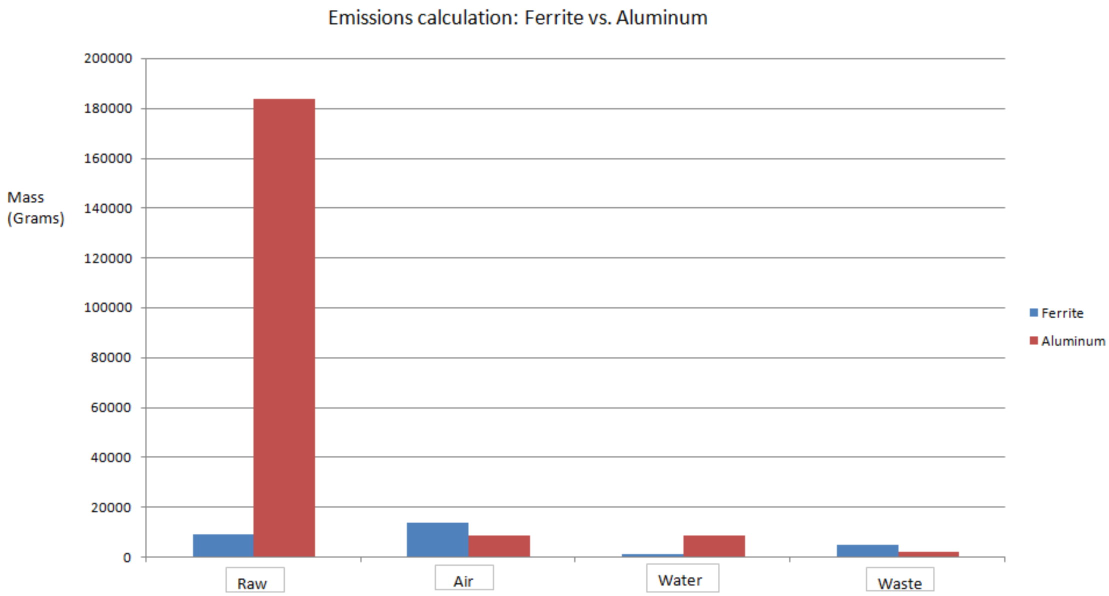
Function: To create an electromagnet by winding magnet wires on it
Objective: Maximize magnetic permeability
Constraint: Price
Material Index: Magnetic Permeability/Availability(price) µ/$



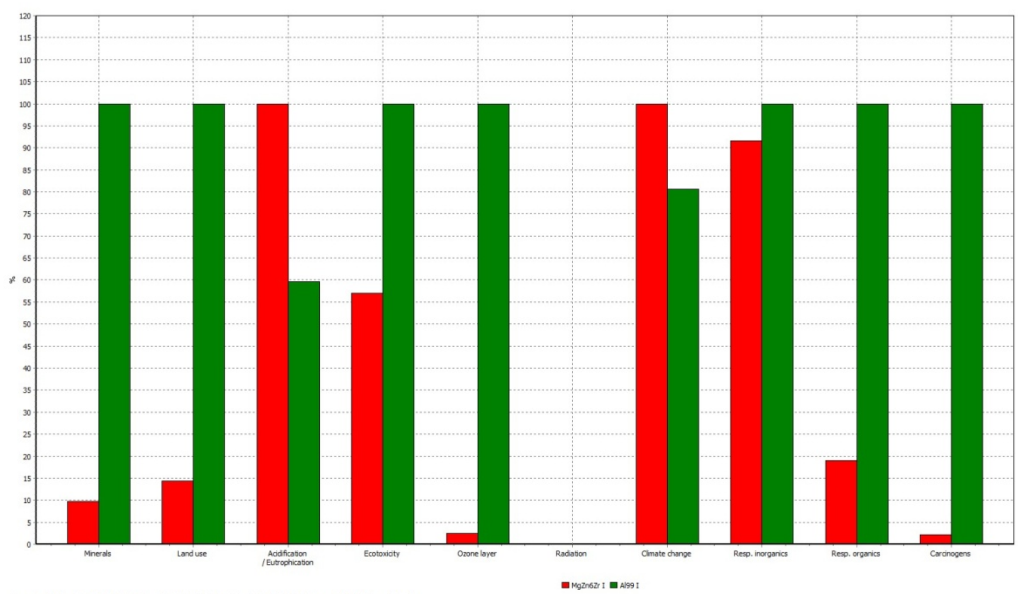
We needed to maximize the magnetic permeability of the toroidal core, to create the strongest electromagnet possible. The top choices we determined from CES was Metglas 2714A (Cobalt based), Metglas 2826MB (Iron-Nickel based), 79Ni-4Mo-Fe Soft Magnetic Alloy "Alloy 4" soft (annealed), 79Ni-4Mo-Fe Soft Magnetic Alloy "Alloy 4" soft (annealed), and 79Ni-4Mo-Fe Soft Magnetic Alloy "Alloy 4" cold rolled. We could not select the Y-axis property as price as we had hoped in CES. We did not choose any of these materials, but rather selected to use Ferrite B (Mn-Zn Ferrite) because of its' low cost and availability when we searched for magnetically permeable materials. We were not able to find other materials with such high magnetic permeability than our ferrite core.

2. Material Selection (Environmental Performance):

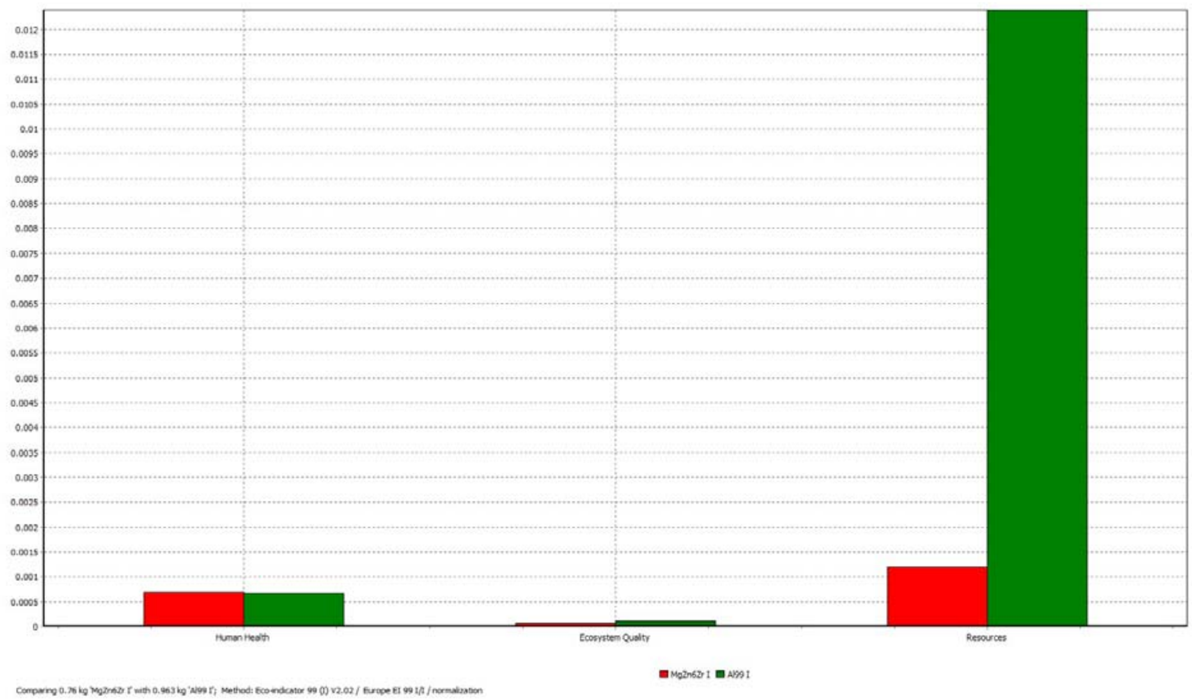
Emissions Comparison: From our emissions calculations, we see that aluminum has a much higher impact on the environment overall because of the much greater raw material emission compared to the ferrite. Aluminum has nearly 20 times more of an impact on the environment. Air emission and waste emission is comparable, but water emission for the ferrite is about 8 times more than aluminum.

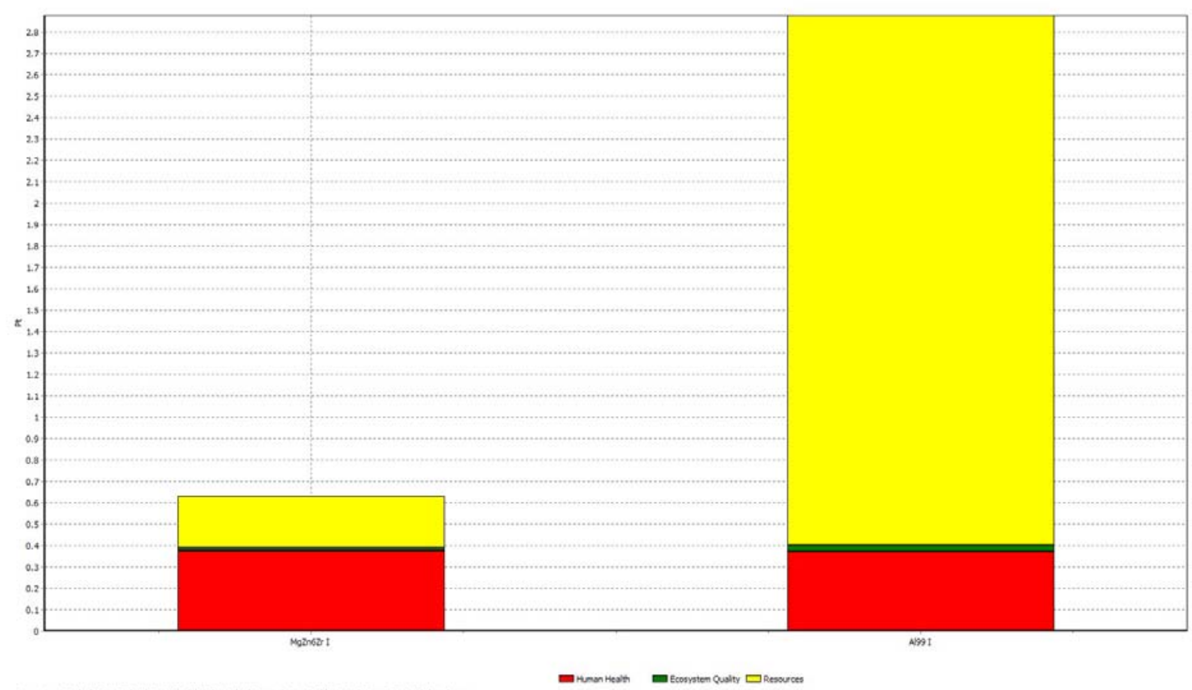


Characterization Impact Assessment: According to SimaPro EcoIndicator 99, Aluminum has a higher impact on the environment in the categories “minerals”, “land use”, “eco-toxicity”, “ozone layer” “resp. inorganics”, “resp. organics”, and “carcinogens”. The ferrite has a higher impact on the environment in the categories “acidification/eutrophication”, and “climate change”. Overall, aluminum has a larger impact on the environment.



Normalization /Single Score: According to SimaPro EcoIndicator 99, ferrite and aluminum is comparable in terms of impact on human health, and the ecosystem. However, in terms of depletion of resources, Aluminum is a much more rare resource, thus the impact is calculated nearly 10 times more or the aluminum. Overall, as can be seen in the single score plot, Aluminum has about 4 times more impact than the ferrite.





3. Manufacturing Process Assignment:

1. The purpose of our product was mainly to provide Professor Gillespie with an experimental research apparatus which could be used to further investigate the idea of using an eddy current brake system in a force feedback keyboard. While the intended end result of his research is to

come up with a commercially viable product, it is very unlikely that our specific prototype would ever need to be replicated. The only plausible reason to make additional models would be if other educational institutions wish to conduct similar research, or if the current model breaks. As a result we speculate that there will never be a demand for more than approximately 10 to 20 models, and therefore certainly no need for a plan to mass produce them.

2. Given that any additional models would be made by hand and not mass produced, the manufacturing processes for machining the aluminum disc and the ferrite core would be very similar to the way in which we produced them. Assuming that the majority of large research oriented universities will have access to similar facilities and machinery to the University of Michigan, we would recommend the same process be followed for additional models. The ferrite core is too hard to be machined in a traditional machine shop, but it can be easily and accurately machined to within acceptable tolerances using a water jet cutter. This method will be both the most cost effective and time efficient way to machine the core. The disc is slightly more time consuming to produce manually in the machine shop using a mill, however machining the disc in this way will always produce a finished product to within acceptable tolerances. This is of course assuming that all of the machining is done correctly. Depending on the circumstance, it may be worthwhile to attempt to find a pre-manufactured disc since the actual size of the disc is not important to the functionality of the product. This would likely be a less cost effective approach but would save manufacturing time.

Biographies

Ben Davis
I was born in Saginaw, Michigan, and have lived in a small nearby town named Hemlock my entire life. Since I was little, I've always been mechanically inclined, taking everything apart just to learn how it works. This was instilled in me early on by my Grandfather, a.k.a. "Mr. Fix-it." He could fix just about anything – he once purchased a crashed plain for $1 at an auction and repaired it to full operating condition, and it has been flying for over 40 years. Being a kid from a small rural town where AP classes are unheard of and academics aren't exactly their best, it was an honor to be accepted and attend the University of Michigan. I was the only person from my graduating class to come here. I am now in my senior year in Mechanical Engineering. I chose this major because I feel it covers a wide variety of topics which I am interested in. Through my studies, I have decided I would like to pursue a career in the aerospace industry, and perhaps later go to graduate school and get a degree in aerospace. I enjoy a good challenge and learning opportunity. I also enjoy music and play the bass guitar. Together, these things drew me toward this project, and I am very interested in creating a successful prototype.

Paul Gunckle
I am a senior in Mechanical Engineering from Clarkston, Michigan. Given that my father got his undergraduate degree in electrical engineering and my mother in mechanical engineering, pursuing my own undergraduate degree in some sort of engineering field seemed like a logical place to begin. Throughout my educational experience at Michigan, the design classes (ME 250 and 350) were the most enjoyable for me. I enjoy the process of coming up with an initial idea, and through a design process bringing that idea into reality. Additionally, for this project in particular my interest stemmed from the fact that I am musically inclined. I have played the piano since I was in elementary school, and have also taught myself base and lead guitar since attending college. As a result this project was an easy first choice for me during the project selection. I plan on graduating in December 2009, and probably taking whatever job is available to me at that time. Though I doubt that graduate school is in my immediate future, I am definitely considering the possibility of getting a graduate degree at some point down the road.

Masato Kihira
I was born in Nagoya, Japan, but moved to Southeast Michigan before experiencing my first birthday. My father was an electrical engineer and his career had led him to work for the automotive industry in Michigan. I always had an interest in Science and Engineering, and I chose mechanical engineering as my major because it was so versatile. I was amazed when I realized that anything we see or use in the modern world had a mechanical engineer's hand in it. It was perfect when I was still not sure about what I wanted to do or engineer for a living. I worked full-time as a Co-op for the Japanese Auto-maker Toyota for two semesters at the Technical Center in Ann Arbor, and this was undeniably one of the most important experiences I have had in my life. The job experience taught me not only how to act and think like a corporate Engineer, but also how to perform when there are high-expectations, and how to be accountable as a responsible working adult. However, I also realized that I am not satisfied with a job that asks me to Engineer something that I am not interested in so much, such as an automobile. Another passion in my life is music, as I played piano most of my life. Over the course of my college education I realized that my passion for music was too great and I decided to pursuit a

career that will enable to combine my two passions of Engineering and Music. Evidently, I was ecstatic when I realized that one of the ME450 projects was about enhancing synthesizer keyboards. In the future I hope to make a living by engineering musical instruments or anything that pertains to music. I am also contemplating taking more formal education in music, such as a pursuit of Masters in Fine Arts or studying audio or acoustical engineering.

Zheng Qu

After two years' undergraduate study in college of engineering of Shanghai Jiao Tong University, I transferred to UM in Fall 2007. The reason I chose Mechanical Engineering as my career is the technology appealing and responsibility it provides in my life. The explanatory course I took in Summer 2006, Introduction of Engineering, provided me with a panorama on Mechanical Engineering. I resonantly agree that mechanical engineer should be a group of professional experts who could bring cutting edge science and technology into people's ordinary life, and a group of conscientious innovators who could turn aggressive scientific discoveries into efficient environment-friendly technology that could be used to preserve the earth and humankind. Greatly encouraged by this exciting ethic of mechanical engineer, I felt sincerely I want to be one of these people.

In general, I grew up in a rigorous academic environment that bestows me with solid technical skills and strong volition. Through substantial courses and innovative research work in this area, I found that system dynamics and control plays a crucial role in a mechanical or electrical system design. Thus, I am motivated to contribute to the development of system dynamics and control applications in people's everyday life and seek for a greater opportunity to be involved into the research work on such applications.

Ethics and Environmental Impact Essays

Ben Davis:

The only major ethical issue we came across during the development of our product was that between safety and ease of use. The easier all the components are to access, the less safe the product is. This is due to the multiple high voltage power supplies and the disk spinning at high RPM's. In the end, we determined that it would be best to keep the prototype as easy to use as possible, as it is only intended for use by a select few people and is only an experimental apparatus.

If, for some reason, our project was mass produced and given to the general public, it would be extremely dangerous. Without knowing the basic safety requirements of using the equipment in our system, users could very easily become injured. Any decision to mass produce our prototype would be extremely unethical. Additionally, our prototype is not environmentally friendly. It uses an extremely large amount of power (about 1500W) and only powers a single piano key. Again, it was designed as a basis for experimentation and any later designs that may become commercialized would definitely have to be more energy efficient and safe.

Although this project isn't very environmentally friendly or safe when in the hands of the general population, I believe that it is still exceptional for ME 450 standards. Because the prototype is only going to be used in a controlled environment, with limited use, and by trained individuals, no one will be harmed and the power consumption will not be significant.

Paul Gunckle

Throughout the design, fabrication, and testing of our prototype (force feedback keyboard), a few minor ethical issues were brought to our attention. First, the design involves an aluminum disc that rotates at very high speeds as well as a wire coil through which a large electrical current passes, both of which could potentially pose safety hazards. Second, the design is not very environmentally friendly in that it is very inefficient from a power consumption standpoint.

The ethical concern with the first issue is not whether our product would be safe to be used by society; there are many existing products that can potentially be hazardous if used incorrectly. The concern is simply that adequate measures be taken to inform users of the correct way to use the product, as well as the possible consequences of improper use. In our case however, it is likely that any hazards would be caused not by the user, but by the machine malfunctioning. The most realistic health threat that our product could cause is that it could become a fire hazard if by some circumstance current was allowed to run through the wire coil for a long period of time. While this is a possible scenario, it is extremely unlikely to ever occur.

I feel that the more important ethical issue is the negative impact that our prototype has on the environment. We used a 1000 Watt power supply to power our coil, and in order to get the best output force we completely stretched that power supply to its limits. It would be possible to use an even larger power supply to further increase the force output. In addition we used two separate power supplies to power the other components of the system. Since our prototype only involved one key, if it were to be extrapolated to a full keyboard the power requirements would be absolutely staggering given the intended function of the product. Without further research into using power more efficiently within our system, our product will never be environmentally friendly or commercially viable. I feel that it would be ethically wrong to release a product in this day and age that is so inefficient in its power use.

Zheng Qu:

Safety Goes first: Ethics in Force Reflecting Keyboard

In Winter 09's ME450 project, Professor Gillespie sponsored and instructed a project that exploits the possibility of a brand new design of force reflecting keyboard using Eddy Current Brake as a force actuator. Our team was responsible to build the prototype and conducted measurement experiments. During the design process and experiments process, we became aware of the hazard associated with this design and Eddy Current Brake itself. Although in our prototype, we only used a mediocre motor and execute low speed tests only, yet we tried every effort to ensure the safety during these processes because we know how severe damage it could cause once things go wild. Upon the time of delivery, we want to share our experience in this issue, and alert the future users of our prototype and users of possible product using this new technology.

First I want to talk about the powerfulness of an eddy current brake and its possible applications in household and other everyday utility. As we consulted with Professor Gillespie, we are informed with the potential strength of an eddy current brake. The mathematical model does provide a convincible prediction on how large the force output will be delivered by this little device. We estimate the maximum force output given our prototype and the results surprise us. A normal operation of 4 A coil current at 1000 RPM disc speed will give us approximately 100 N force output. Although the experiment data denied this prediction, yet we were still not able to determine the cause of the failure of our experiments. That means the potential force output of our device is not controllable yet. Moreover, the high sensitivity of our device with respect to the current change and air gap change makes us worried about the possible hazard caused by the environment change that may occur during its duty in household.

Imagine that our force reflecting keyboard is commercially manufactured and put into an ordinary household. The keyboard sits in the living room and a boy is playing with it. A naughty girl may shake it as she is crying for play. A carelessly installed screw looses up and disc wobbles between the gaps. The tremendous amount of the force will send whatever loosen parts out and become high-speed flying objects. Or imagine that an eddy current brake is used as a bicycle brake. Long time fatigue of shaking on the peddle pavement makes it loose. A wheel may fly out and hits a pedestrian. Or imagine that an eddy current brake is used as an automatic baseball pitcher machine. A trainee may throw back a pitch as he/she is annoyed with today's performance. The machine sends out a noise and, a bunch of flying pieces. These kinds of scenario may happen once in a year or even in a decade. However, who could guarantee that it will not cause causality?

I admitted that further research may bring things under control and reduce the possibility of failure close to zero. But before that is done, this device may have already been in the market. We have seen many cases that a "smart" market manager pushes an incomplete design into the market. The engineer responsible for this design may argue with his/her manager that this design is not sophisticated and its performance is not predictable. A "smart" manager may weigh the profit of new product and its possibility of failure, and decide to compromise the unknown factor. In this case, the engineer could still argue. But worst case scenario, the manager has an independent other group of engineers to produce a "favorable" report that declares the mildness of this design, as we found out in our experiments, this conflict will go on and on. For an engineer's integrity, this engineer should gain the courage to quit and be different.

I believe, as an engineer, for each time we find the discrepancy between our experiments and mathematic model, we should be extremely careful. Sometime we may lack the strong ability to see a design in its whole picture. We may not be able to foresee that our proposal to deny might actually serve as a proposal to try out. Someone and some organizations are eager to risk their money and opportunity to become a master of a product of revolutionary. The compromise, in most cases, is people's life and all. For our prototype and design idea, and its possible future uses and applications, the design engineer should always keep in mind that what if, even in a tiny possibility, his design fails. It is not about a remanufacture of several loosen parts, yet it is about a life and all.

Masato Kihira:

In the process of further product development and eventual commercialization for our force feedback keyboard, many ethical issues concerning safety for the user, as well as the impact on the environment must be considered.

First, our prototype uses an electromagnet that could potentially reach very high temperatures from the high current loads. This could melt components in the system which will destroy the product, or even start a fire and potentially seriously harm human beings. Multiple safeguards to keep the temperature of the electromagnet low must be taken to keep the product and the user safe. Some preliminary ideas are metal fins and a cooling fan to keep the temperature of the electromagnet low, and an automatic shut off system with a sensor if the temperature of a component is too high. Also, the product uses aluminum discs which rotate at a high velocity. If the discs get misaligned or the eddy current brake system breaks down, the high velocity components can again destroy the product or potentially harm human beings. Again, safeguards must be taken to minimize the risk. Proper housing and good stability of the structure and system components could be a resolution for this problem.

Environmental impact of the product must be also seriously considered. Our product uses an aluminum disc, which is a rare resource which also uses large amounts energies to produce. Our product will most likely use multiple discs, so a significant amount of aluminum will be used, which will have a high impact on the environment. The fact the even after commercialization, the overall number of the product manufactured will be not very massive will keep the overall impact on the envrironment low. Proper methods to re-collect the product and recycle its' components should be placed. Another concern is the product's high power consumption. For our prototype that has only 1 piano key, we needed three power supplies, with 1 that uses 1000 Watts. Power consumption must be minimized by other optimization methods, and the system must be designed so that unnecessary power is not used when the user is not playing the instrument, and run efficiently when it is being played.

Our product is definitely beneficial to the music industry and society with further design improvements, greatly connecting the keyboard musician to his/her instrument. However, the price, safety, and environmental impact must be considered seriously to have a feasible commercialization future. It will be sort of impractical and ridiculous to make a product that harms the environment or the user way to just engineer an instrument that can replicate the physical feel of various instruments.