

High Precision Thrust Balance Development at The George Washington

IEPC-2017-405

*Presented at the 35th International Electric Propulsion Conference
Georgia Institute of Technology • Atlanta, Georgia • USA
October 8 – 12, 2017*

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Abstract: We report on the design, development, calibration, and testing of a torsional micro-Newton thrust stand developed at The George Washington University. The development of this device is part of an effort to increase the thruster characterization capabilities in the laboratory. Calibration was done with electrostatic fins and the resulting displacement was measured using a capacitive sensor. The thrust stand described herein has a resolution of less than 2.5 μN . The thrust stand has been calibrated for forces between 2.5 μN to up to 30 μN by applying voltages between 75 V and 300 V, respectively. This resulted in a displacement of 43 nm and 650 nm, respectively.

Nomenclature

A	=	Electrode Surface Area
ESF	=	Electrostatic Force
ϵ_0	=	Permittivity of Free Space
I_{sp}	=	Specific Impulse
L	=	Distance between electrodes
$\bar{Q}$	=	Mean Ion Charge State
V	=	Applied Voltage

I. Introduction

THE market of small satellites (< 50 kg) has seen an accelerated growth in the last few years. According to SpaceWorks¹ last forecast and market review, over 450 small satellites have been launched in the period between 2013 and 2016, more than twice the number of satellites launched in the years prior to 2013 combined. From the nearly 700 small satellites launched between 2000 and 2016, approximately 565 were CubeSats, i.e. satellites with a mass between 1 to 10 kg¹. From these, less than 10 were launched with a propulsion system onboard and only two of them were electric micro-propulsion (eMP) devices². The two eMP devices flown were The George Washington University's (GW) Micro-Cathode Arc Thruster (μCAT ^{3, 4}), and Massachusetts Institute of Technology's (MIT) electrospray⁵. Other eMP systems are currently being developed or have been developed but have yet to be flown, such as Clyde Space / Mars Space's pulsed plasma thruster (PPT⁶), or the University of Michigan's CubeSat Ambipolar Thruster⁷. In the last few years, the complexity of CubeSat missions has steadily increased. The first missions were generally technology demonstrating missions, such as the Canadian Advanced Nanospace eXperiment Program (CanX-1) mission⁸. Current and future missions are much more ambitious, for example both NASA's Mars Cube One (MarCO⁹) 6 U CubeSats, which will launch together with InSight, NASA's next Mars lander. These will be the first interplanetary CubeSats and will have a propulsion system onboard to perform orbit trajectory corrections. These new and complex missions will require micro-propulsion systems. Hence, important development and

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characterization of propulsion systems will have to take place. Thrust measurements are an essential tool in the characterization of propulsion devices. They provide insight into the thruster's performance and can be used to derive other important parameters, such as the specific impulse, or I_{sp} . Herein, we present the status quo of the thrust stand capabilities at The George Washington University, with a brief description of the Micro-Cathode Arc Thruster and a historical curiosity.

II. The Micro-Cathode Arc Thruster

The μ CAT is an electric propulsion system based on the well-researched ablative vacuum arc or 'cathodic arc' process^{10,11}. This physical phenomenon erodes the negative electrode (cathode) with every discharge. In this case, this is highly desirable as the cathode is the thruster's propellant. Therefore, during each discharge, a small amount of metallic propellant is eroded, ionized, and accelerated. The efficiency is enhanced by a magnetic field¹². The magnetic field is caused by the arc current as it travels through a magnetic coil prior to arcing between the electrodes. The device and the main components can be seen in Figure 1. A spring is used as a feed system to ensure that there is always propellant available for the next discharge. The system can be pulsed and thus, throttled by simply changing the discharge frequency. At a discharge frequency of 10 Hz, the power consumption is approximately 1 W for the current version of the μ CAT. The thruster can be pulsed at frequencies between 1 and 50 Hz, depending on the requirements and mission needs. The frequency is limited by the thermal properties of the components used for the casing and most importantly, the feed system's spring, which runs the risk of getting annealed at high temperatures.

The physical nature of the arc discharge allows any conductive (solid) material to be used as a propellant¹³. The eroded material is, to a large degree, fully ionized. Additionally, it is common that the particles are multiply ionized. In the case of tungsten, the mean ion charge state $\bar{Q}$ is 4.6+ and approximately 94% of the ions have a charge state equal or higher than 3+¹⁴.

The fact that the discharge can ablate any conductive material allows the thruster to operate with different metals, each with different physical properties, giving the mission designer flexibility when it comes to the mission's design, e.g. nickel will produce a higher thrust compared to titanium, but the latter would offer a higher specific impulse under unchanged discharge conditions. The system does not require any pressurized tanks or other components that may be required when dealing with propellants such as xenon. This confers the advantage of greatly reducing the system's complexity and risk involved. Additionally, only an electrical connection is required to operate the thruster, since the propellant and all necessary components are integrated within the thruster's structure. Consequently, the μ CAT technology offers opportunities that are unmatched by most gas-fed propulsion systems, such as the ability and flexibility of attaching the thrusters to deployable booms to increase the torque for RCS maneuvers. To operate the thrusters, a voltage between 15 to 25 volts is required to energize the system. The booster circuits convert the energy, producing an instantaneous peak arc discharge of approximately 50 A. This instantaneous current ablates a small fraction of the cathode and ionizes it, producing a quasi-neutral plasma that does not require a neutralizer. The plasma plume is almost fully ionized hence eliminating potential self-contamination due to the charge exchange process in the case of a weakly ionized plasma. Nickel and titanium cathodes (propellant) have been characterized for the use in this technology and have resulted in specific impulses of 2200 s and 2800 s. The energy consumption is approximately 0.1W/Hz for 2 micro-N-s impulse bits.

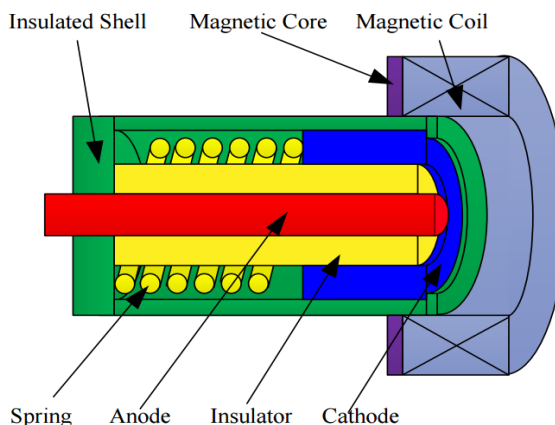


Figure 1. Schematic of a μ CAT used for RCS. The size of the device shown is approximately. 2.5 cm in length.

III. A Historical "Thrust" Measurement

An interesting event took place at the Westinghouse Electric and Manufacturing Co. in East Pittsburgh, twelve years after R. Goddard patented the world's first electrostatic thruster¹⁵ and five years after K. Tsiolkovsky suggested the use of ions for thrust generation¹⁶. Here, in 1929, R. Tanberg may have inadvertently made the initial steps toward a future space technology. With his experiment, Tanberg identified that not only does the cathodic arc discharge produce a force, but that it can also be measured¹⁷. From the force, he could deduce the approximate velocity of copper ions produced by a DC arc by measuring the force applied by the ejected plasma on the copper cathode. His goal was to prove the vacuum arc produced high-velocity ions and from that, to estimate the cathode spot temperature. A

simplified schematic of the measuring device is shown below in Figure 2. He obtained the force applied by observing the deflection of the cathode with scale located under it. For a current between 11 A and 32 A, Tanberg estimated the force per unit current in vacuum ($0.2\text{-}10 \times 10^{-3}$ Torr) to be approximately

$$\frac{F}{I} \approx 17 \pm 3 \frac{\text{dynes}}{\text{A}} \approx 0.17 \pm 0.03 \frac{\text{mN}}{\text{A}} \quad (1)$$

This force is attributed to the high velocity of the vapor jet emitted from the copper cathode. The vapor jet refers to both the ionized particles as well as the neutral particles that comprise the jet. Several other authors measured the force on the cathode at higher background pressures (>5 Torr) as well and came to similar results¹⁸⁻²². The authors reported lower forces than the ones measured by R. Tanberg. This can be attributed to the jet interaction with the background gas.

Even though this device was most not intended to be a means of propulsion, the experiment that R. Tanberg performed was indeed a thrust measurement. We can consider this to be the first of its kind with a technology that is currently used in an electric propulsion system, more so when one considers that this technology has been tested in space. R. Tanberg's velocity estimation yielded an ion velocity of approximately 16 km/s, which has an error of less than 20% when compared to the values measured by A. Anders and G. Yushkov using precise equipment²³. Tanberg attributed this velocity to an extremely hot cathode spot and estimated its temperature to be between $5\text{-}7 \times 10^5$ K¹⁷. K. Compton disagreed with these results and attributed the high velocities to electrostatic forces and introduced an accommodation factor α to account for these velocities¹⁹, a result that was also accepted by E. Kobel²¹. Meanwhile, E. Easton agreed with R. Tanberg on the origin of the high ion velocities to be thermal²⁴. It was not until 1934 when L. Tonks explained that the reason for the high velocities is the high pressure exerted by the electrons in the plasma, an element that had been overlooked in prior models, even though both the thermal and electrostatic components influenced the velocity of the ions²⁰.

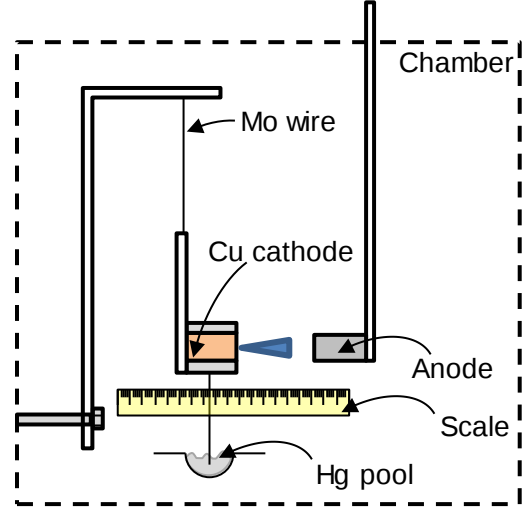


Figure 2. Apparatus used by R. Tanberg to determine the force applied to the cathode by the ejected vapor jet. Adapted from Tanberg, 1930.

IV. Thrust Stand

A. The Thrust Stand

The thrust stand described herein was designed at The George Washington University's Micro-Propulsion and Nanotechnology Laboratory. The device is part of an effort to increase the capabilities of the laboratory to include thrust at micronewton levels. It is designed to accommodate the Micro-Cathode Arc Thruster described in section II, and will also be capable of accommodating new developments of this thruster. The system is a torsional thrust stand which can be seen in Figure 3 and was machined completely out of 6061 aluminum. The torsional thrust stand was selected over hanging and inverted pendulums due to the fact that they are usually the more precise than hanging and inverted pendulum stands²⁵. Torsional thrust stands have been well described in prior publications²⁵⁻²⁹. The thrust stand is mounted inside a stainless-steel vacuum chamber with a diameter of 60 cm with a length of 120 cm on four vibration isolators to reduce pump-induced vibrations onto the thrust stand. Pumping is done with an Alcatel rotary vane roughing pump capable of bringing the pressure down to 3.5×10^{-2} Torr. A Leybold-Heraeus turbomolecular pump is used to bring the pressure down to 8×10^{-6} Torr. Both the thrust stand and the vacuum chamber are grounded.

As with other thrust stands, thrust is obtained by measuring the displacement of the thrust stand's arm when the thruster is fired. The displacement is then correlated to the displacement resulting from a known force produced by a calibration device. The calibration device used herein will be described in subsection B. Torsional thrust stands are designed in such a way that the displacement produced by the arm is small enough to allow the use of the small-angle approximation²⁵. The system has a total arm length of 61 cm and is suspended by two Riverhawk 5010-400 flexural pivots with a diameter of approximately 8 mm. The system is designed in such a way as to allow a quick exchange of pivots if the sensitivity of the system needs adjustment. The thruster is mounted on one side of the thrust stand's arm, while the damping system and the calibration system are mounted on the opposite side to balance the center of mass

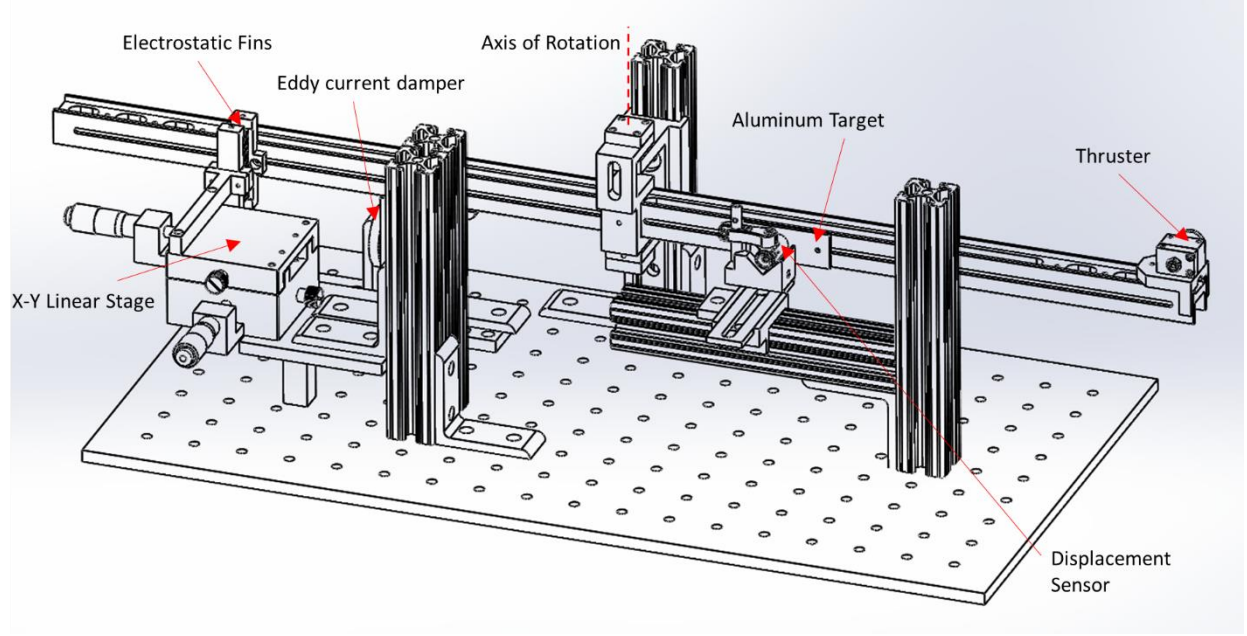


Figure 3. CAD representation of the torsional thrust stand

to make it coincide with the axis of rotation as much as possible. J. Ziemer showed that a torsional thrust stand is prone to non-linearity if the center of mass and the rotation axis do not coincide²⁶. Measurement of the displacement is done with a Micro-Epsilon capaNCDT CS-1 capacitive displacement sensor with a linearity of 1.5 μm and a resolution of 0.75 nm. The device has a measuring range of 1 mm. The sensor outputs a voltage between 0 and 10 volts depending on the distance between the sensor and the target, therefore, a signal of 5 V means that the sensor is 500 micrometers away from the target. Data acquisition is done with a LabView virtual instrument (VI) with the help of a four-channel National Instruments NI 9125 DAQ board with BNC connectors. Data is stored in the form of .csv files and then processed with MATLAB 2017a. Damping of the system occurs via a custom-made eddy-current damper, which consists of two permanent magnets discs mounted approximately 25 mm away from each other and facing the same direction to create a uniform axial magnetic field between them. An L-shaped aluminum bracket is attached to the thrust stand's arm in such a way so that part of the bracket meets the magnetic field.

B. Calibration

The thrust stand is calibrated by using electrostatic fins. This method is commonly used for these types of thrust stands because of its simplicity, since it only requires a voltage source to be operated. Additionally, this calibration method is contactless. This type of calibration system has been described in prior publications^{28, 30}. The electrostatic force (ESF) between two plates is described by as follows²⁸,

$$F_{\text{plates}} = \frac{1}{2} \epsilon_0 \left(\frac{V}{L} \right)^2 A \quad (2)$$

where ϵ_0 is the permittivity of free space, V the applied voltage, L the distance between the two plates, and A is the cross-section of the electrodes. Equation (2) shows the $1/L^2$ dependence of the distance on the force. The equation does not account for possible fringing effects in the electric field³⁰. This equation does not accurately describe the force that occurs in electrostatic fins, and therefore, a new equation is needed. A. Yan³⁰ approximated the ESF with the following equation:

$$F_{\text{ESF}} \approx 2N\epsilon_0 V^2 \left[2.2464 - \frac{(c+g)}{\pi x_0} \right] \quad (3)$$

In equation (3), N , c , g , and x_0 each denote the total number of fins, the thickness of each fin, separation between fins, and engagement distance between fins, respectively. These variables are represented graphically in Figure 4. The electrostatic force using this formula for $N = 19$ (total amount of fins) is plotted in Figure 6 (top left). The electrostatic fins developed for this project had a length of 12 mm, a thickness of 1 mm and a width of 5 mm and can be seen in Figure 6 (top right). The bottom comb had 10 fins and the top comb had 9 fins for a total of 19. Both are insulated from their respective holders by a PTFE insulator. An interesting observation from Figure 6 (top left) is that after a certain engagement distance x_0 , the change in ESF is only minor. This is the case for $x_0 \gg c + g$, where equation (3) becomes nearly independent of the engagement distance x_0 . Figure 6 (bottom left) shows this observation. The red line represents the mean of the curves from Figure 6 (top left). The error bar was calculated using one standard deviation. The blue line represents the mean for engagement distances between 6 mm and 11 mm. The highest standard deviation occurs at 200 V. For the red graph, the standard deviation from the mean is approximately $2.31 \mu\text{m}$, whereas for the blue graph, the largest standard deviation is a tenth of that of the red one. Therefore, once inside the vacuum chamber, it is not completely necessary to know the engagement distance with a high degree of precision, if it is above 6 mm. After $x_0 > 6$ mm, the error decreases to approximately 1-2%. Figure 6 (bottom right) shows experimental data for $x_0 = 4.6$ mm, $x_0 = 7$ mm, and $x_0 = 7.8$ mm. One standard deviation was used as the error. The simulated ESF data was calculated by using equation (3) with $N = 10$ (highest amount of fins in one comb), and $N = 19$ (total number of fins). The ESF is underestimated for $N = 10$, and overestimated for $N = 19$, which shows the importance of corroborating simulated data with experimental data.

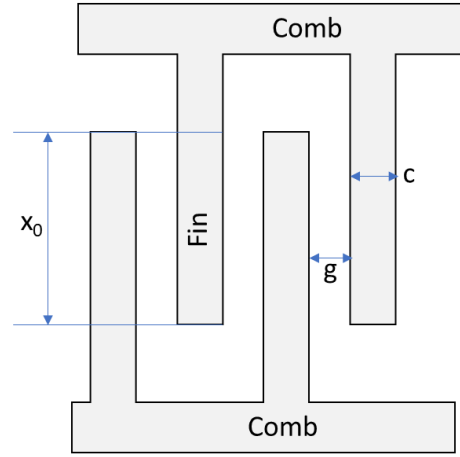


Figure 4. Annotated graphical representation of the combs and fins.

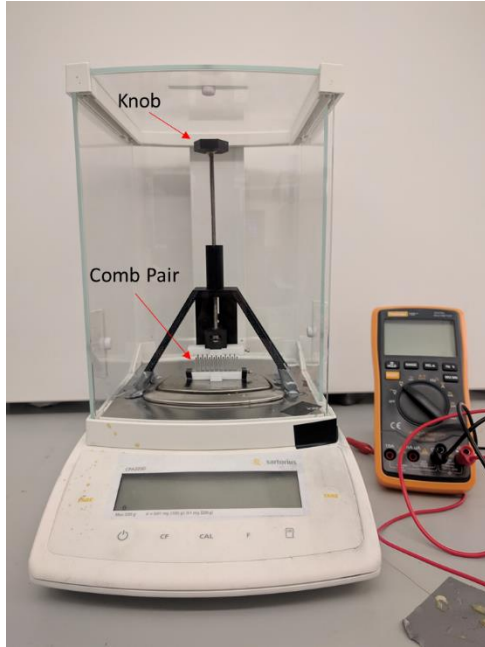


Figure 5. Calibration setup using a high-precision scale.

Measurement of the electrostatic force was done with the help of a high-precision scale. The scale used was a Sartorius CPA225D precision scale with a resolution of 0.01 mg (for masses up to 100 g). One comb was placed on the scale's measurement platform, whereas the second comb was mounted on a 3D printed holder. The system was designed in such a way as to allow linear displacement of the top comb by rotating a small knob. The handle transfers the movement to the comb with a threaded rod. This device is shown in Figure 5. A closeup of the fins and their respective insulators can be seen in Figure 6 (top right). To collect the data, a voltage from a high-voltage power supply was reduced by means of a voltage divider to get voltages between 50 V and 200 V, the equivalent to approximately 2.5 to 25 μN if $x_0 > 6$ mm. A digital multimeter was used to measure the voltage that was applied between the combs. The wire going to the bottom comb, i.e. the one mounted on to the scale, was selected to be as thin as possible to avoid any possible effects from adding possible errors to the measurement. The thin enamel-coated copper wire was also taped off to the scale in two positions to absorb any vibrations that could be transported through the wire. Prior to doing this, it was noticed that the vibrations from the wire were causing the measurement to be very unstable, to the point where no accurate reading of the scale could be done. The source of the vibrations was the air blown out by the air conditioning system in the laboratory. Once the scale's glass doors were taped and the cable was secured on two positions, the effects of the air flow were null. This improvement stabilized the measurements significantly. Ten measurements were performed at every voltage level to verify the repeatability of the measurement. For each voltage level, the mean and the standard deviation were calculated. Figure 6 (bottom right) shows some of these measurements. Once the relationship between voltage and ESF were measured using the scale, it was necessary to relate these two measurements to a displacement on the thrust stand. The combs and insulators used in the first part of the process

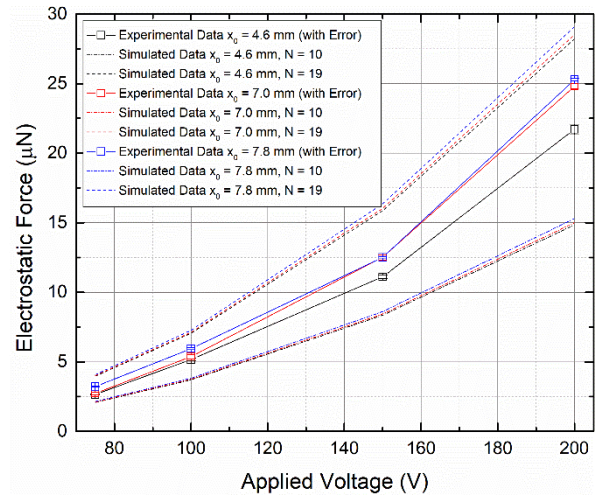
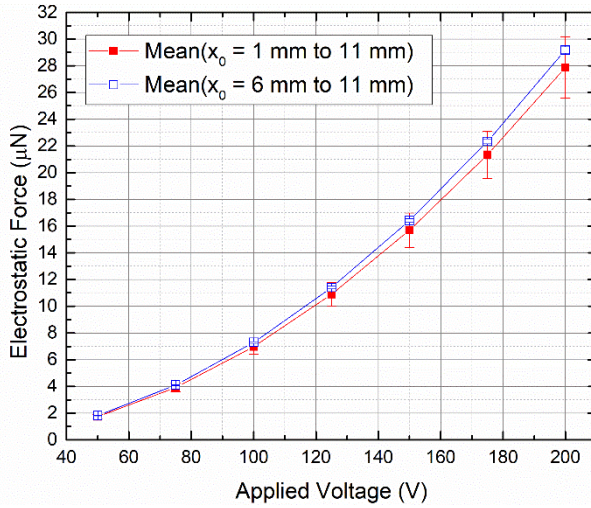
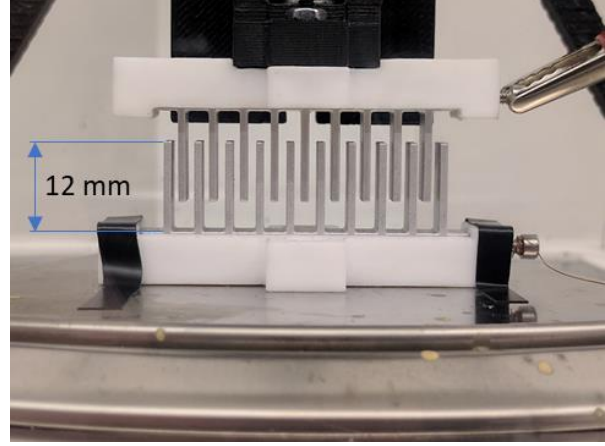
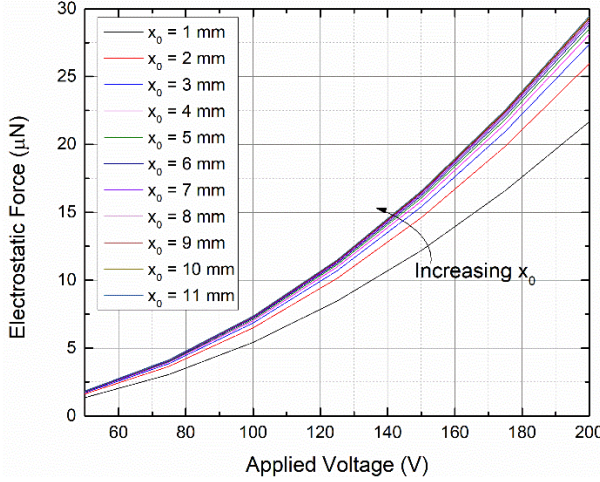


Figure 6. Top Left: Simulated ESF using $x_0 = 1$ mm to $x_0 = 11$ mm and $N = 19$. Top Right: Picture of the electrostatic combs used in this project. Bottom Left: Mean and errors of ESF. Bottom Right: Experimental data vs. simulated data for both $N = 10$ and $N = 19$.

were duplicated and installed on the thrust stand system. This prevents having to move the components back and forth between the scale and the inside of the vacuum chamber.

Once inside the vacuum chamber, the chamber was pumped down to 3×10^{-5} Torr and the experiment was performed. This time, since the resulting ESF for a given voltage had been previously measured, it was time to measure the displacement produced by this force. The goal of this procedure is to obtain a relationship between the applied voltage and the equivalent displacement, and therefore, using the information in Figure 6, we can then associate the applied force to the displacement. The response of the thrust stand to different voltages is shown Figure 7. At first, a voltage of 75 volts was applied, and was increased to 100 V, 150 V, 200 V, and 300 V. The data was acquired with a LabView VI and saved as a CSV file. Data post-processing was done with a MATLAB script written by the author. The script first smoothened the data with a Butterworth Filter (red curves in Figure 7). To measure the displacement after a voltage had been applied, the size of the “step” had to be measured. A graphical interface allows the user to select several points in the plot with the mouse. Once the points were selected, the MATLAB script calculated the average between each pair of points. The result was a horizontal line with the average of all the data values between each pair of points. The top graphs in Figure 7 show the averaged step. Once the steps had been calculated, the MATLAB script analyzed the delta in displacement between each step. Additionally, the program provided an averaged value using the data from all the steps (bottom right of Figure 7). The calibration responses show some non-linear behavior of the thrust stand. This is most likely because the wiring was not done in the common “waterfall”²⁵ configuration. Moreover, a drift in the displacement can be seen. The thrust stand, in its current state, is not thermally isolated and is therefore not in a controlled temperature environment.

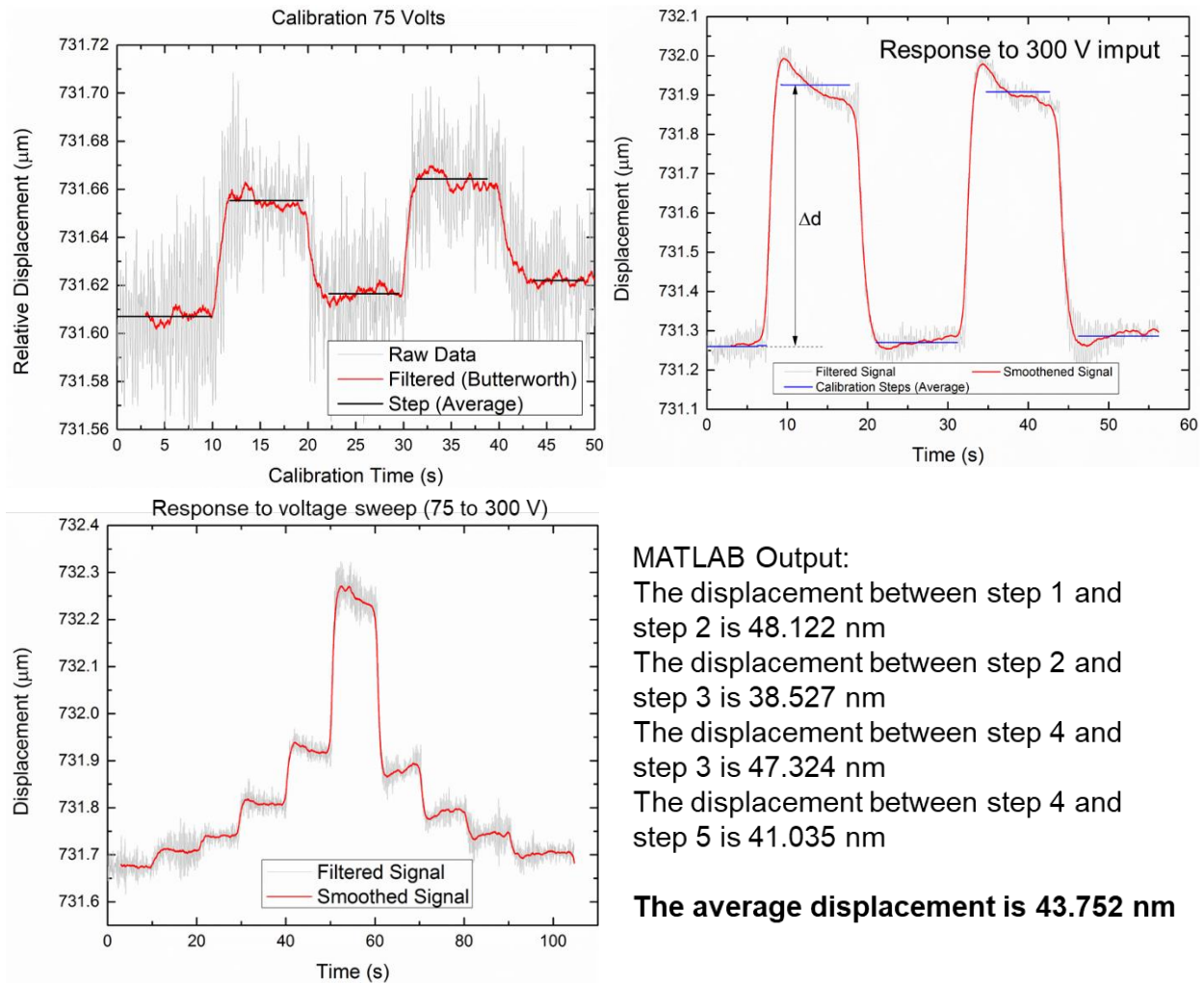


Figure 7. In vacuo calibration results. Top left: Thrust stand response to a voltage of 75 V (approx. 2.5 μN). Top right: Thrust balance response to a voltage of 300 V (approx. 30 μN). Bottom left: Thrust stand reaction to a voltage sweep (10 seconds per step) from 75 V to 300 V. Bottom right: Example of MATLAB output. The steps shown are the steps from the 75 V thrust balance response (top left).

The thrust stand was tested as is, despite non-linearities, to perform a brief test with a simplified version of the μCAT thruster. This was done to see the response of the thrust stand to the μCAT discharge, and not to perform an accurate thrust measurement. This simplified version used a central copper cathode as propellant. The thruster was initially fired at 1 Hz, and the second test was performed at 50 Hz. The results of this test will be shown in subsection C. The discharge current was measured to be in the range of 44 A per pulse. This was measured outside the chamber with a 0.1 V/A Pearson coil.

C. Results

The thrust balance's response to the μCAT thruster is shown below in Figure 8. The image on the left shows the thrust stand's response to the thruster pulsing. A series of peaks can be seen. These occurred every 1 Hz and happened every time the thruster was fired. Given the nature of the capacitive displacement sensor used for this experiment, the peaks observed are electromagnetic interference (EMI), caused by the temporal change in the thruster's electromagnetic field during the discharge. This caused the signal-to-noise ratio to be extremely low, and thrust could not be determined properly. An attempt at filtering this data using MATLAB's Hammel filter was successful. The filter removes data points that are outside three standard deviations from the mean. The filtered data can be seen in Figure 8, right. Even though the peaks from the thruster's EMI were eliminated, the remaining data was inconclusive and prevented the author to measure thrust. The EMI was also noticed sporadically during calibration, but could not

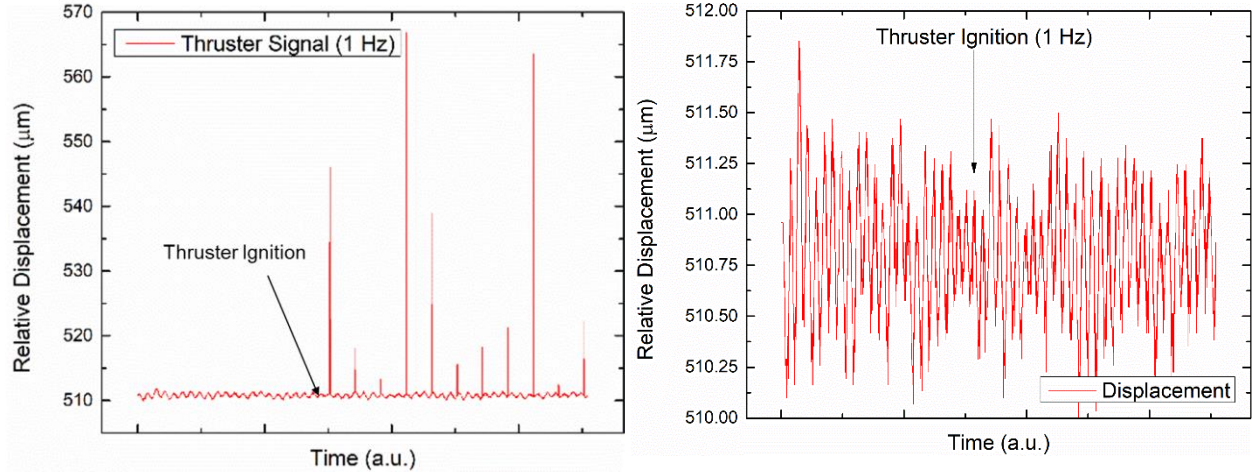


Figure 8. Thrust balance's response to the μ CAT pulsing. Left: μ CAT firing at 1 Hz. Right: Filtered signal using MATLAB's Hammel filter. An error in the export of the data caused a loss in the time data (x-axis) and therefore, the table shows arbitrary time units. Each peak (left) occurred every 1 Hz.

be repeated. An attempt at firing at higher frequencies is shown in Figure 9. The thruster was fired for 15 seconds. The EMI signal was large enough to cause the natural oscillations (like the ones shown in Figure 8, right) to become a nearly flat line. No useful data could be extracted from this graph and all filtering attempts were in vain.

D. Lessons Learned and Next Steps

The data obtained during the thruster discharges showed clearly that the sensor chosen for this endeavor was not the right one. Even though this system has a high accuracy of 0.2 nm (static), it is extremely prone to changes in electric fields inside the chamber. Therefore, it will be necessary to change the sensor. A D-63 laser displacement sensor from Philtec is currently being considered as a replacement for the CS-1 displacement sensor. The D-63 system uses fiber optics and therefore, the sensor electronics can remain outside of the vacuum chamber while the measurement head is inside it. This will allow us to decouple EMI from the sensor electronics and therefore, we should be able to have a much more precise measurement without noise. Additionally, the cables inside the chamber that lead to the thruster are producing a non-linearity in the measurements. This will be changed in the next iteration and we will switch to a waterfall cable arrangement. Furthermore, a test device, such as a small cold gas thruster, will be built and used to verify the thrust stand. A thermally-controlled system for the thrust stand is currently being considered as an option to reduce temperature-related drift. Given the parameters of the vacuum chamber, this may be a difficult endeavor, but nevertheless, it should be considered if accurate measurements are to be made.

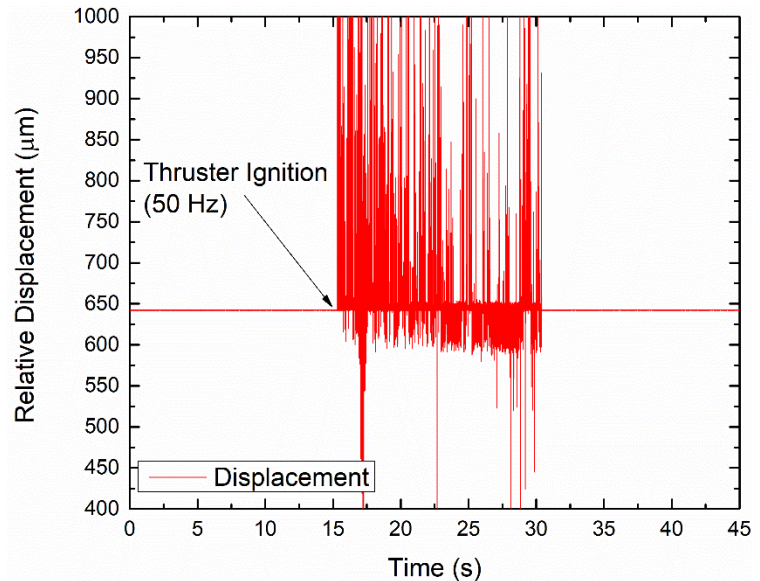


Figure 9. Response to the μ CAT firing at 50 Hz.

V. Conclusion

A torsional thrust balance was designed, tested, and calibrated. The thrust stand had a resolution of less than 2.5 μ N, which is smaller than the thrust we expect to measure when firing the μ CAT system, and was calibrated in the

range of 2.5 μN to approximately 30 μN . The system is still work in progress and the next steps will ensure that the system has a more linear behavior. We expect to verify the thrust stand with a cold gas system in the near future.

Acknowledgments

The authors would like to thank the NASA DC Space Grant Consortium and Vector Space Systems Inc. for their support.

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