Analysis of Solenoids as a Means of Exploring the Prototyping Process

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Abstract

This project is an offshoot of the Hammond Organ MDP team's work to bring an electronic organ into the 21st Century. This led to a discussion of the use of solenoids as a mechanical playback system. In turn, this paper aims to document the application of the prototyping process onto the selection of solenoids and an exploration of the differences between first principle models and their empirical counterparts. This was accomplished by using software to develop a first principles model and comparing it to an empirical dataset of solenoids. In addition, the model was run through an optimization tool to identify general predictive trends for future use.

Keywords: Prototypes, Meta-modeling, Design Process, Regression

1 Introduction and Background

This paper explores the process of prototyping solenoids to determine which solenoids would perform the best from a given set. It also explores the use of modeling as a means of determining usefulness when physical testing is unavailable. It would be useful for the reader to have some familiarity with the aforementioned concepts and the decisions that led to them to gain a better understanding of the work presented here. The following sections provide a brief introduction to Hammond Electronic Organs, the ArtsEngine Group, and the Previous Team. In addition, there will be a brief explanation of the general prototyping process.

1.1 Hammond Electronic Organ

The Hammond series of electronic organs first began production in the mid 1930's. They began as a way to bring organ music out of churches and into the home. Over time however, their use became more common by jazz musicians due to the wide variety of notes and effects that the Hammonds were capable of when paired with a Leslie speaker.

1.2 ArtsEngine

ArtsEngine is an interdisciplinary initiative of the five North Campus schools and colleges: A. Alfred Taubman College of Architecture + Urban Planning; Penny W. Stamps School of Art & Design, School of Music, Theatre & Dance; College of Engineering; and School of Information. Found within the Duderstadt Center, it is a group that aims to develop multidisciplinary ideals as driven by the collaboration between the arts and sciences to maximize the potential of students on North Campus. In 2016, they were gifted a deconstructed Hammond M3 organ for their use.

1.3 Previous Hammond Organ Team

In 2017, the ArtsEngine group tasked a team of students to begin restoring the organ in their possession. This primarily took the form of cleaning off the organ and ensuring the components still worked. In addition to this work the team began re-wiring the components to increase their modularity and exploring means of allowing the organ to record what was being played using sensors underneath the keys.

1.4 Current Teams Objectives and Work

In 2020, the ArtsEngine group once again tasked a team of students to continue work on the deconstructed organ with the goal of modernizing the organ. After two months of discussion the team decided that a modern device should be capable of interacting remotely and split into two sub-teams to explore the problem. The first sub-team worked on creating an application that could store and transmit stored music data to the organ. In addition, they also worked towards making the organ more accessible by making an application that would translate a drawn image into a music file which could then be played. The other sub-team focused more on finding ways to take this information and playing back using the organ. Prior to the shutdown due to COVID-19 the sub-team had determined that solving the problem electronically introduced issues that the team lacked the experience to fix. As a result, the decision was made to use a series of solenoids to linearly actuate the keys at the proper time, producing sound using the existing infrastructure.

1.5 Scope and Purpose of Paper

The purpose of this paper is to describe and analyze the prototyping process using the solenoids identified as candidates in the Hammond MDP project. This begins by determining the desired characteristics before exploring modeling as a decision-making tool. This analysis is performed both from a first principles model and from empirical datasheets relating to the solenoids identified as candidates. As a conclusion, the best performing solenoid will be selected with a rationale detailing why it is the best suited for the task.

1.6 Review of Literature

2 Methodology

Once the design parameters were identified they were then separated into the design space and the objective space for analysis. Using this distinction modeling was then performed both from first principles and from empirical results.

2.1 Determining Design Parameters

To begin the prototyping process the parameters of interest must first be identified. This is to ensure that testing takes place in the most efficient manner possible and addresses as many considerations at once as possible. For the purposes of identifying possible parameters I explored three modes of identification: requirements to actuate the keys, requirements to fit within the organ, and requirements to address other concerns. A brief list can be seen below in Table 1.

Table 1: Description of Possible Design Parameters

Function Parameters	Housing Parameters	Other Concerns
Pull Force	Size	Power Draw
Pull Speed	Recoil	Heat Generation
Variance	Weight	Duty Cycle
Pull Length	Attachment	Life time

Of these parameters, several were discarded for the purposes of testing as they would not yield significant differences over the testable candidates, such as the pull speed, the weight, and the recoil of the solenoids.

2.2 Identifying Possible Constraints

Once the design parameters were identified it was important to note if any would constrain the function of other parameters. Prior to analysis, it was noted that cost is frequently a constraint in addition to the constraints added by the solenoids being placed within the organ limiting the possible size and volume of the solenoids.

2.3 Isolating Design and Objective Space

Having identified my parameters and possible constraints the next step was to identify which parameters I would aim to maximize going forwards and how the solenoids would be described. For the purpose of analysis, the design space was initially chosen to be the radius of the solenoid, the height of the solenoid, and the voltage of the solenoid. These three parameters were chosen as a means of identifying possible candidates clearly with minimal overlap. The objective space was chosen to be the pull force of the solenoid and the power draw of the solenoid. This provided an answer to two concerns when looking at solenoids and provided the opportunity to maximize one objective while minimizing the other.

2.4 Modeling

Having identified the desired parameters two models were constructed. The first used a first principles equation to predict the pull strength of a solenoid using the radius, height, and voltage as references. It could also be used to find the power draw. The second model used results from datasheets to map a regression onto the space.

3 Results

The data from the models were separated into 3 categories: direct mapping, objective space, and design space. The first was a look at how the first principles model compared to the empirical data. The second was a plotting of the objective results of the empirical data to determine the pareto curve. The third was to determine the optimal solenoids and pick a best choice.

3.1 Direct mapping

The first attempt at using a model to prototype the solenoids involved plotting the force and power as functions of the radius, height, and voltage of the solenoid. This involved a first principles equation to predict the force and power with the force results shown in Figure 1 below.

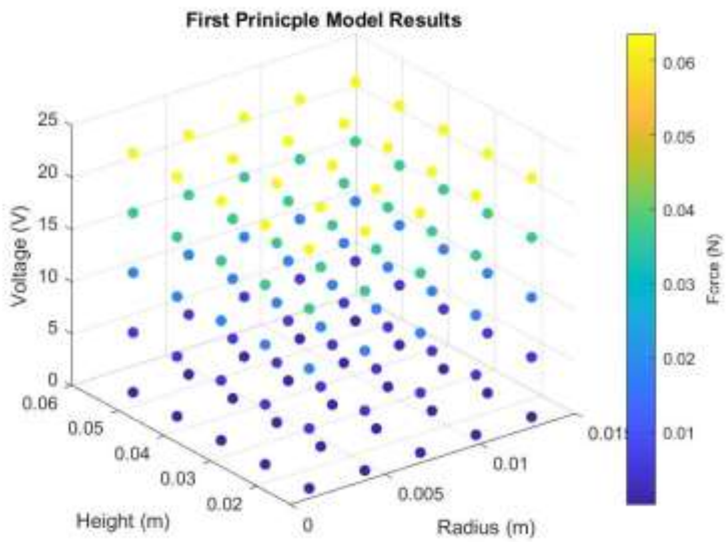

Figure 1: First principle plot of Force model

This model predicted that voltage was the dominating factor when determining the force of a solenoid. The equation used to predict force (eq. 1) relies on current. This current is a function of the voltage and resistance. The resistance is a function of the height and radius of the solenoids. In addition, the order of magnitude for the force was at least 2 time higher than the height and radius giving a disproportionate weight to its value.

$$F = (n * I)^2 * \mu_0 * \frac{A}{2*g^2} \qquad \text{eq. 1}$$

The results from empirical data sheets were also plotted to observe the accuracy of the model. (Figure 2). When compared to the first principles model several differences are apparent. The first is that the first principles model predicts a force that is orders of magnitude below the empirical results. The next is the commercial solenoids run in series which are design to mitigate the impact of voltage on the force of the solenoid, which contradicts a core assumption of the current model. The empirical results do demonstrate a trend of increasing force as the dimensions increase.

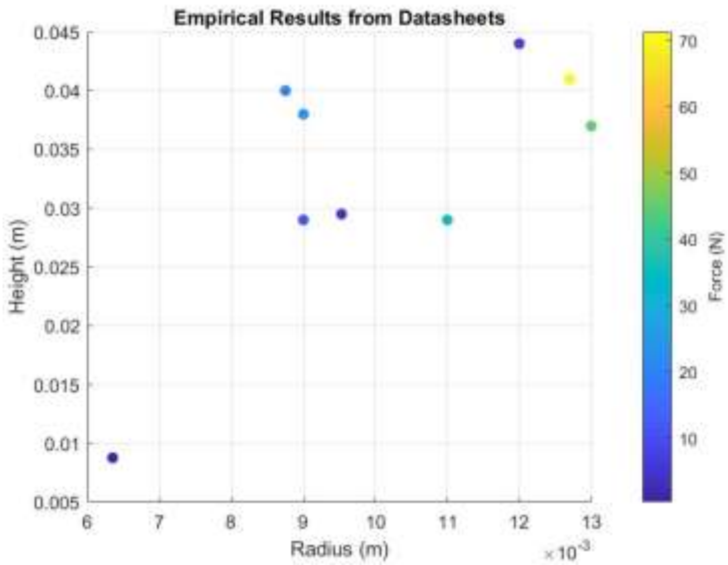

Figure 2: Empirical Results of Force from datasheets

3.2 Objective Space

Having observed possible errors in the first principle model, it was decided to simply observe the performance of the solenoids in the objective space using the empirical datasheets. The results were split into two sections one limited by the duty cycle remaining continuous (Figure 3) and the other allowing for all possible duty cycles (Figure 4).

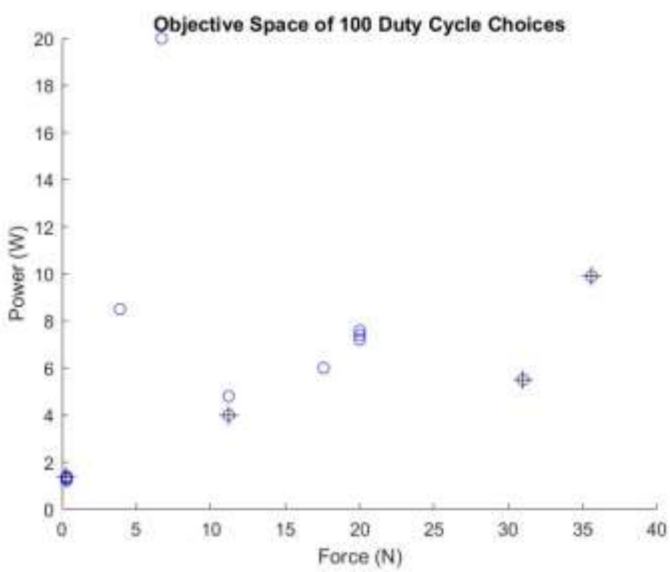

Figure 3: Objective space from Empirical Data for 100 Duty Cycle

The continuous space demonstrated a general trend of increasing power when increasing force which is consistent with the expected results from Eq. 1, as an increase in current translates to an increase in both power and force assuming all other factors being kept constant.

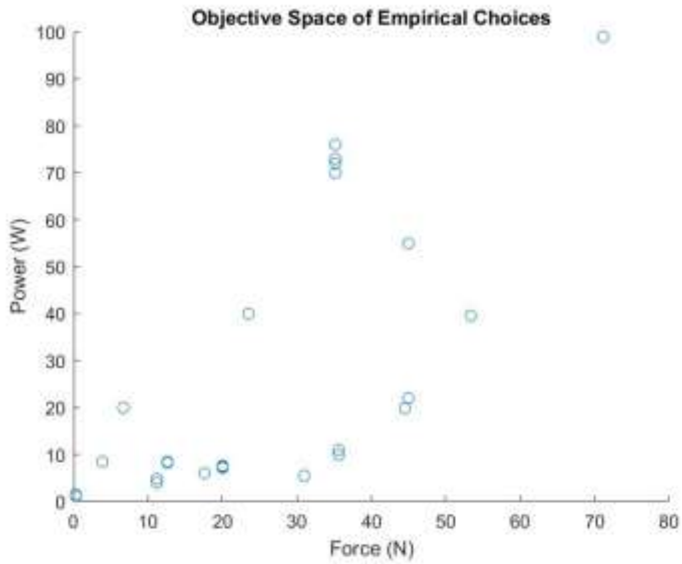

Figure 4: Objective space of All Empirical Results

The objective space results for all data showed a wider spread of results, though they generally still followed the previous trend with few outliers.

4 Discussion

The analysis of the results of the project. This will include a discussion of how to improve the first principles model and a look into why it performed in comparison to the empirical data. Following that will come a discussion of the impact of duty cycle on the objective space. Then the ideal solenoid for this application will be selected and any observations of the design space will be made.

4.1 First Principles Model Failure

Taking a look at the first principles model makes it clear that there were flaws in the assumptions made during its creation. The first major flaw was the assumption that varying the voltage would increase the force as a result. However, it is clear that commercial solenoids are made to be consistent at a variety of inputs and can accommodate the varying voltages. Another issue that this flawed assumption created was that the voltage varied on a level orders of magnitude larger than the other inputs, which would inflate its impact when compared to the smaller changes made to radius and height. A third issue was that the model did a poor job of accounting for the constants used to vary the inputs. The diameter of the winding, the material of the wire, the number of loops, and the gap of the solenoid were assumed to be either a constant value or one that varied with one of the inputs to simplify the model. These assumptions underestimated the force that could be output and given time could be adjusted to create a more faithful model.

4.2 Pareto Curve in Objective Space

Looking at the results of the objective space in a meaningful fashion requires pairing down the total set of results into the pareto set. This set provides the set of choices that either minimize power for a given force, or maximize force for a given power. While there are options that exist outside of the domain, they are less optimal for the given consideration which helps to limit the domain. The pareto curves are seen in Figure 5 (pg. 7) for both the 100 duty cycle case and the all solenoids case.

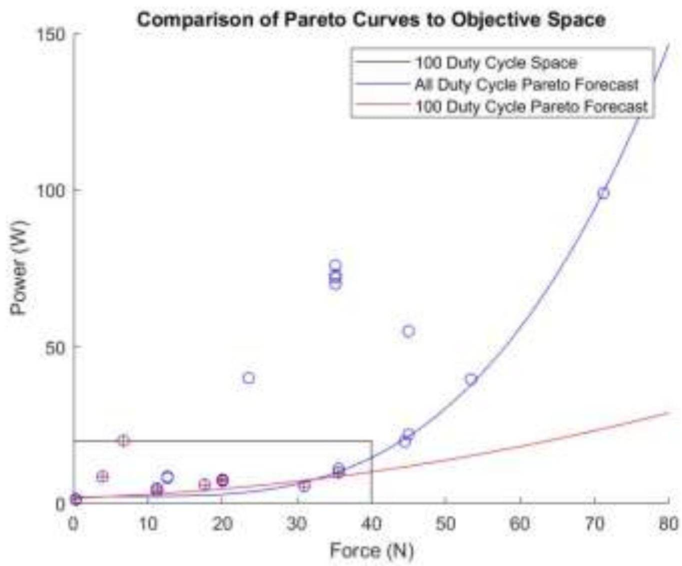

Figure 5: Overlay of Objective space with Pareto Curves.
The 100 Duty cycle case is bounded by a box.

The addition of lower duty cycles allows for more power in a given solenoid, but the returned force rises at a quicker rate than is projected by the 100 duty cycle case. This implies that while it is possible to get more force for a given solenoid by increasing the power, it is probably more efficient to increase the dimensions of the solenoid if space allows. While interesting, it is of little concern for this analysis as all tested solenoids surpass the force threshold of 0.2 N, mitigating the need for such measures.

4.3 Pareto Curve in Design Space

Having identified the solenoids in the pareto set within the objective space it was then important to see how the solenoids performed in the design space to see if there were any correlations that could aid in streamlining future prototyping attempts. This translation is seen in Figure 6 (pg. 8). There is a rough correlation between the size of the solenoids and their performance. It appears to taper off at the extreme edges, though that could be a function of the solenoids observed and further analysis would need to be done to determine the exact bounds and equation. In the end, the solenoid identified as the best choice was determined to be the one with a radius of 9 mm and a height of 29 mm. While this solenoid is not the smallest, and thus having the least power draw, it does however address a dimensional constraint of the solenoids needing to be able to have a draw length of a half inch or 0.257 m.

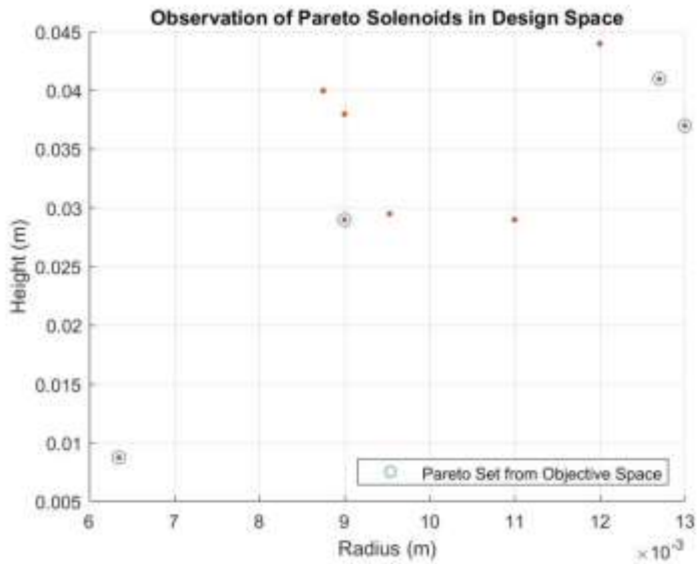

Figure 6: Pareto Set in the Design Space, baring Voltage

5 Recommendations

The recommended solenoid from those analyzed is the DSOL-0630 series. This solenoid has the second lowest power draw from those analyzed while still surpassing the set force threshold. This is good because there will be at least 88 solenoids in the circuit with the plan being to operate up to 10 at once. Minimizing the power draw helps to make this feasible and reduces concerns from heat generation as well. It is a better choice than the lowest power draw solenoid because of a constraint on the required draw length being above 0.026 m from prior testing on the organ itself. In order to provide this draw length the height of the solenoid needs to be above 0.026 m to function as expected due to the properties of the magnetic field within a solenoid.

Given more time, it would be interesting to look into refining the models used in this analysis to increase their predictive capabilities or otherwise reduce the errors in selecting a solenoid. Another avenue for analysis would be to gather a larger data set of solenoids and observe if the trends seen within this dataset persist on a larger scale.