Development of a Micro-Thruster Impulse Measurement System Using Optical Sensors

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ABSTRACT

A new method for measuring performance of a micro-thruster is suggested in this paper. A few thrust stands have been developed for measuring micro-level thrusts. This paper describes a different measurement method that can minimize the calibration involved in the measurements, while providing the capability of directly measuring the produced minimum impulse bit. The underlying theory and the theoretical background for the measurement mechanism are described here. The theory and method is verified using computer simulation, and the result is given in this paper. The theory has also been tested on an actual hardware. The prototype measurement system has been tested inside a vacuum chamber for verification of the theoretical and simulation results. Actual experimental data was used to verify the theory, and a test cold gas thruster was also employed for final testing and verification of the measurement system.

INTRODUCTION

The satellite technology has greatly advanced and accelerated over the recent years.¹⁻³ With the increase in demand for satellite services, satellites in the sky have been increasing in both number and complexity. More capability means delivering higher accuracy, and more demanding requirements imposed on the attitude control system also led to new advancements in propulsion technology. Driven by a desire to increase efficiency, electric propulsion systems such as ion thrusters, micro pulsed plasma thrusters, etc. have experienced much attention.¹⁻³ These thrusters deliver thrust at a specific impulse much higher (an order of magnitude) than the chemical thrusters. The lower thrust level of these thrusters can also mean a more accurate and 'finesse' attitude control. Producing thrust in milli-newton, or sometimes micro-newton range, the electric thrusters can maintain and control a satellite's attitude with relatively low fuel quantity throughout the mission life.

Because the thrust produced is at such a low level, it becomes quite challenging to accurately measure the performance of electric propulsion systems. The most widely used strain gauge setup cannot measure thrust at milli- or micro-newton level. Moreover, many types of electric propulsions that produce such low level of thrust produce impulse bits rather than sustained thrust. Some of the examples are micro pulsed plasma thruster where the fuel (usually Teflon) is ablated by electric shock to produce thrust, and MEMS thruster where a group of miniature rockets are machined into a small single chip to be ignited individually. The important performance measurement for these thrusters is not the actual thrust, but the minimum impulse bit produced by each firing.³ These thrusters are used in bang-bang control, and it is critical to know how much energy is delivered to the satellite every time a thruster is fired. Measuring the minimum impulse bit presents an additional challenge because most of the performance measurement setups are developed to measure thrust, or derive impulse by measuring the thrust of a propulsion system.

This paper suggests a new method for characterizing the performance of a micro-thruster. It uses a pendulum and a pair of optical sensors to measure a difference in swing time to determine minimum impulse bit of a thruster. Conventional methods also employ pendulums to measure micro-level thrust. In the case of the conventional methods, thrusters are fired while the pendulum is at a stationary position, then the displacement from the center is measured to deduce the thrust produced. However, calibration of the setup and error reduction has posed a great challenge in obtaining a good measurement. Thrust stands for such low-level output thrusters involve quite stringent and rigorous calibration steps before the thruster performance can be measured. The method of clocking the swing time suggested in this paper has the advantage of greatly reducing the calibration and effect of uncertainty errors. Also, the method suggested here is for measuring the impulse bit produced by the thruster, not the direct thrust, which is better suited for electric propulsion systems.

TRADITIONAL MEASUREMENT STANDS AND PROPOSED SYSTEM DESIGN

Measurement of small thrust or forces has been a problem of interest for a long time. There has been many devices and methods devised to measure extremely small forces. Use of pendulum has been widely preferred because it provides a near-frictionless condition. Other methods used are a double pendulum setup and MEMS devices. Some of these ideas are introduced here.

Laser Interferometry

Basic concept behind the thrust measurement is to measure the displacement caused by thrust firing. Thrusters are usually hung from a fixed point, like a pendulum, and the firing of the thruster generates a small displacement of the pendulum. This small displacement is measured to deduce the thrust output of a thruster.^{4,5} The displacement measurement is usually done by using a laser distance sensor. Due to extremely small measurement required (on the order of micrometers), laser interferometry is often used to increase the fidelity of the sensor.^{4,5} A generic setup is shown in Figure 1.



Figure 1: Depiction Of Thrust Stand Using Laser Interferometry

Rotating Platform/Torsional Balance

A typical rotating platform measurement stand sits on a minimal-friction pivot. The platform usually consists of two extended arms, with a test thruster at one end and a counter balance on the other. The pivot point is made to be as frictionless as possible in order to minimize damping effects. As the thruster fires, it creates a torque about the center of the platform, and rotates the arms. By measuring the amount or rotation, the thrust can be calculated.⁶ Identical thrusters can be placed at the end of each arm in order to magnify the effect of the thrusters, and also to create a pure rotational torque, for a better measurement. The displacement can be measured using a Linear Voltage Differential Transducer which converts the rectilinear motion of an object to an electrical signal.6



Figure 2: Generic Rotating Platform Measurement Stand, As Viewed From The Top

Proposed Measurement System Design

The setup of the impulse measurement system suggested in this paper is shown in Figure 3. A thruster hangs from a pendulum of 0.5m in length. The pendulum with a thruster attached swings from an initial displacement angle of 5 degrees. A thruster firing occurs(one impulse bit) at the time of release, then the pendulum swings through a pair of sensor gates. Each sensor gate consists of an optical sensor that logs the time when the optical LED light is blocked by the swinging pendulum. The time it takes for the pendulum to swing through two sensor gates is measured, and the impulse bit is quantified from the measured travel time.



Figure 3: Setup Of Simulation Model Including Sensor Gates

The calculation of minimum impulse bit delivered by the thruster is done by measuring the travel time through a pair of sensor gates. Measurements for two separate swings are recorded. The first swing, a 'control swing', is a natural swing of the pendulum from release, without firing the thruster. The swing time measured for the 'control swing' is used as a baseline. A second swing involves firing of the thruster at the time of release. As soon as the pendulum is released from the initial position, the thruster fires, adding energy to the system from its minimum impulse bit. This thrust firing occurs within the first 0.1 second time period, before it reaches the first sensor gate. The impulse calculation is derived by comparing the measured time for these two swings. The absolute swing time is irrelevant. Only the difference in travel time between the two separate swings is required for calculating the added impulse. The time difference can be directly correlated to the increase in initial velocity, thus the measured time difference can be directly converted to minimum impulse bit produced by a thruster. This method has the advantage of minimizing calibrations and setup time. Much of error sources, including the effect of temperature, act equally for both swings. By taking comparison values (not absolute values), most of error sources are included and negated by the first 'control swing'.

THEORY OF IMPULSE MEASUREMENT USING OPTICAL SENSORS

Theoretical Model

The theory behind this impulse measurement system described in this paper is based on the basic concept of the conservation of momentum. Let us first imagine a system where an object is dropped from a given height, in a vacuum environment, as shown in Figure 4. In both cases, the positions of point A and B are the same. In Case 1, the time it takes for the object to travel the distance between the point A and B is fixed for a given initial condition. If the travel time between point A and B can be measured, the initial velocity of the object as it enters point A can be calculated.



Figure 4: Depiction of Velocity Associated With Falling Objects

If the object in Case 2 has a different initial energy, then the travel time for Case 2 will be different from that of Case 1 because the velocity at point A will be different. Thus, the initial velocity at point A for both cases can be calculated if the travel time from point A to B, Δt , can be measured. In other words, the energy state at point A for both cases can be determined from measured Δt .

Now, let us consider a situation where the initial drop location for both cases is the same. If all the conditions are the same, then Δt measured for both cases should

also be the same. However, if some amount of energy is added to the system in Case 2 right after the release, then the velocity at point A will be higher than that of Case 1. If the added energy is quantified by ΔV (change in velocity), then the initial velocity at point A for Case 2 will be a certain amount larger than Case 1.

This principle can be utilized in measuring the impulse produced by a thruster. Since it is obviously quite impractical to drop thrusters from a height, a pendulum setup is used for minimizing friction, and taking advantage of the constant gravitational acceleration. As described in the example above, the pendulum is released from a certain height, and swings through two points marked as point B and C, as shown in Figure 5.



Figure 5: Pendulum Dynamics

Let us assume a case where the pendulum starts from rest at point A (Figure 5). As it swings from point A to B, the pendulum gains a fixed amount of velocity, ΔV_0 . As the pendulum continues its swing, it takes a certain amount of time, Δt , to go from point B to C. For a case where the pendulum starts from point B, but with an initial velocity ΔV_0 , then the travel time Δt will be the same for both cases. If the initial velocity ΔV added at the start(point B) is exerted by a thruster, then by measuring the travel time Δt , ΔV can be inferred. In other words, if we can measure the swing time, then the impulse imparted by the thruster can be determined.

Governing Equation

The system described in Figure 5 can be expressed by generic equations of motion. However, in the case of a pendulum, as shown in Figure 5, the system cannot be described by a simple equation. The acceleration vector is constantly changing in respect to the direction of motion, making it quite difficult to describe the motion using analytical equations. The accelerations and velocities at any given moment during the swing are given by Equations (1) and (2), referencing Figure 5.

$$Acceleration = g \cdot \sin(\theta) \tag{1}$$

where *g* is the earth's gravity.

$$Velocity = V_{previous} + acceleration \times timestep$$
(2)

In order to derive an exact period, or the time it takes for the pendulum to swing through a given distance, an iterative computation is required. If there was an impulse applied to the system, then an increase in velocity is exerted. This can be added to the velocity equation above as an addition of an increment velocity. The relationship between the added velocity, ΔV , and the applied minimum impulse bit is given below.⁷

$$I_{\min} = F \cdot t \left[\frac{kg \cdot m}{s} \right]$$
(3)

where F is the thrust produced by the test thruster, and t is the duration of the thrust.

$$\Delta V = \frac{I_{\min}}{mass} \left[\frac{m}{s} \right] \tag{4}$$

And the addition of the impulse shows up in the velocity equation by being included in the term $V_{previous}$, described by Equation (2). Since the main parameter of interest is time, integrating the equations given above cannot be easily achieved. Therefore, computer computations and simulations, coded in C⁺⁺, are used to analyze the parameters involved in the pendulum swing.

COMPUTER SIMULATION

Simulating Swing Motion

The physical setup assumed by the simulation is shown in Figure 3 above. The simulation assumes an instantaneous impulse addition to the system, but this is not true in real life. The actual operation of the thruster will involve an opening and closing, including a constant range (although small) in between. The test setup was arranged such that the thruster turns on at the exact moment of release, and the error associated with the discrepancy between the computer model and real life application is analyzed to be less than 1%. The computer simulation can be modified to compensate for this error, if needed.

$$Period = 2\pi \sqrt{\frac{L}{g}} \left(1 + \frac{1}{4} \sin^2 \frac{\theta_{\text{max}}}{2} + \frac{9}{64} \sin^4 \frac{\theta_{\text{max}}}{2} + \dots \right)$$
(5)

Analytical calculation of the swing time using the above equations was performed on a PC using C^{++} language programming. Equation (5) given above can be solved for oscillation period, with some simplifying assumptions. However, mathematical solution cannot be applied to this case because the measurement required is not the period of the pendulum, but the time it takes to swing through a certain portion of the swing. Furthermore, a precise value must be obtained in order to compare the small measurement values of micro-

level results. To accommodate these constraints, swing calculations were made using very small increments $(10^{-9} \text{ second increments})$.

The simulation model was based on the local acceleration at each point, incremented by a short time duration. At each calculation point, the acceleration due to gravity was calculated, then the velocity vector was updated accordingly. This calculation was performed at each 10^{-9} second increment. The equations used for the calculation are described above, by Equations (1) and (2).

Simulation Results

The plot shown in Figure 6 is an ideal test result, obtained through a computer simulation. If the system was setup perfectly with all dimensions and angles set to the exact specifications, above curve can be obtained. However, in the real-world case, the system setup contains discrepancies in dimensions.



Figure 6: Plot Of Applied Impulse Vs. Measured Delta Time

One major source of dimensional error in setting up the system is the initial release location. Spacing between the sensors may not be exact, but is consistent due to the fact that the sensor stand is made of a single piece of metal. While not perfectly spaced, the actual sensor distance can be accurately measured and compensated. The release mechanism, however, needs to be able to adjust the location for testing purposes. As such, it is quite difficult to match the release distance exactly. When tests are performed, this uncertainty in the distance value generates discrepancies in the data, resulting in an offset from the simulated values. Because the generic formulation used for calculating the impulse is not linear, a new trend-line equation must be formulated for each test case.

This does make the formulation more difficult. However, the difficulty can be somewhat mitigated by



Figure 7: Swing Time Difference (Free-Swing Time - Impulse Applied Measured Time) Plot Per

Release Point

the fact that the discrepancy in distance is in one direction. In other words, the distance discrepancy only needs to be considered in positive direction (increase in distance from ideal) and not in the negative direction (decrease in release distance). The ideal release distance is exactly equal to the location of the second sensor gate. If any kind of opposing force such as friction exists, the pendulum would not reach the second sensor due to the dissipated energy. To ensure the triggering 'wing' to reach the second sensor gate, the release distance actually has to be increased from the ideal distance (the minimum distance). Figure 7 shows the plot of applied impulse vs. measured time curves for each initial displacement values.

In order to determine the initial offset, it is better to match it to the simulation data than making actual measurements. Figure 8 represents the matching process of the time measurement obtained by the first control swing and its initial distance offset. Once the initial physical displacement offset is calculated from Figure 8, an appropriate curve to be used in Figure 7 can be identified.



Figure 8: Matching Of Free-Swing Time And Initial Displacement Offset

THEORY VERIFICATION BY TEST

A prototype thrust stand has been developed in order to verify the theory and the results of the simulation. The swing time of a control swing, without the thruster firing, is measured, followed by a measurement of swing time of the thruster swing, with the thruster firing, and the two measured times are compared to obtain the time decrease. This time difference can be applied to formula obtained from simulation to calculate the applied minimum impulse bit.

Verification Of Proposed Method

A known offset must be used in verifying the proposed measurement stand. Since thrusters can have a varying output, and performance of the thrusters is the subject to be measured, a forced distance offset was used instead to verify the system. Figure 9 depicts the offset setup used for the test.



Figure 9: Placement Of Spacer In Release Mechanism

A spacer of known thickness $(10\mu m)$ is placed between the electromagnet and the aluminum structure to reduce the initial angle. In order to calculate an equivalent increase(decrease) in energy due to the spacer, the thickness of the spacer is converted to vertical displacement distance. This can be done by calculating the vertical displacement and deriving and equivalent increase(decrease) in velocity by equating the potential and kinetic energy.

Each spacer has the effect of an added impulse bit with a magnitude of approximately 4.55mNs. When the spacer is removed, the travel distance of the pendulum is increased by $\approx 10 \mu m$, which increases the initial velocity of the pendulum as it reaches the first sensor, effectively simulating an addition of an impulse. In other words, as each spacer is removed, it has the effect of adding approximately 4.55mNs impulse to the system. The result of the tests using a single spacer is given in the following section

Verification Of Simulation Data

Data obtained using a vacuum chamber has been collected in order to verify the theory presented in this paper and the data generated by the simulation. This test was geared specifically for the measurement system used for this paper. For different thrusters, a different characterizing step may be required due to the changes in geometry and mass. However, once a characterization is completed, the setup does not require additional calibrations before each test. A trend data can be generated for each case, and used for subsequent tests without having to run simulations or calibrations every time.

As mentioned previously, installing a spacer will result in a simulated impulse of 4.55mNs. Using the measurement system and the methodology described previously, test data was consolidated into a single point value, and then converted into an impulse value. The test result has produced a measured impulse value of 4.59mNs. A statistically combined data is shown in Figure 10.

Figures 10 show matching of the consolidated test data using spacer with the formulation generated. In particular, it shows a statistically combined point with deviation shown as error bars. Note that it closely matches the interpolated formulation line. Figure 11 shows the test result using multiple spacers. Each circular point on the plot represents over 100 test points. In both figures, the top and the bottom curves represent formulated delta time vs. applied impulse curves for each initial position offset. An interpolation of the formula is required for data that fall between the lines. The Test Trendline represent the interpolation line obtained using the swing time of the control swing. As can be seen from the figures, the formulation and actual test data show a satisfactory match. Error between the theoretical and experimental values are approximately 1%.



Figure 10: Example Matching Of Test Result With Formulation. Test Result = 4.59mNs

The result shown verifies that the proposed thruster performance measurement stand can be used to measure small impulses. The error bars have a value of \pm 56µs. This error value represents 2 x standard deviation of the data, and a more detailed description is given in following sections.



Figure 11: Data Using 1, 2, And 3 Spacers, Corresponding To 4.55mNs, 6.59mNs, 7.89mNs Respectively

Application Of Measurement System Using A Cold Gas Thruster

Characterization of the measurement system is done by a computer simulation, and has been verified by experimental data. To demonstrate an example of the application, the performance of a real thruster has been measured. Because the laboratory does not currently own an electric propulsion system, a small cold gas thruster has been developed in order to obtain application data.

The cold gas thruster has been tested using the final model of the measurement system. Figure 12 shows a picture of the test setup. The uncertainty, or standard deviation, of the time measured by the system is 14µNs. The standard deviation, for the cold gas thruster on the other hand, is 118µNs. An increase in the discrepancy is inherent to the thruster itself, and can be attributed to many characteristics of the thruster such as the flow momentum change of the propellant, vibration induced by 'slamming' valve seat, inconsistencies in valve actuation, etc. Representative graph of 50 data points is plotted on Figure 13. The data points are collapsed statistically into a single point, with $2 \times \sigma$ error bars, so that it can easily plotted to show the data correlation with the theoretical formulation generated through simulations.



Figure 12: Picture Of A Cold Gas Thruster Setup On The Measurement System



Figure 13: Matching Of Measured Thruster Swing Time Difference To Formulation

The theoretical output of the cold gas thruster, taking into account the geometrical and physical characteristics of the valve and the nozzle, was calculated to be 1.816×10^{-2} N. The valve actuation speed is documented to be approx. 5ms for each opening and closing. Actual firing of the thruster was programmed to continue for 20ms. Accordingly, the minimum impulse delivered by the thruster is 372μ Ns. Impulse value calculated using formulation is 367μ Ns. This shows an excellent match between the theoretical value and an actual test value. However, due to a large standard deviation, the impulse range should be expanded to cover the uncertainty area.

ANALYSIS OF RESULT

Uncertainty Analysis Between Actual And Simulated Data

A formulation curve cannot be generated for every test case. Equations relating each data curve can be devised, but it would introduce unnecessary complications with little gain. The method used in this paper was to tabulate the trend data, then use interpolated values for test data that falls between two formulated curves. For the calculated impulse of $4 \sim 5$ mNs range, the error was about 1% when comparing average values. However, as described below, data generated by the measurement system has a standard deviation of 14µs. This factor needs to be considered.

Data has shown that the uncertainty in the measurement system output is due to random error, and follows a normal distribution. $\pm 2\sigma$ will include over 95% of data. All data collected will have this uncertainty value of 2σ = $\pm 28\mu$ s attached due to the random error. In the case of test data verification, however, the delta time value has $\pm 56\mu$ s uncertainty because two measured time values are used to obtain this value. This uncertainty value must be analyzed in order to characterize its effect on the actual calculated impulse result.

In the case of this paper, the test range for verification was between 4 and 5mNs of impulse. For this case, $\pm 56\mu$ s random error results in approximately 3% of error. Including the 1% error from data matching, the overall error for the formulation was approx. 4%, in respect to the test data.

Another source of error is in the interpolated data. Unless a simulation is performed to extract a formulation that exactly matches the control swing time conditions, error associated with interpolated value cannot be avoided. In the case of the test data matching with the formulation given, however, the interpolated error is included in 1% discrepancy between the test data and the formulation.

In summary, quantifying of uncertainty value will vary depending on the impulse range of the subject thruster, due to the relatively large standard deviation associated with the measurement stand. For testing of thrusters that generate lower impulse, more improvements to the measurement system must be made to be able to accurately characterize the subject thruster. For the case of test data obtained for system verification purposes, the total error was less than 4%.

In case of the cold gas thruster, the impulse data average value shows an excellent match with the formulation value: $5\mu Ns$, a mere $\sim 1.5\%$. However,

when the standard deviation of the data is considered, the results quality is drastically reduced. The standard deviation of 118µs in measured swing time is quite large. This translates into approximately ± 128 µNs discrepancy in the calculated impulse value. This means that the thruster output is quoted not as a single value, but has to be lists as a range of values: applied impulse = 239µNs to 495µNs.

CONCLUSION

A few thrust stands have been developed in order to characterize and verify the performance of microthrusters. However, these precision measurement stands require rigorous calibration procedures. This paper presents a different measurement stand that minimizes the required calibration. In addition, the method suggested in this paper measures the applied impulse directly, which is more advantageous and accurate when dealing with bang-bang type thrusters.

The impulse applied is calculated by comparing the swing time of two separate swings. By measuring the time decrease from the control swing to the thruster swing, many sources of error can be eliminated by the virtue of being included in the system. The measurement of relative value requires much less calibration steps than measuring absolute quantities. By measuring the time differences, the applied impulse can be calculated using tabulated values generated through simulation. The tabulated value accounts for the initial distance measurement error, and interpolated values within the formulation can be used to calculate the applied impulse value by making swing time measurements of both a free-swing and the thruster swing.

The computer simulation validates the measurement theory. The actual hardware for measuring the impulse, and at the same time validating the theory and analytical model, has been developed and tested. A known fixed input, a spacer, was used to match the actual test data with the theoretical formulation values. A satisfactory match between the two types of data was found with an associated error of 4%, which verifies that the suggested method can be applied for performance characterization of micro-thrusters. The obtained data and results show a clear correlation between the simulation results based on theory, and actual hardware.

In addition, a micro cold gas thruster has been developed to validate the formulation. A close correlation was shown between the impulse value calculated from the measured data, and the theoretical impulse value. However, due to the nature of the thruster and its operational limitations, a large standard deviation in the collected data could not be avoided. Although the data scatter is wider than was originally expected, the collected data still shows a good match when compared to the formulation data obtained through computer simulations. The testing and analysis validates that the proposed method can be used to actually test micro-thrusters in order to measure the minimum impulse bit produced. The proposed measurement system design offers a method for measuring applied impulse directly, and with minimum required calibration.

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