<u>Internship Report:</u>

Design of Thrust Balance for µNs Impulse Bit Measurement

I) Introduction

a) Problematic

The Laboratório de Sistemas Espaciais (LaSE, Laboratory for Space Systems) in the Universidade de Brasilia (UnB) is developing a Pulsed Plasma Thruster (PPT). In order to better understand the performance characteristics of the PPT and of the future Thrusters that will be developed in the lab, the research team needed to be able to measure the thrust of the propulsion systems being developed. The subject of my internship was therefore to develop a system capable of measuring the thrust and impulse bit of the PPT being developed.

b) Pulsed Plasma Thruster

A PPT is an electric propulsion system mainly suited for nano and micro satellites due to its simple design and low thrust.

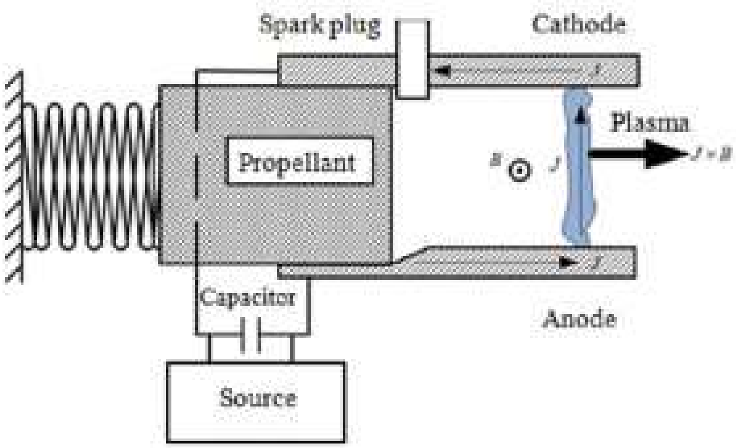


Figure 1: PPT Schematic Layout (Manente, 2023)

The PPT works by ablating and ionizing a propellant (generally PTFE) with an electric arc generated by a spark plug. This plasma is the accelerated using an electric field to create thrust. The creation of plasma is controlled by the electric arc that pulses at a given frequency. Therefore, the impulse provided by the system can be easily controlled by controlling the number of discharge arcs. The impulse created by a single discharge arc is the minimum impulse the PPT can provide it is called an impulse bit.

c) Impulse Bit

The impulse of a thruster is the integral of the thrust it produces over time: $\boldsymbol{J} = \int \boldsymbol{T}\, \boldsymbol{dt}$, with $\boldsymbol{T}$ the thrust in N and $\boldsymbol{J}$ the impulse in Ns.

This metric is used in propulsion to calculate the speed differential Δv (m/s) of a spacecraft of mass M (kg) due to the action of a thruster: $\Delta \boldsymbol{v} = \boldsymbol{M} * \boldsymbol{J}$

The duration of a PPT pulse being extremely short and small PPTs like the one developed in the LaSE having small thrust, the impulse bit is in the 10 to 100µNs range.

The most precise method to measure an impulse bit is to calibrate the response of the thrust balance. For this, a known impulse is applied to the balance and the maximum deflection of the resulting oscillation is measured. However, method necessitates the use of a very precise load cell and data acquisition system to precisely measure short low thrust impulses that would be applied on the balance. These sensors are very rare and expensive, making them unviable for this project. To calibrate the thrust balance, the analytical formula of the impulse bit was therefore used (Koizumi, 2004) :

$$\boldsymbol{J} = \frac{\boldsymbol{A} * \boldsymbol{I} * \boldsymbol{\omega_0}}{\boldsymbol{L_s} * \boldsymbol{L_T}}$$

- $\boldsymbol{A}$**:** the maximum deflection (m)
- $\boldsymbol{I}$**:** the moment of inertia of the complete system (kg·m2)
- $\boldsymbol{\omega_0}$**:** the natural pulsation of the system (rad/s)
- $\boldsymbol{L_S}$; $\boldsymbol{L_T}$**:** the distance between the pivot axis and respectively the sensor and the thruster (m)

d) Thrust Balance Principle

A Thrust Balance is a mechanical system used to measure thrust. Small electric propulsion thrusters such as the ones designed in LaSE have thrust ranging from 10µN to 1mN. To measure this level of thrust, special, extremely high sensitivity balances need to be developed. Here is an overview of the basic designs found in literature for thrust balances:

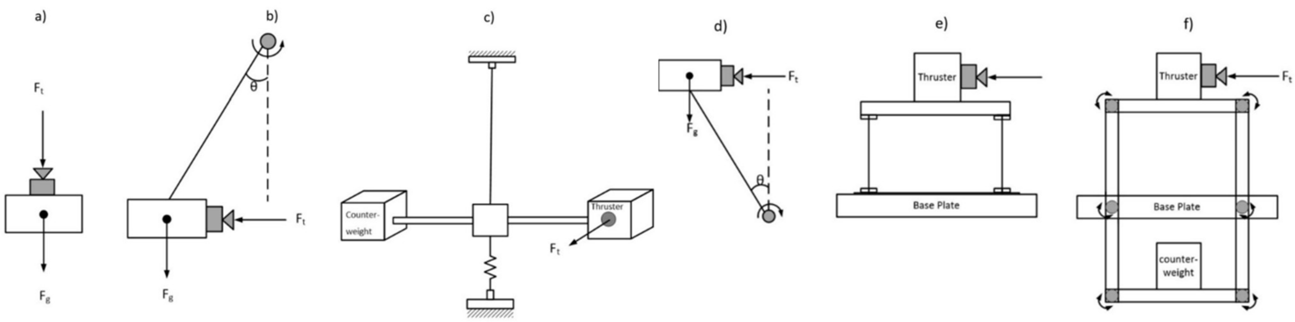


Figure 2: Types of Thrust Balances (Neumann, 2021)

a) Vertical Weight Cell: a very simple design with the thruster directly placed on a weight cell measuring the thrust in addition to the thruster weight. This design is not suitable for electric propulsion systems which have very low thrust to weight ratios.

b) Basic Pendulum: a simple design where the deflection caused by the thrust is measured. However, it offers low sensitivity due to the effect of gravity.

c) Torsional Pendulum: Same principle as the basic pendulum but placed horizontally to avoid the effect of gravity. This design requires a frictionless pivot to function which can be hard to acquire.

Figure 3 : Flexural pivots used in torsional pendulums

d) Inverted Pendulum: Same principle as the basic pendulum but placed inverted to amplify sensitivity. However, this design necessitates and active control loop measurement method which is complex to implement.

e) Dual Inverted Pendulum: Same principle as the inverted pendulum but more stable.

f) Counterbalanced Dual Inverted Pendulum: Very stable inverted pendulum that doesn't require an active control loop but at the expense of a complex design with many moving parts. The sensitivity is tunable with the addition of counterweights.

II) Design of LASE Thrust Balance

a) Thrust Balance Type

The literature agrees that the torsional pendulum is the best solution to measure low impulse bits. However, the flexural pivots necessary for the design of such a system were not available in the time frame of my internship. Therefore, it was decided that a simple pendulum would be designed to measure thrust in the LaSE. This design was chosen for its mechanical simplicity compared to a counterbalanced dual inverted pendulum and because it does not require an active control loop which is both expensive and time consuming to implement and calibrate.

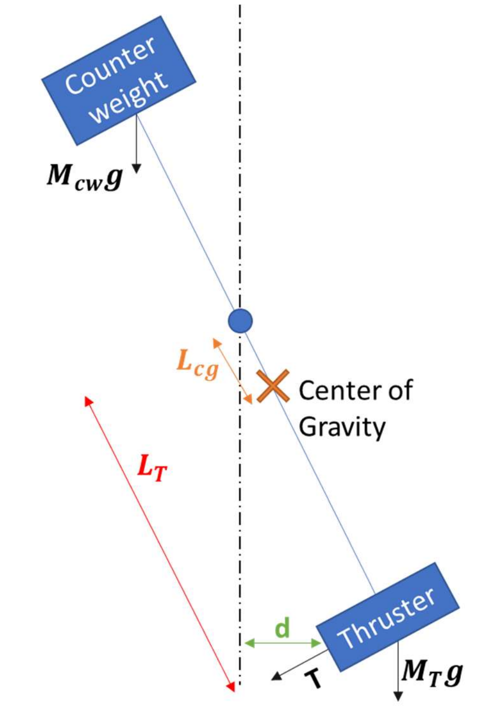


Figure 4: Design principle of the LaSE Thrust Balance

The inherent weakness of the inverted pendulum is that gravity exerts a force that decreases the sensitivity of the thrust balance. Ideally, a thrust balance would have the highest deflection possible for the applied thrust but in a pendulum where the centre of mass is far from the axis of rotation, that is not the case. To counteract the effect of gravity, a counterweight can be added to the system to bring the centre of gravity as close to the centre of rotation as possible.

In that case, we can calculate the deflection $\boldsymbol{d}$ (m) of the system under continuous thrust (= static system) as being:

$$\boldsymbol{d} = \frac{\boldsymbol{T} * \boldsymbol{L_T}^2}{(\boldsymbol{M_T} + \boldsymbol{M_{cw}})\boldsymbol{g} * \boldsymbol{L_{cg}}}$$

- $\boldsymbol{T}$: the applied thrust (N)
- $\boldsymbol{L_{cg}}$; $\boldsymbol{L_T}$: The normal distance (m) between the pivot and respectively the centre of gravity and thrust application point
- $\boldsymbol{g}$: The acceleration of gravity (m/s^2)
- $\boldsymbol{M_T}; \boldsymbol{M_{cw}}$: The masses (kg) respectively of the thruster and the counterweight (neglecting the others masses)

We can calculate the static sensitivity $\boldsymbol{S}$ (m/N) of the system as being: $\boldsymbol{S} = \frac{\boldsymbol{d}}{\boldsymbol{T}} = \frac{\boldsymbol{L_T}^2}{(\boldsymbol{M_T}+\boldsymbol{M_{cw}})\boldsymbol{g}*\boldsymbol{L_{cg}}}$

Therefore, to maximize sensitivity, the distance between the thruster and the pivot needs to be maximized. On the other hand, the total weight of the balance and the distance of its centre of gravity to the pivot need to be minimized. However, the centre of gravity must stay under the pivot for the system to be stable. To tune the sensibility of the balance to different thruster mass and thrusts, the counterweight position will be adjustable which will in turn adjust the position of the centre of gravity of the balance relative to the pivot axis.

b) Technological Choices

a) Pivots

The pivots in a thrust balance require virtually no friction and hysteresis. For these reasons, traditional ball bearings cannot be used as even the most precise ball bearings have friction. Therefore, the ideal solution is to use the elasticity of a material with very low damping as a pivot. Stainless Steel blades can be used as they will provide a corrosion free elastic behaviour. A 0,1mm thick, 20mm wide blade was designed to act as a pivot as it had previously been tested for use in a counterbalanced dual inverted pendulum (Kokal, 2023). These blades were dimensioned to hold up to 10 kg of mass, the pendulum weighing 8kg with the counterweights installed, it can hold a 2kg thruster.

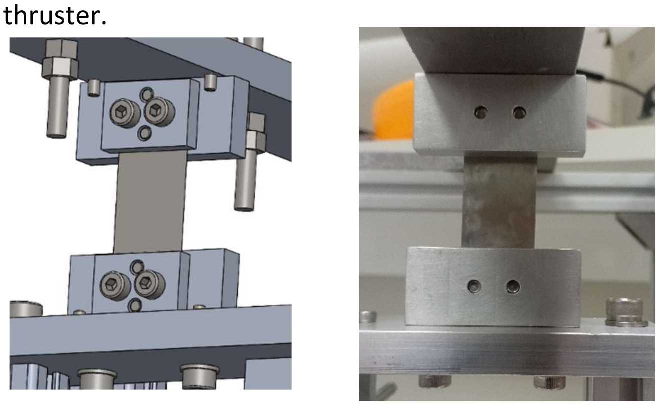


Figure 5 : CAD and picture of the pivot blades

b) Displacement Sensor

The displacement of the thrust balance under thruster load will be around 10 to 100 µm. To have an accurate measurement, the error of measurement of the sensor was fixed to 5% or 0,5 µm. Furthermore, for the impulse bit measurement, the balance will be in motion; to capture this dynamic signal, the sensor must have a high enough sampling frequency. Finally, the sensor must not enter in contact with the thrust balance as the resulting friction would falsify the measurement. Two solutions have been widely used to measure thrust balance displacements: optical sensors (Anselmo, 2019) and LVDT sensors (Kokal, 2023). Optical sensors are a common and reliable way to measure displacement, however, for the range and precision required for this project, they are hard to procure and expensive. The TE Connectivity MHR-050 LVDT along with the Metrolog SD20 Digital Usb LVDT signal conditioner were chosen because they fit the technical requirements, the budget and the acquisition time frame for the project.

The sensor has a 5mm range with a 0,15% linearity (0,75 µm but it is in reality be significantly less due to the very small measurement range used). The signal conditioner has a 24-bit (>1nm) resolution. The limiting factor of accuracy in the measurement is not the precision of the sensing equipment but the electrical and mechanical noise of the system.

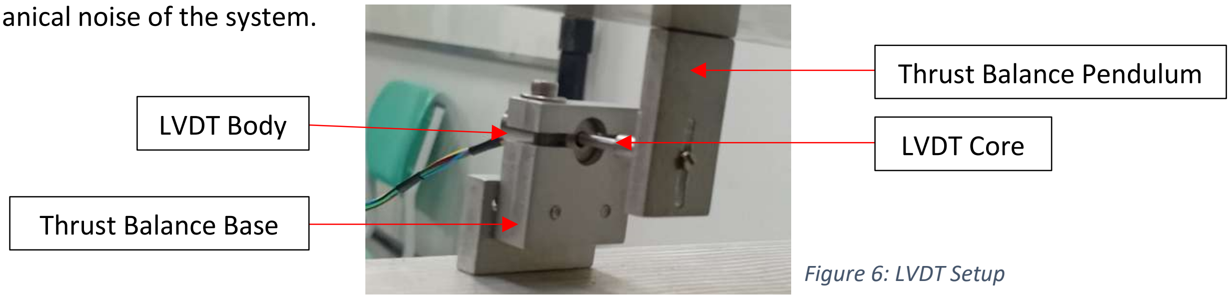


Figure 6: LVDT Setup

An LVDT or linear variable differential transformer is a sensor formed of a body with a coil and of a cylindrical core that moves freely within a hole in the body. The movement of the core within the body creates variations in induced voltage of the coils which can be correlated to a displacement. In practice, the input and output signals of the factory calibrated LVDT are managed by the usb signal conditioner and outputted as digital distance and time data for which a python script was created to live plot the displacement.

c) Magnetic Damper

The oscillations of the system being virtually undamped, an external damping mechanism has to be implemented to return the system to its initial motionless state. However, during the Ibit measurement, the system has to be turned off. An easy implementation of a disengageable brake is an eddy current damper (Kokal, 2023) formed by a copper plate moving in between to electromagnets creating a braking force on the system. In figure 7, we can see that the eddy current damping significantly increases the amplitude damping rate compared to the free oscillating pendulum.

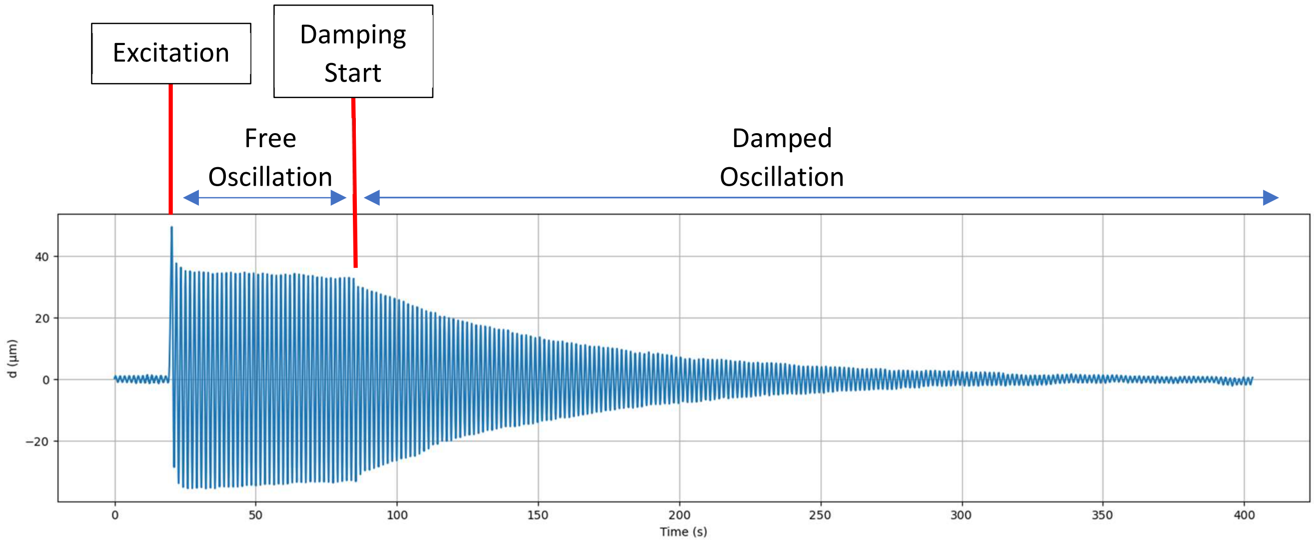


Figure 7: Dampened pendulum oscillations

c) Thrust Balance Design and Assembly

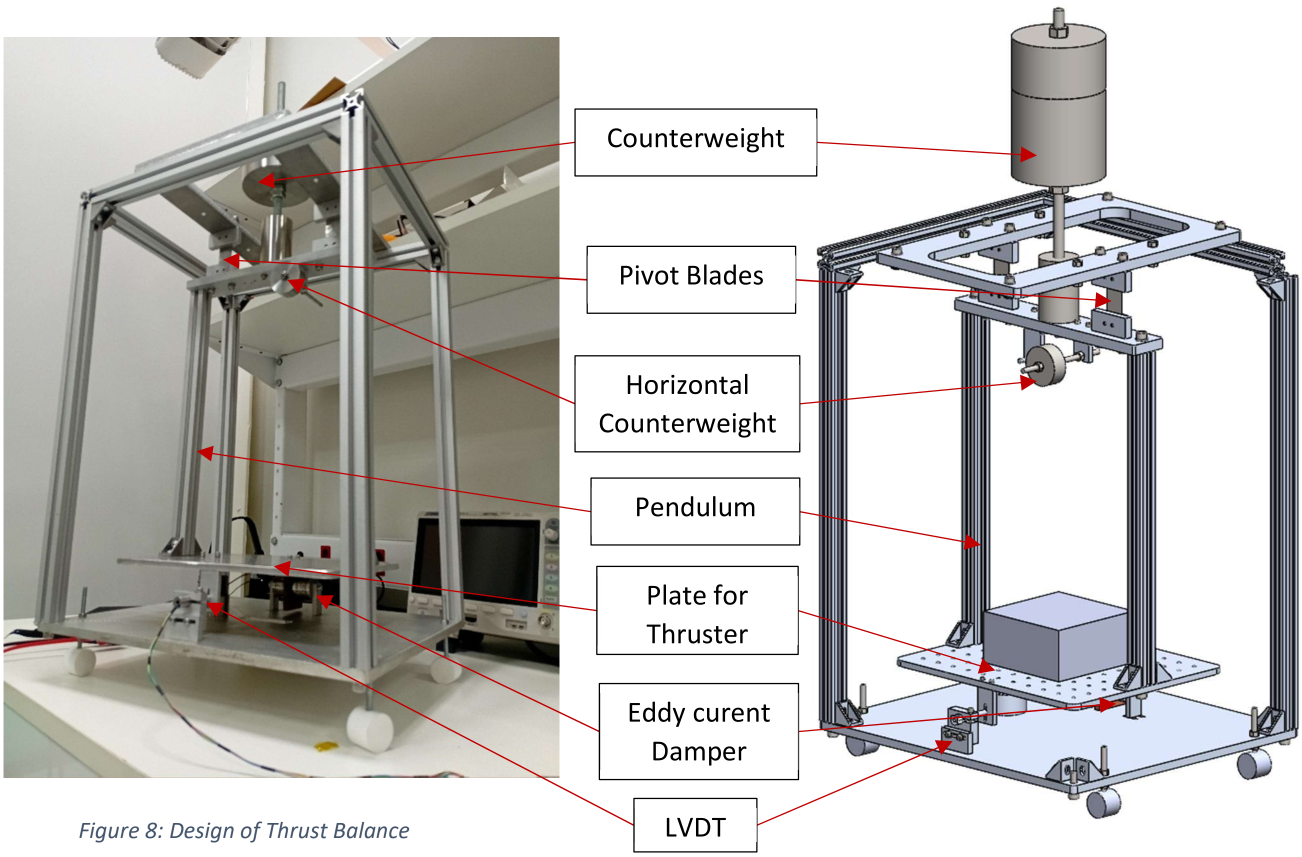


Figure 8: Design of Thrust Balance

III) Calibration

All the calibration process must be performed without moving the counterweight or the thruster position as they affect the system behaviour. All the following calculations take into account that displacement (and therefore angles) are small, appropriate approximations are made.

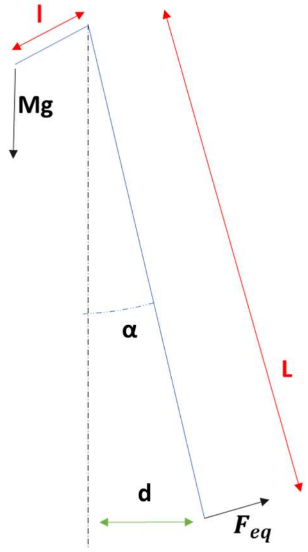


Figure 9: Rigidity Calculation

a) Rigidity

To find the angular rigidity of the system, a weight **M** (kg) is hanged at a known distance $\boldsymbol{l}$ (m) from the pivot axis. Knowing the distance of the thruster from the pivot axis $\boldsymbol{L}$ (m) and the acceleration of gravity $\boldsymbol{g}$ (m/s^2), we can calculate $\boldsymbol{F_{eq}}$ (N) the thrust provided by the thruster that generates an equivalent moment to the hanged mass at the pivot axis: $\boldsymbol{F_{eq} = Mg\frac{l}{L}}$

We can then calculate the angular rigidity of the system $\boldsymbol{k_\theta}$ (Nm/rad) as:

$$\boldsymbol{k_\theta = \frac{F_{eq} * L}{\alpha} = \frac{Mgl}{\frac{d}{L}} = \frac{MgLl}{d}}$$

For more precision, we plot multiple points ($\boldsymbol{\alpha_i}$; $\boldsymbol{F_{eq\,i} * L}$), the slope of the resulting curve is $\boldsymbol{k_\theta}$. The masses and equivalent thrust used for calibration are shown in Annex 1. The calibration masses were made using sewing string and aluminium foil which was weighed with a 0.1mg error.

By the same method of hanging weights, we can calculate the linear rigidity $\boldsymbol{k}$ (N/m) of the system such that: $\boldsymbol{k = F_{eq}/d}$; with $\boldsymbol{d}$ the displacement (see figure 8) and $\boldsymbol{F_{eq}}$ the equivalent thruster force to the applied mass. This enables the measurement of continuous thrust (static force).

A rod with grooves has been designed to accurately place the calibration weights on the system. A 0.52mm offset has been measured to the pivot axis. Therefore, the grooves are respectively placed at a horizontal distance of 5.52, 10.52 and 15.52mm $\boldsymbol{(l)}$ from the pivot axis.

The plot below shows the displacement of the pendulum under a static force. The oscillations of the pendulum being hard to damp, the static deflection is measured from the average position shift.

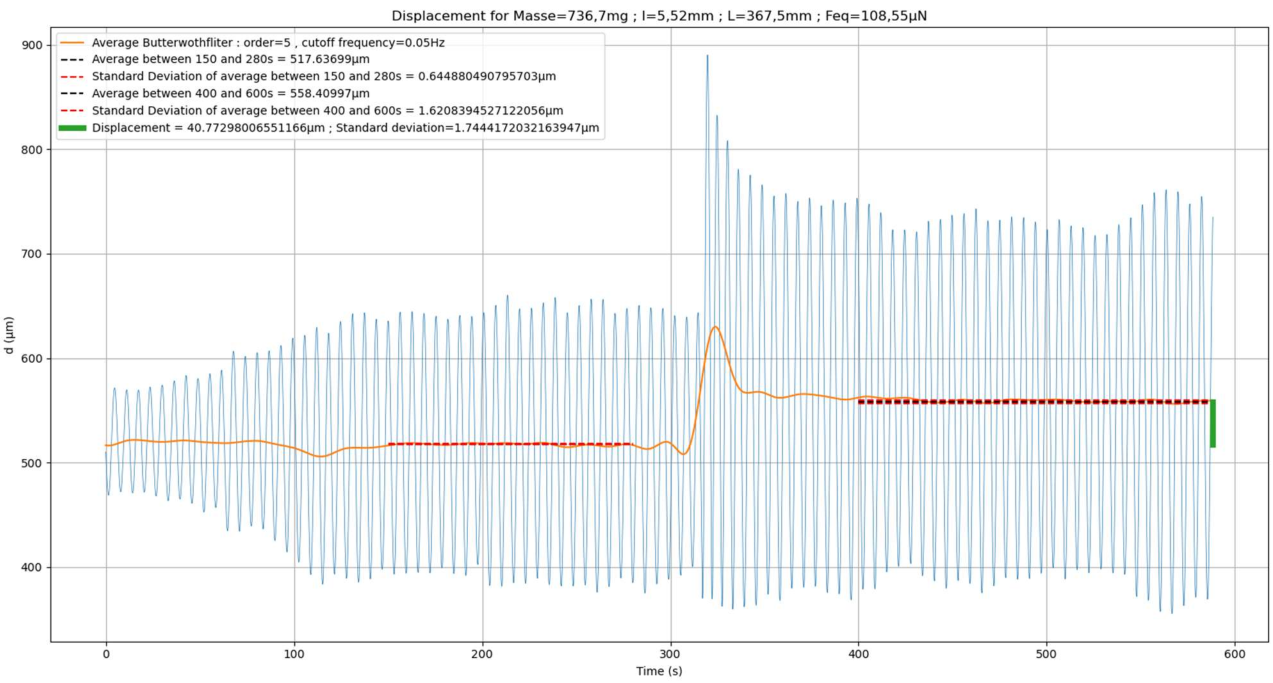


Figure 10: Deflection of pendulum under static load

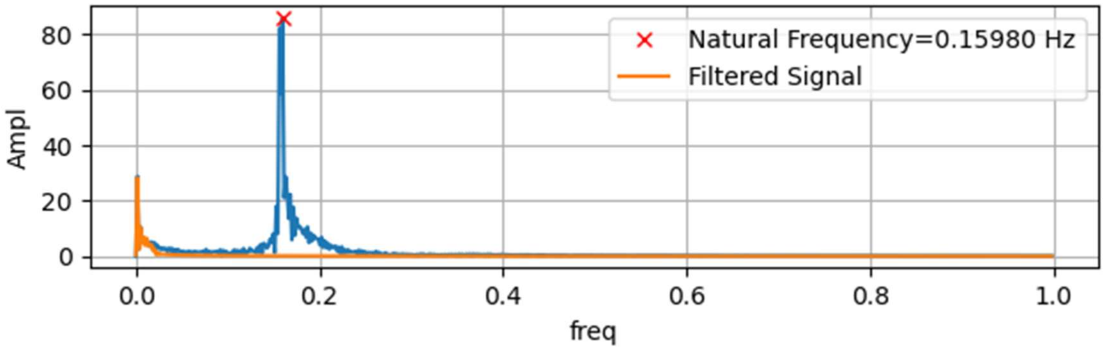


Figure 11: Filtering of Signal in Figure 10 (Order 5 Butterworth filter with cutoff frequency at 0.05Hz)

b) Natural Frequency

The natural frequency of the system can be found by performing a Fourier transform of the displacement over time for the free oscillating pendulum. The system can be seen as a one degree of liberty system with the single motion being the rotation around the pivot axis. However, since blades are used instead of pivots, other movements are possible.

A second mode of the system is a rotation around the vertical axis. This secondary mode is around 3.5Hz for the empty pendulum while the primary mode $\boldsymbol{f_n}$(Hz) is around 0.6Hz. Therefore, the secondary mode can be filtered out with a digital filter. Furthermore, the secondary mode necessitates an off-axis solicitation to be excited which will not happen with under thruster loads. And finally, this mode naturally heavily dampened and disappears after around 5 periods.

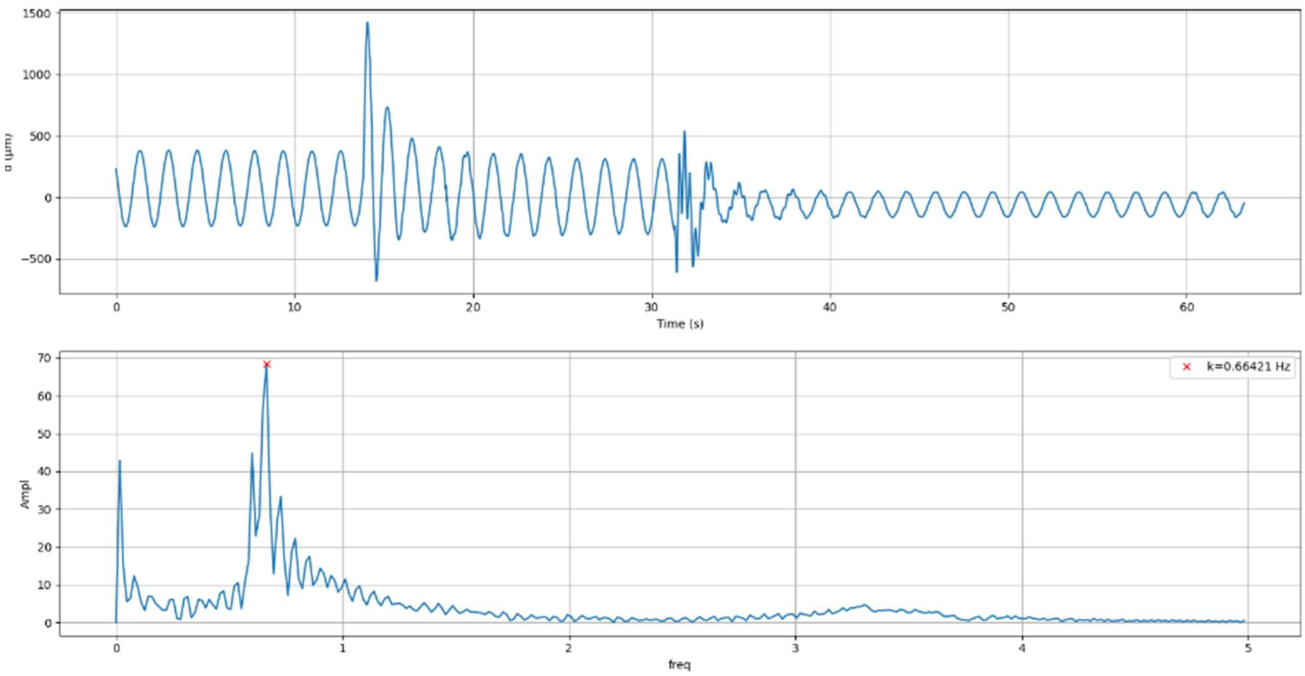


Figure 12: Time and frequency based plots of pendulum oscillation with secondary mode

Figure 10 is an example of a heavily disturbed acquisition created by hitting the frame of the thrust balance around 15s and 32s. The secondary oscillation swiftly disappears and the Fourier transform of the signal shows that the primary mode in the set configuration is $\boldsymbol{f_n = 0.66}$Hz and the secondary mode has a smaller amplitude and is around 3.5Hz. Due to the geometry of the pivot, the secondary mode is less rigid if the balance is at its rest state therefore, it is more likely to be excited when the amplitude of the 1rst mode is low (<10µm peak to peak).

The following graph shows the system free oscillation with no perturbation and a digital filter with a cutoff frequency at 2Hz.

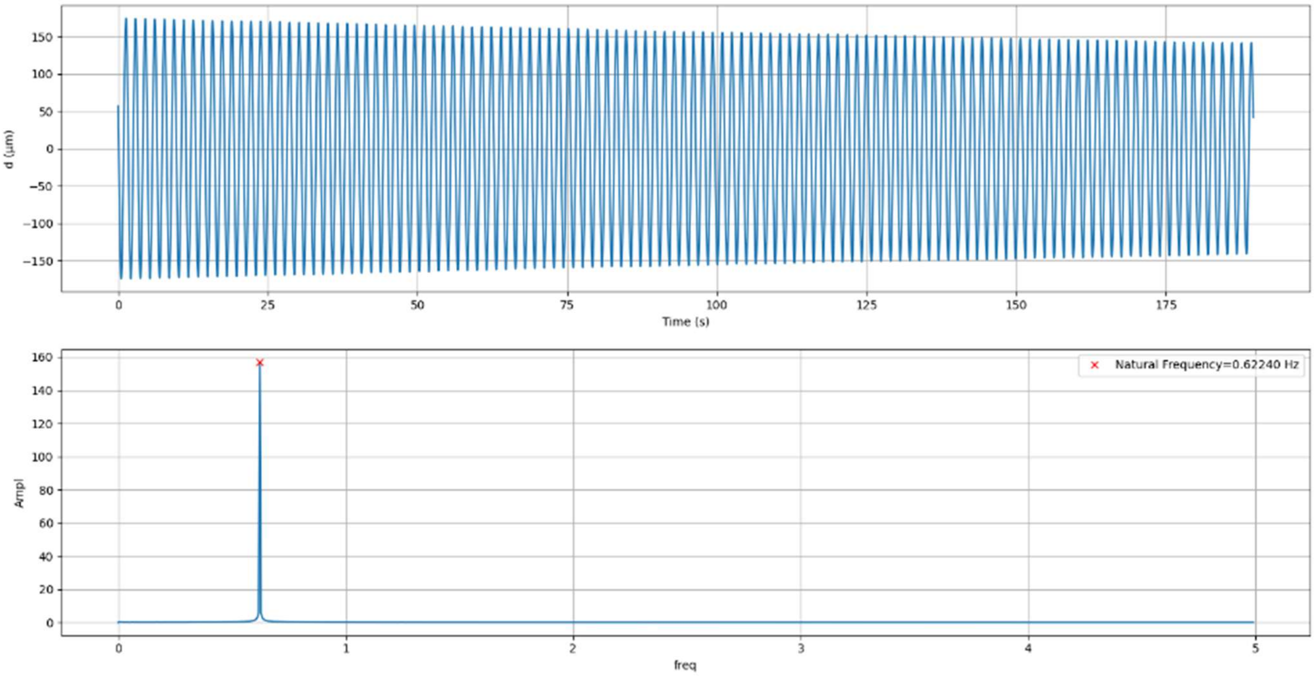


Figure 13: Time and frequency based plots of pendulum oscillation without secondary mode

c) Moment of Inertia

The moment of inertia $\boldsymbol{I}$ (kg.m^2) of the system can be calculated by: $\boldsymbol{\omega_0} = \sqrt{\frac{\boldsymbol{k_\theta}}{\boldsymbol{I}}} \Rightarrow \boldsymbol{I} = \frac{\boldsymbol{k_\theta}}{(2\pi f_n)^2}$

IV) Initial Testing and Feedback

a) Calibration

As shown in figure 13, the natural frequency of the movement of the pendulum can be precisely calculated from the Fourier transform of the signal.

The rigidity of the balance wasn't measured during the timeframe of this internship. However, it was shown in Figure 10 that an appropriately large deflection with minimal uncertainty can be obtained. This implies having to set the counterweight at a position where the balance is sensitive enough without being too sensible to background vibrations causing noise and imprecisions.

To measure rigidity, a stable deflection must be observed with no drift in the average position of the pendulum. To measure potential average pendulum drift, the damped pendulum movement was measured during 20 minutes. Figure 14 shows that no continuous drift in average in one direction was happening and that the drift in average was negligeable (<0.1 µm standard deviation). Furthermore, this shows that for this configuration (Natural frequency =0.6Hz; Sampling Frequency = 55Hz), a 1000-point average of the signal will give an accurate measurement of the position of the pendulum.

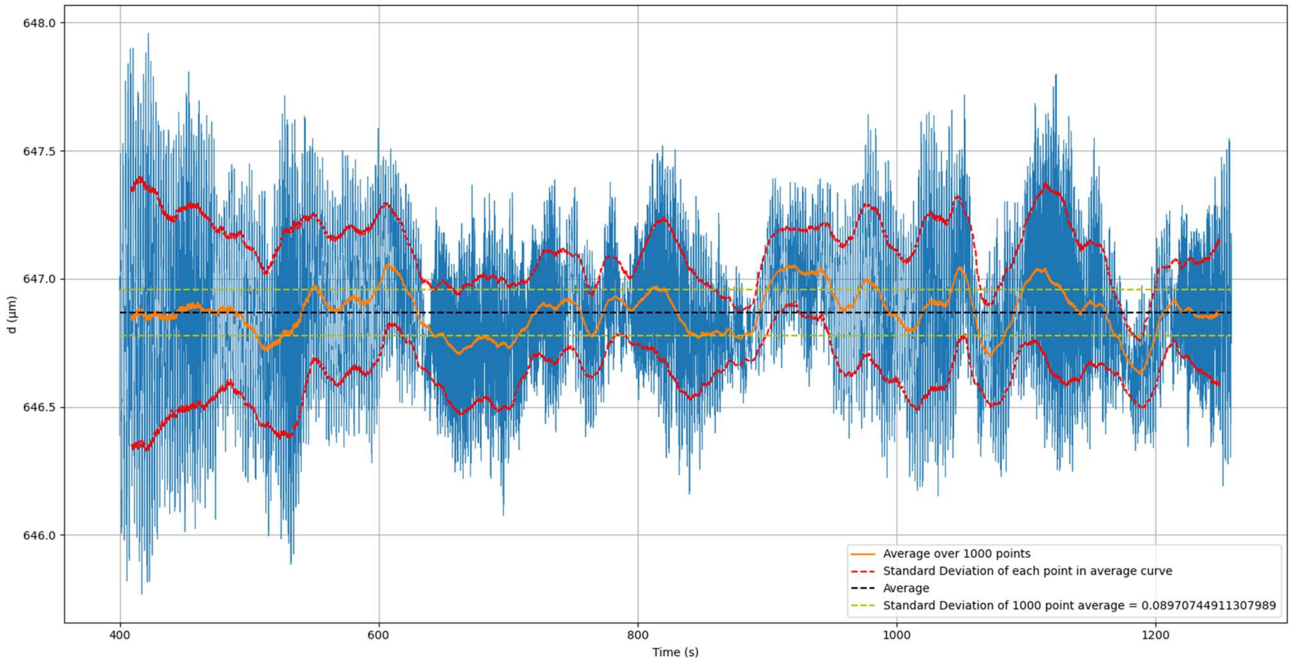


Figure 14: Static drift of average

b) Improvements

a) LVDT Placement

Setting up the LVDT and the horizontal counterweight so that the LVDT core slides into the body without touching it has been a tedious process. To make this process easier, the LVDT core should be held in place with a new design that guarantees that it is in the axis of motion. Furthermore, the body should be held in place with a system allowing 3 axis movement easily and precisely. A micrometre stage could be used for this task.

b) Pivots

The pivot system in the current design uses blades which are difficult to manufacture precisely and that allow transverse movements to happen. A new pivot system has been designed using a knife edge resting on a surface below. This system could induce more friction but at the benefit of are more stable movement. Another benefit of a knife edge pivot is that the pivot axis is fixed in place and easily measurable compared to the blade pivots where the pivot axis is only estimated to be at the middle of the blades.

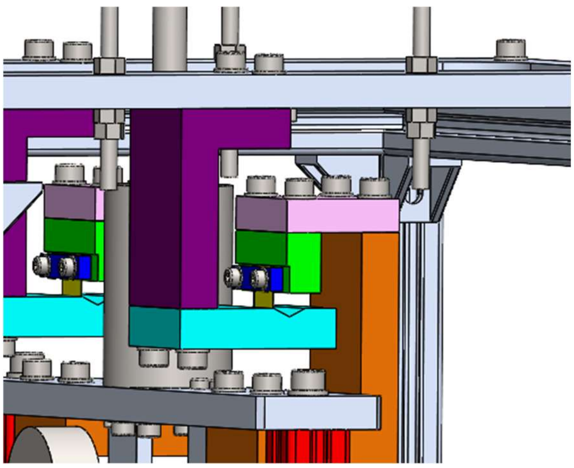


Figure 15: New Pivot Design

V) Bibliography

Anselmo, I. (2019). Torsional thrust balance for electric propulsion application with electrostatic calibration device. *Measurement Science and Technology*.

Koizumi, K. A. (2004). Development of thrust stand for low impulse measurement from microthrusters. *Review of Scientific Instruments*.

Kokal, S. C. (2023). *Development and tests of a thrust stand with an in-situ null position adjustement and calibration method for low power plasma thrusters.* Results in Engineering.

Manente, M. (2023). *Next Generation CubeSats and SmallSats.* Elsevier.

Neumann, S. S. (2021, November 23). Thrust measurement and thrust balance development at DLR's electric propulsion test facility. *EPJ Techniques and Instrumentation*.

VI) Table of Illustrations

Table of Contents

VII) Annexes

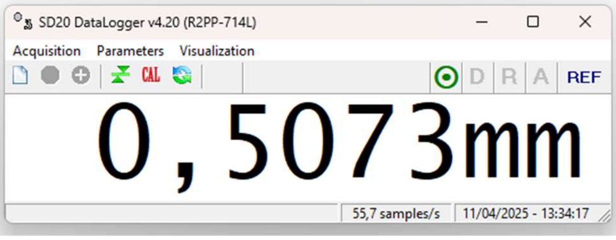
a) Annex 1: Masses that were made for the rigidity calibration and the equivalent Thruster Force

		Masses that were made			
L (m)	0,3675	l (m)	0,00552	0,01052	0,01552
N°	Mcal(mg)	Mcal (kg)	Feq (uN)		
1	66	**0,000066**	9,725113	18,53409	
2	109,1	**0,000109**		30,63742	
3	181,3	**0,000181**		50,91259	75,11059
4	736,7	**0,000737**	108,5529	206,8798	
5	1201,5	**0,001202**		337,4047	497,7682
6	2679	**0,002679**		752,3157	1109,88

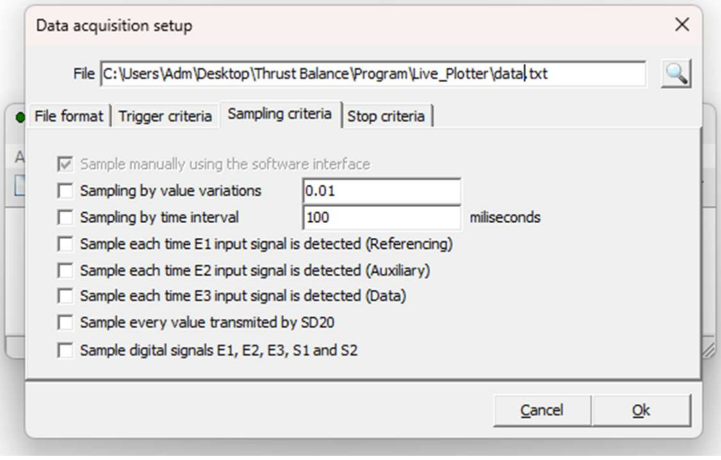
b) Annex 2: Metrolog SD20 Datalogger Tutorial

a) Plug Sd20 usb connector in computer

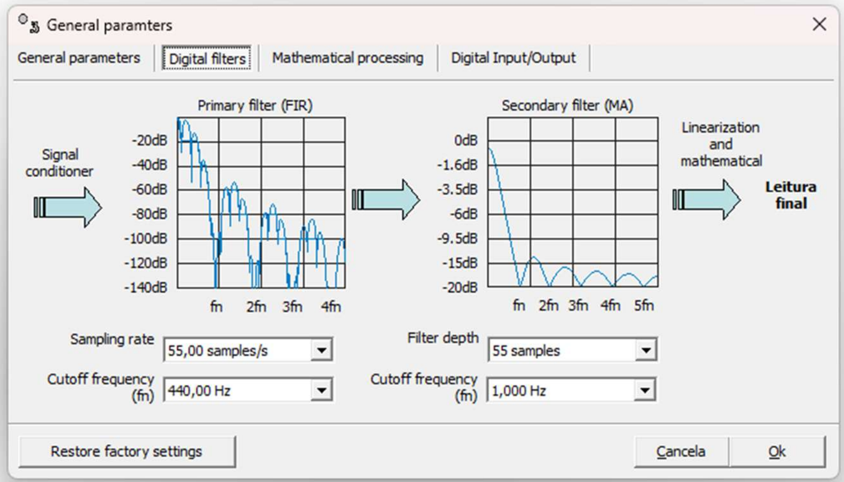
b) Open SD20 Datalogger program



c) In Acquisition: select filepath and "sample every value transmitted by sd20", press ok



d) In SD20 Parameters / Digital Filters: Select Sampling Rate and Cutoff Frequency



c) Programs for Thrust Balance Data Analysis

a) Live Plotter

This script live plots the SD20 signal.

1. Input “filename” the filename that is being written by the SD20 Datalogger
2. Input “windowsize” the width (in seconds) of the display window
3. Input “Ns” the number of samples for initial average and calculation of sampling frequency
4. Launch program and SD20 Datalogger Acquisition
5. Wait for Ns samples to be collected
6. Close liveplot window before stopping the data acquisition in the SD20 Datalogger.

b) Fn Calculation

This script plots the full averaged data, does an fourier transform of the signal and can also filter the signal as in Figure 11 and 13.

1. Input “Filename”, the name of the file to be read
2. Input “filtering” as Boolean: if True the signal will be filtered if False go to step 2
    a. Input “cutofffreq” the cutoff frequency of the filter
    b. Input “order” the order of the filter
3. Input “MaxF” the maximum frequency to display in the FFT plot

c) Find Deflection

This Script Plots the signal, averages it and finds the difference in average between two parts of the average as in Figure 10. This script is to be used to determine deflection of the pendulum caused by a calibration mass. Start acquisition without the calibration mass, wait 2min, add calibration mass, wait two min and stop the acquisition.

The average curve is made by filtering the signal and keeping only the lowest frequencies. The cutoff frequency of the Butterworth filter and its order can be determined with “Fn Calculation” script. If the parameters of the filter aren’t properly set, part of the lower frequency apmplitude may be filtered out. However, this will not affect the measurement, as only the standard deviation is calculated from this. In this case, on the final plot, the calculated average for each part (dotted black line) will be shifted compared to the full average (orange line).

1. Input “Filename”, the name of the file to be read
2. Input “Find_diff=False”
3. Input “cutofffreq” and “order” determined in Fn Calculation
4. Run Script
5. Find the start and end times at which to measure the averages. Input these times as lists in time1 and time2.
6. Input “Find_diff=True”
7. Run Script