Optimizing the Movement of a Precision Piezoelectric Target Positioner

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I. Abstract

For any successful laser fusion experiment on the OMEGA or OMEGA EP laser systems, a target must be accurately positioned and stabilized at the location of beam convergence. New technology in the form of piezoelectric motors greatly improves upon the drawbacks inherent to existing DC motors and gearboxes. Unlike those conventional systems, piezoelectric motors can operate at cryogenic temperatures inside the target chamber. This eliminates the need for a long stalk conducive to vibration and a warm operating environment. Eventually, these motors might also provide a means of actively stabilizing the target by compensating for tremors in real time. In order to gain a better understanding of these miniature motors, an experiment was carried out to determine the force a piezoelectric motor could produce with various frequencies, voltages, and materials. At cryogenic temperatures, it is essential to optimize the functionality of the motor so that it moves efficiently and does not bind. It was discovered that the piezoelectric motor exerted the most force while containing slides made of polyether ether ketone (PEEK), at a frequency of 894 Hz and a voltage of 126 V.

II. Introduction

At the Laboratory for Laser Energetics, cryogenic targets are currently positioned in the vacuum chamber with DC motors and high-ratio gearboxes (the motor output must be geared down to provide very small increments of motion). In order to use these components, which must remain warm and thermally isolated to operate, targets are placed on the end of long, insulating stalks. This approach suffers from several disadvantages that include larger size and mass, susceptibility to vibration, heat loading of cryogenic pumps, limited position resolution, and gear backlash. Piezoelectric motors, when employed in the target chamber on all three axes (x, y, and theta), can solve these problems due to their characteristics and manner of operation. The motors can work at cryogenic temperatures, directly coupled to a shorter target stalk. For this reason, targets move more precisely with less induced vibration or oscillation. Furthermore, piezoelectric motors are compact and yet still provide significant levels of force (up to approximately 1 kg) and a step size of microns (the sending of a single electrical pulse). The design of the motor also involves a high degree of static friction that can impede motion when the piezoelectric element is not in use, thereby dampening instabilities from the external environment.

A piezoelectric motor is a small device that relies on an applied electric voltage to move. Its operation is unique: it utilizes the “slip-stick” effect that takes advantage of the difference between static and kinetic friction. As outlined by D. W. Pohl[1], a waveform is applied to a static piezoelectric element, which applies force to a set of rails. The carriage rides on these rails as they are pushed in one direction until the force of static friction is exceeded by the force imparted by the element. At that moment, the carriage breaks free and enters kinetic friction. The waveform drops off (and as a result the element contracts and the rails return to their previous state), but the carriage continues sliding due to its momentum and inertia. Finally, kinetic friction brings it to a halt, at which point some net displacement has occurred on the axis of the piezoelectric element’s expansion. The carriage, having undergone one step, is again in static friction. For target positioning, this constitutes the smallest amount of distance the target can be moved – and due to the miniscule nature of the “slip-stick” effect, this is on the order of microns. If further movement is desired, the waveform can be repeated many times a second to generate a significant linear displacement.

III. Initial Preparation

First, it was necessary to establish what it meant to “optimize” a piezoelectric motor. It was decided that the piezoelectric motor would be quantified in terms of maximum force exerted. To measure this, the motor would be attached to either a force gauge or load cell that could provide an accurate measurement of the motor’s performance. Since a load cell was on hand (Figure 1), it was tested for reliability and accuracy prior to connecting the piezoelectric motor and its associated equipment. The cell was connected to a computer with an analog to digital converter; it was subsequently calibrated and zeroed. Two separate experiments, one with beakers of water (of known volumes) and one with standardized masses, were performed to determine if the load cell was consistent and whether it could predict the amount of mass or the mass of the beaker placed on it. Figure 2 shows a plot of voltage versus mass, the data resulting from the standardized mass experiment. Different masses failed to yield linear and predictable changes in voltage. The load cell was 13% off in predicting the mass of the beaker and 15.6% off from a 500 g mass. Evidenced in Table 1, the load cell lacked consistency across different usage periods. In the three different tests noted, the cell’s voltage was recorded with nothing present to serve as a reference value and point of comparison. The resulting zero mass voltages fluctuated on each of the three separate occasions – a predicted mass difference (based on the first day’s zero value and a constant, best-fit slope generated from multiple mass tests) showed a variation of approximately 80 grams. As a result, a more stable force gauge was necessary.

To be used in the experiment, the new gauge would require high accuracy and sensitivity to measure slight differences in force output from the piezoelectric motor.

Mechanical force gauges, which allow for a manual reading of force at various integer values, were insufficient. In order to create an optimal experimental set-up, a digital force gauge was obtained that could interface with a computer for automated data acquisition. Additionally, the waveform generator's major components were assembled to create a device that could run up to five channels at once with whatever waveform, frequency, or voltage that was desired (Figure 3). This machine is crucial to the operation of the piezoelectric motor, as it externally applies voltage to the piezoelectric element.

In this experiment, the waveform and motor utilized are shown in Figures 4 and 5, respectively. The exponential waveform was determined[2] to be optimal at maximizing the "slip-stick" effect and, therefore, efficient translation of the carriage. The motor itself was designed at the Laboratory for Laser Energetics for use in the target chamber, as existing options worked sporadically or lacked the robustness needed for cryogenic laser targeting. The motor consists of two major parts, the stationary base and the moving carriage. Figure 6 shows the base with the carriage removed; it is mounted to a large platform of aluminum (for the experiment) with a mounting plate (visible at the corners), and in the center lies the piezoelectric element that supplies the force. Figure 7 shows the carriage that moves on the rails of the base; it interfaces with the base via slides that can be made of different materials. This particular experiment made use of four materials, as shown in Figure 8: stainless steel, PEEK, polyethylene, and Vespel.

IV. Experiment

Initially, despite the understanding that analog gauges wouldn't be feasible for the later part of the experiment, they were used to generate values of range and maximum force to roughly characterize the piezoelectric motor. In addition, the tension placed on the motor via a spring and set screw, the screws holding the slides, and the placement of kapton tape were varied to create the best possible motor functionality. It was discovered that when the slides can flex minutely, the motor operates much more effectively – as a result, Belleview washers were placed on the slide screws to allow for small amounts of compression. The kapton tape, when placed between the slide and carriage (on the side with the tension spring), ensured that the carriage always maintained optimum contact with the rails.

Subsequently, an experiment was performed to identify what frequency, voltage, and material resulted in the maximum force from the motor. Early testing had revealed that the motor needed to be interfaced with a force gauge in a way that dampened vibration; as a result, the set-up involved the motor pushing against a rubber stopper on the end of a rod connected to the digital force gauge (Figure 9). The motor and gauge were mounted to an aluminum plate placed on a level surface (Figure 10). The motor was screwed to the plate, while the gauge was mounted on sliders so that it could be adjusted. The waveform generator powered the piezoelectric motor, while the gauge was hooked up to the main computer. On that computer, custom LabVIEW software was created to both control the waveform generator and monitor the force gauge. In its final form, it was able to test the piezoelectric motor at a certain frequency or voltage setting (holding the other constant), increment that setting, reset the motor to its home position, read the gauge's maximum reported force value and write it to a file, reset the gauge, and repeat at the new setting. After completing the software and set-up, updating the waveform generator's firmware, and performing basic tests, the following was discovered: the motor would not run below 60 Hz or 50 V, and frequency intervals of 10 Hz were too large for the final test (considerable fluctuation in force output could occur inside of 10 Hz increments).

The final experiment was carried out as follows. A given pair of slides, composed of one of the four materials, was mounted to the carriage. The motor was run from 60-2000 Hz, in increments of 2 Hz, at a constant 120 V. At each setting, the force output was measured by the gauge and recorded. This was then repeated two additional times, for a total of three data sets, which were then averaged. From this averaged data, the three strongest frequencies were identified. For each of these frequencies, three tests were run that varied the voltage from 50-140 V, in increments of 2 V, while holding frequency constant at the value determined in phase one of the experiment; each frequency's three trials were then averaged separately. The highest frequency-voltage pair was then recorded for that material, along with the actual force output, for later comparison with the other three materials. This procedure was repeated for all four materials. Finally, it was determined which material, at what frequency and voltage setting, yielded the most force.

V. Results

Figure 11 demonstrates the results of the frequency modulation, for each of the four materials over the entire range of scanned frequencies. It is interesting to note that, regardless of material, the data has relative maxima and minima around the same frequencies (specifically, all surge around 700-900 Hz and 1300-1500 Hz and drop from 1000-1200 Hz) and PEEK appears stronger than the other materials over the majority of the frequency range. Figures 12-15 display the results of the voltage modulation for each of the four materials at their best three frequencies, as labeled. Clearly all four materials have a preference for a voltage near 120 V. Figure 16 contains the optimal frequency-voltage pairs for each of the four materials, and those values constitute the settings at which data was generated for Figure 17; that last figure plots the absolute maximum amount of force output by each material, and is thus the culmination of the experiment. It is easy to conclude that the piezoelectric motor is strongest with slides made of PEEK, putting out almost 800 g at 894 Hz and 126 V. Stainless steel comes in second with a little over 700 g at 732 Hz and 116 V, while the other two materials produce much lower values as shown.

VI. Conclusion

An experiment was performed in order to optimize and characterize the new piezoelectric motor system. These motors have many advantages that encourage the facility to replace DC motors for target positioning, and the only impediment is a lack of finalized design or refined operation of the piezoelectric system. The experiment involved the creation of software which can be used in the future to test the motors, possibly in cryogenic conditions similar to those of the target chamber. Additionally, a comprehensive set of data was obtained that represents motor performance with different materials and settings. It was found that PEEK produced the most force from the motor, followed closely by stainless steel and more distantly by the other two materials, polyethylene and Vespel. It was also found that kapton tape in collaboration with the tension spring, and slight compression on the slide screws, greatly aids motor performance. It is hoped that this experiment increases understanding of the piezoelectric system and will accelerate its adoption at the Laboratory for Laser Energetics.

VII. Acknowledgments

I would like to thank Gregory Brent for his knowledge, insights, time, and patience. He taught me a tremendous amount of information, and even went above and beyond to ensure that I understood topics in electrical engineering beyond those involved in the experiment. His assistance with LabVIEW and numerous suggestions throughout the process will not be forgotten. I would also like to thank David Lonobile, for helping me perfect my presentation and establish an experimental procedure, and Eryk Druszkiewicz, for assisting with load cell validation and project set-up. Lastly, I would like to acknowledge Stephen Craxton for his time and effort in the high school program. If it weren't for his management of the program's organizational aspects, such a wonderful opportunity at the University of Rochester simply wouldn't exist; furthermore, I appreciate his careful review of each intern's materials.

VIII. References

1. D. W. Pohl, "Dynamic piezoelectric translation devices," Rev. Sci. Instrum. 58, 54 (1987)

2. G. Brent, private communication (2010)

IX. Table and Figures

Table 1 The load cell voltages with zero applied mass at three separate times, and resulting mass predictions

The load cell could clearly fluctuate without influence. As shown, this could upset any data taken by up to approximately 80 g.

Test	Zero Mass Voltage (V)	Predicted Mass Difference (g)
July 12	1.2438999	(reference)
July 13, Test 1	1.2452463	+ 79.2
July 13, Test 2	1.2440528	+ 9.0

Fig. 1 The load cell

This is the load cell that was tested for accuracy and reliability. Initial plans consisted of using this device to measure force from the motor, but experimentation proved that this was not feasible.

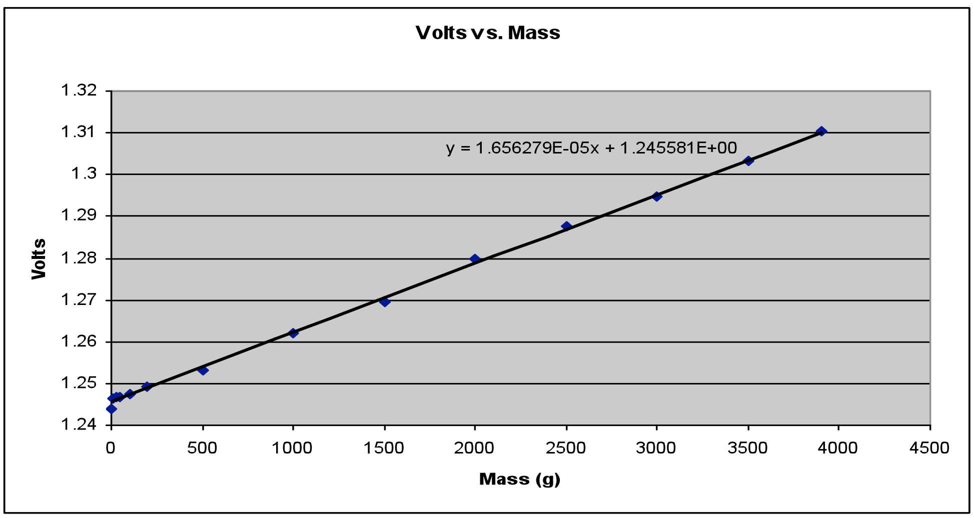

Fig. 2 Graph of volts vs. mass resulting from initial load cell testing

This data helped prove the load cell's inadequacy by demonstrating a slight curvature. Additionally, the slope was unable to yield accurate mass predictions.

Fig. 3 The waveform generator

Constructed for this experiment, the waveform generator was used to send any desired waveform, frequency, or voltage to the piezoelectric element.

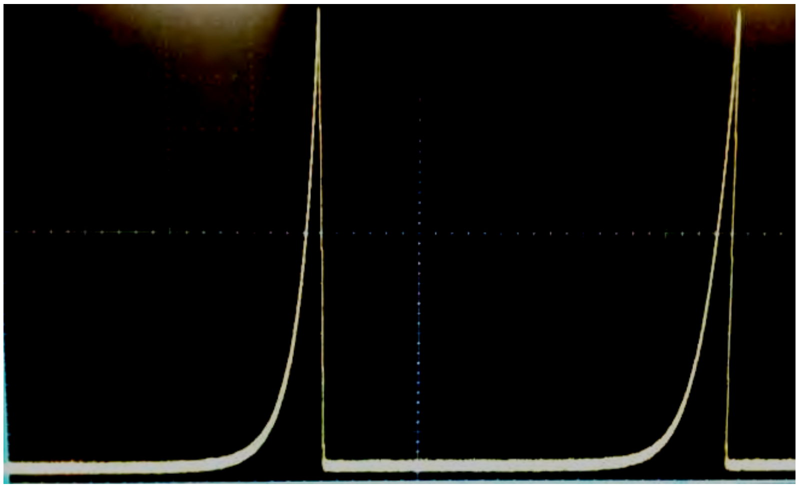

Fig. 4 The exponential voltage waveform used to drive the piezoelectric motor

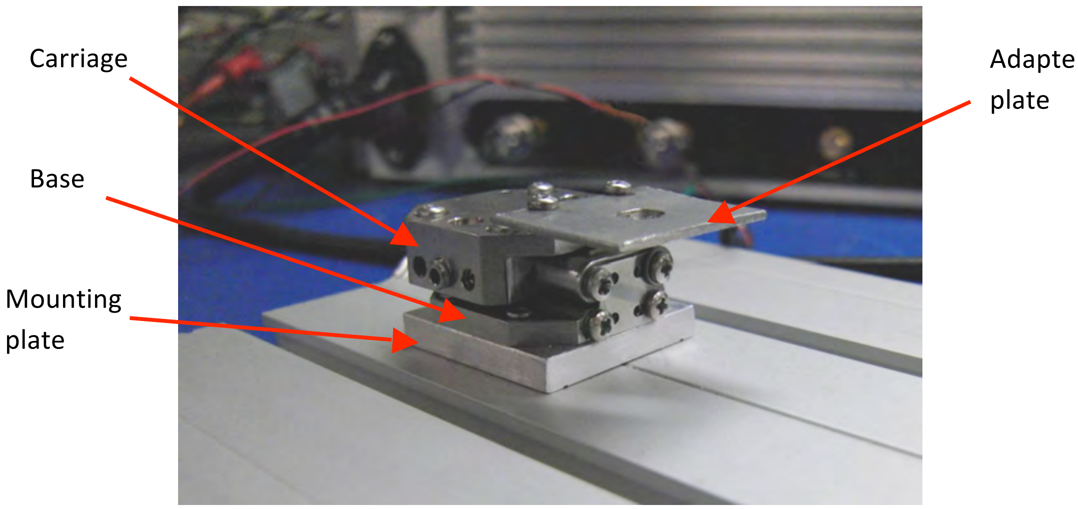

Fig. 5 The piezoelectric motor, as configured for this experiment

Here the motor is fully assembled, and the base, carriage, adapter plate, and mounting plate are all visible.

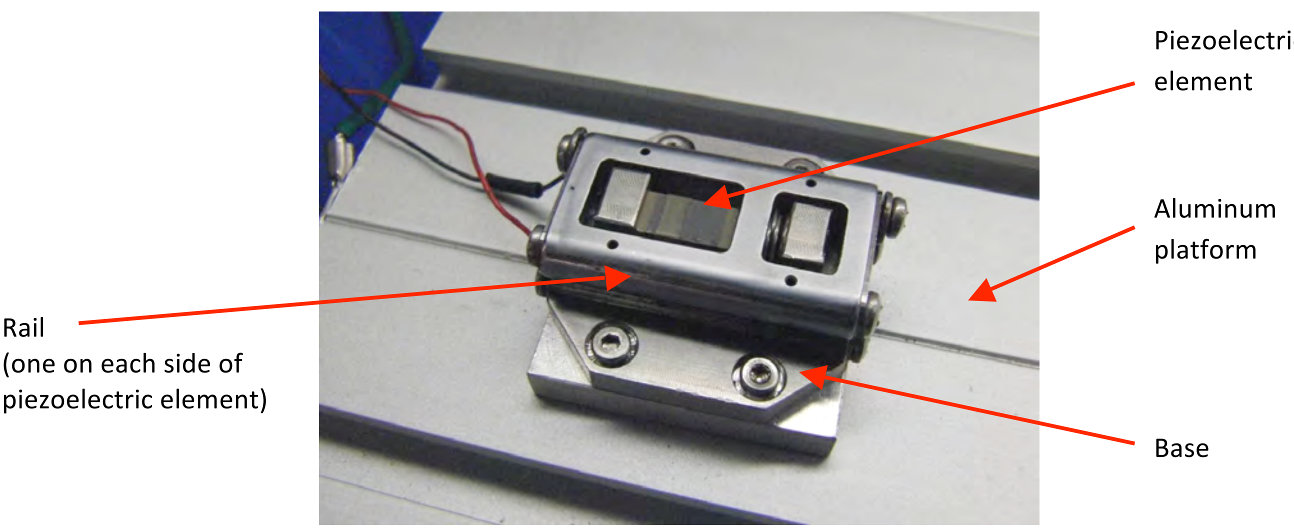

Fig. 6 The base of the piezoelectric motor

In the center of the base (in gray and brown) is the piezoelectric element, which provides the vibrations that drive the motor.

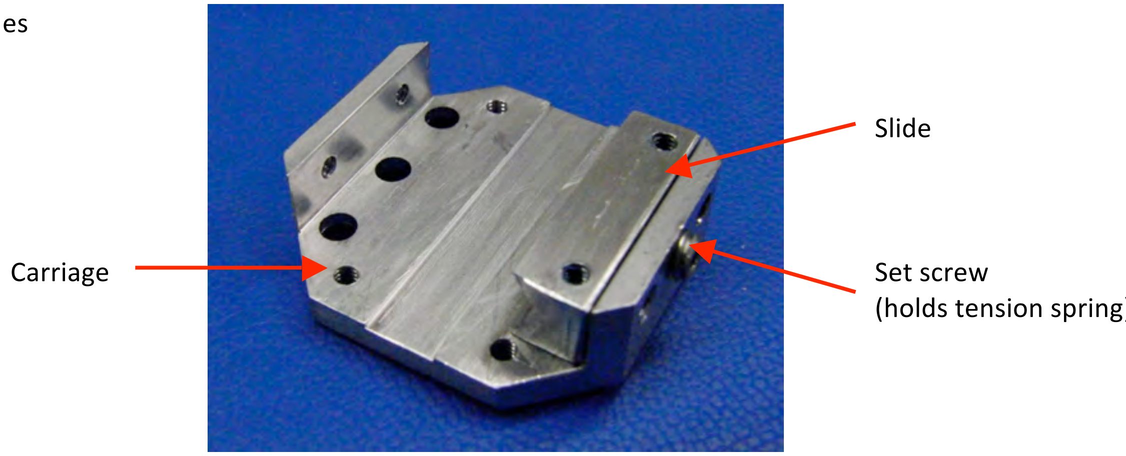

Fig. 7 The carriage of the piezoelectric motor

The carriage of the motor is what actually moves and positions the target. In this photo, the carriage has one of its two stainless steel slides installed on the right.

Fig. 8 The four slide materials tested in the final experiment

These four materials were tested extensively to determine force characteristics. The materials are, clockwise from top left, stainless steel, PEEK, polyethylene, and Vespel.

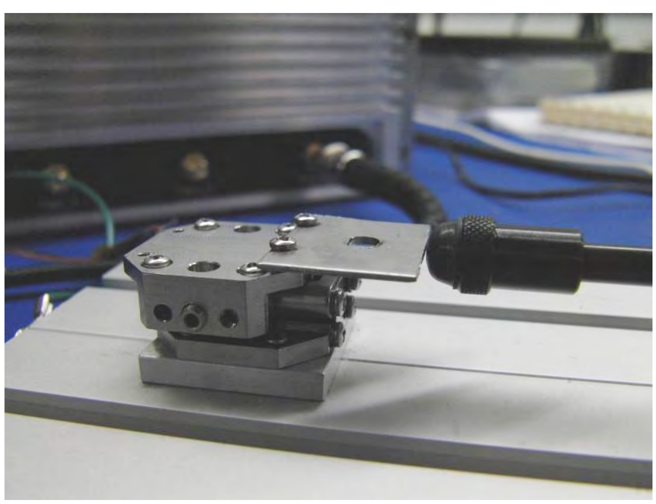

Fig. 9 Piezoelectric motor interfacing with force gauge

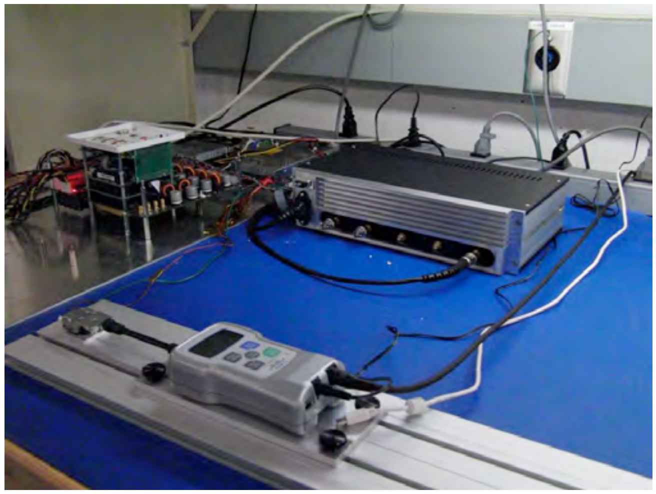

Fig. 10 The final experimental set-up

Here the piezoelectric motor, force gauge, waveform generator, and experimental platform are clearly visible.

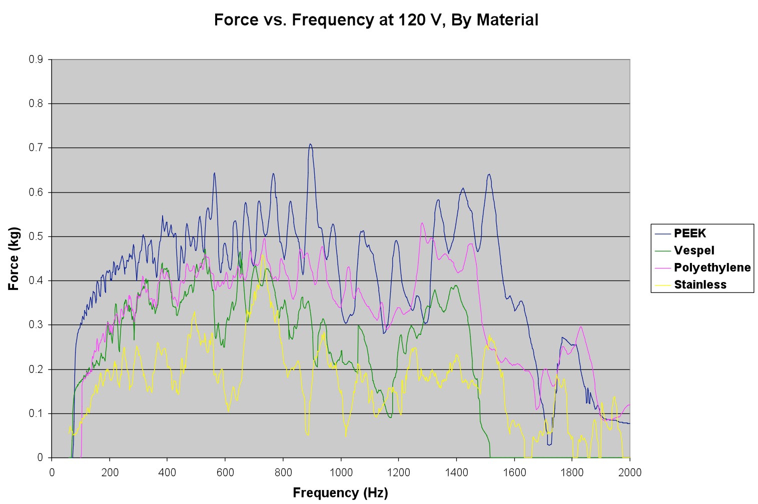

Fig. 11 Forces output by the various materials over the scanned range of frequencies at 120 V

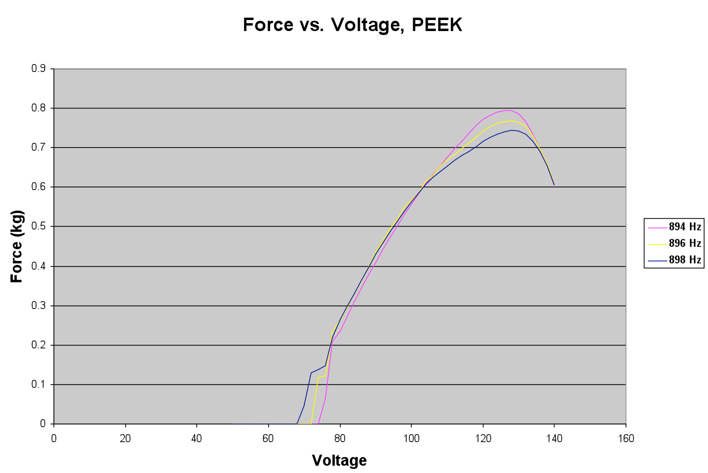

Fig. 12 Force vs. voltage for PEEK slides, at given frequencies

Each frequency line represents the average of three trials.

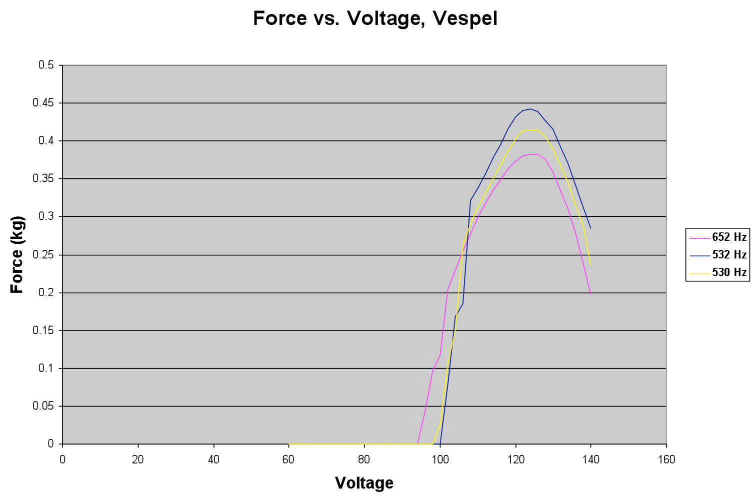

Fig. 13 Force vs. voltage for Vespel slides, at given frequencies

Each frequency line represents the average of three trials.

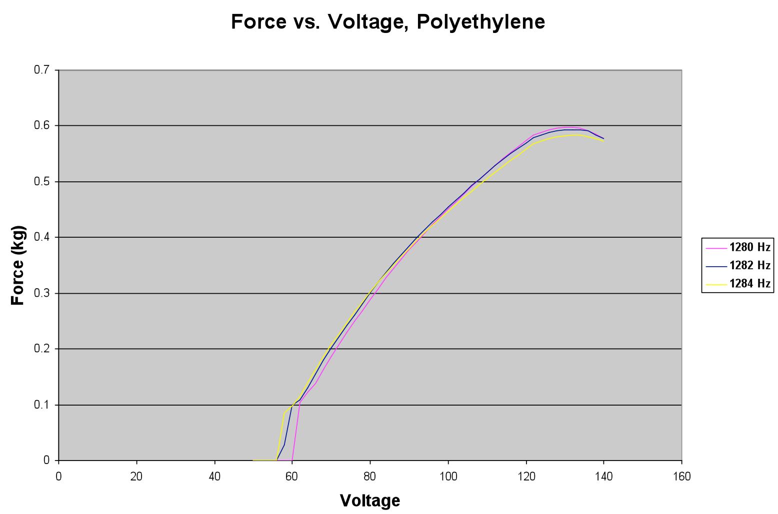

Fig. 14 Force vs. voltage for polyethylene slides, at given frequencies

Each frequency line represents the average of three trials.

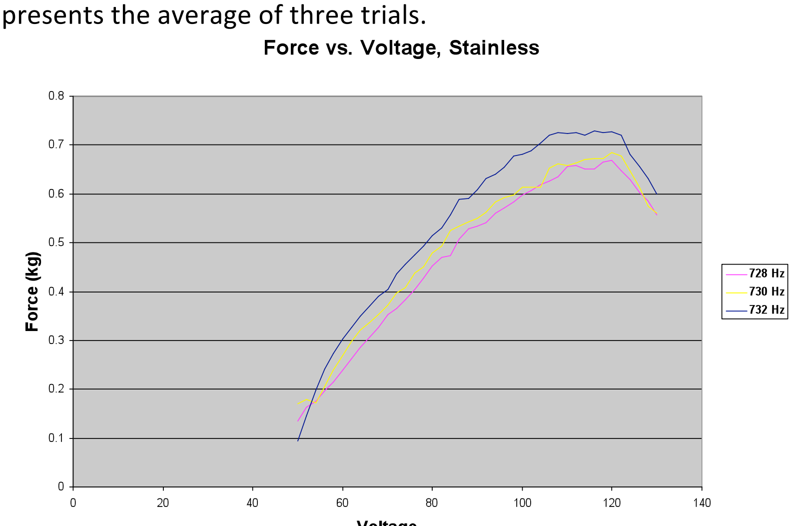

Fig. 15 Force vs. voltage for stainless steel slides, at given frequencies

Each frequency line represents the average of three trials.

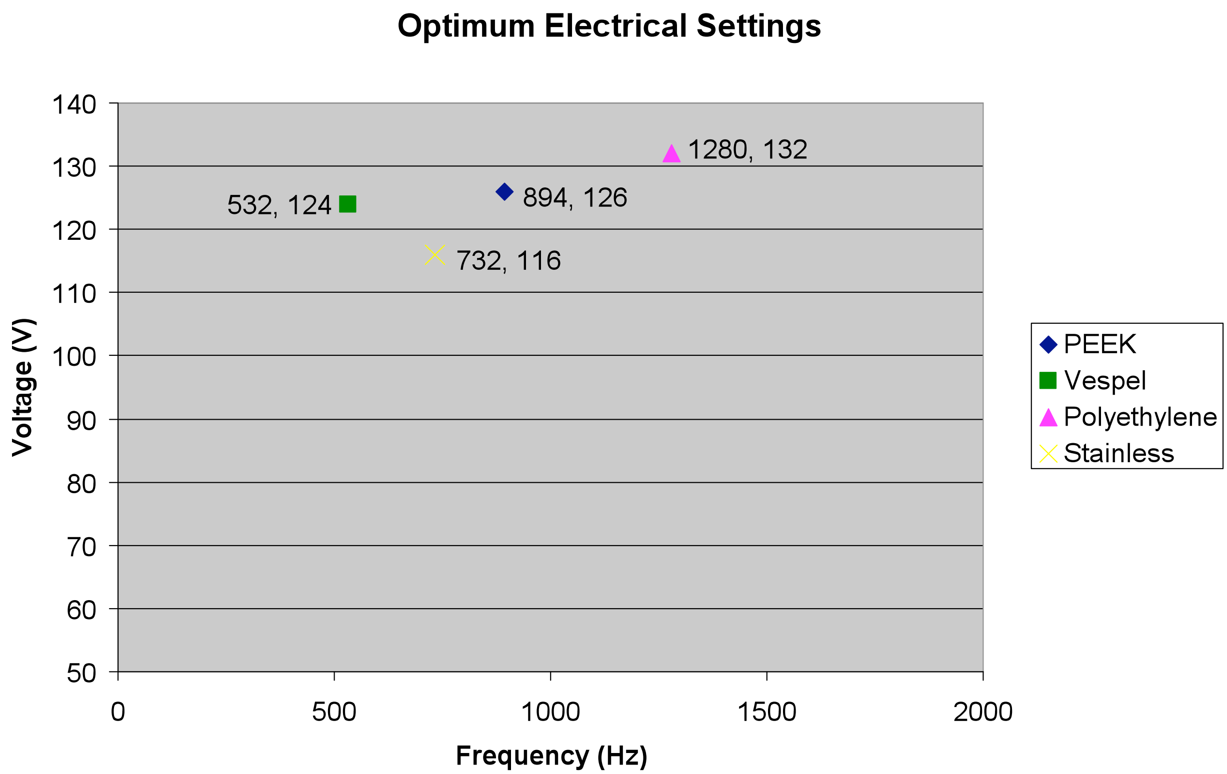

Fig. 16 Electrical settings used to generate maximum force, by material

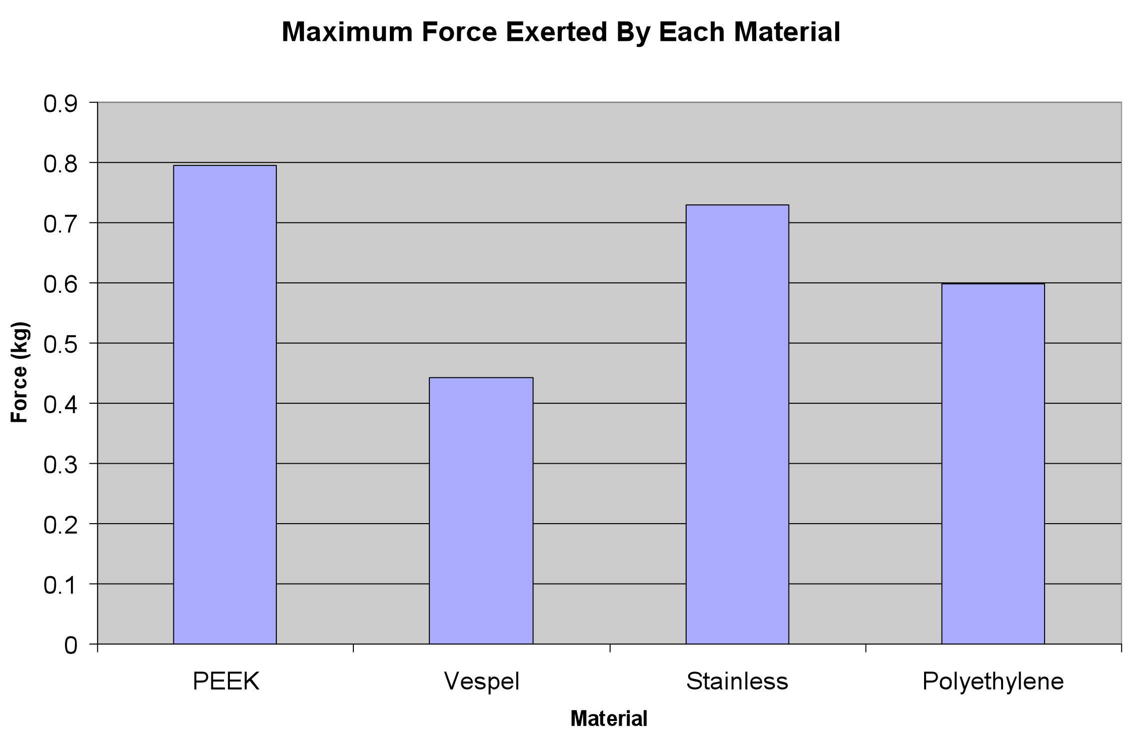

Fig. 17 Maximum forces exerted by each material