TEST AND MEASUREMENT SYSTEM FOR A MICROTHRUSTER SYSTEM OF A NANOSATELLITE

Year 2013/2014
ABSTRACT

Miniaturized satellites which are fitted with microthrusters are gaining in popularity over the past few years. This is because of their simplified designs, small sizes and low weights that effectively reduce their production cost and increase their reliabilities. In order for those satellites to perform complex missions that require precise maneuverability, there is a need to develop a measurement system to measure the performance of the microthrusters. In this report, a torsional thrust stand with a magnetic damping system is designed and calibrated using an electrostatic calibrator. The calibration results showed that the thrust stand is able to measure thrust levels between 46.7μN and 892.71μN with a resolution of 4.67μN and an accuracy of 10% and below. Vaporising Liquid Microthruster, which is developed under the Undergraduate Satellite Programme, is used in the testing of this thrust stand. Although the thrusts of the microthruster lie outside the accurate measuring range of the thrust stand, they were obtained through extrapolation of the calibration curve and its specific impulse and thrust to weight ratio were found to be 5.64s and 0.0461 respectively. In addition, a levelling system with a 2% settling time of 49s is developed in attempt to keep the thrust stand perfectly horizontal during thrust measurements. A PID controller is used in the levelling feedback control loop to provide the desired control actions in the system. In order to further validate the thrust stand’s accuracy, future research such as using the torsional thrust stand to measure a known thrust from a known microthruster in both atmospheric and vacuum conditions can be carried out.

Keywords: Torsional balance, Chemical thruster, microthrust, PID, nanosatellite
# TABLE OF CONTENT

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>ABSTRACT</td>
<td>I</td>
</tr>
<tr>
<td>TABLE OF CONTENT</td>
<td>II</td>
</tr>
<tr>
<td>LIST OF FIGURES</td>
<td>IV</td>
</tr>
<tr>
<td>LIST OF TABLES</td>
<td>V</td>
</tr>
<tr>
<td>LIST OF SYMBOLS</td>
<td>VI</td>
</tr>
<tr>
<td>1. INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>1.1. Scope</td>
<td>2</td>
</tr>
<tr>
<td>1.2. Objectives</td>
<td>2</td>
</tr>
<tr>
<td>1.3. Report outline</td>
<td>3</td>
</tr>
<tr>
<td>2. MICROTHRUSTER</td>
<td>4</td>
</tr>
<tr>
<td>2.1. Specific impulse</td>
<td>4</td>
</tr>
<tr>
<td>2.2. Thrust to weight ratio</td>
<td>5</td>
</tr>
<tr>
<td>2.3. Types of microthruster</td>
<td>6</td>
</tr>
<tr>
<td>2.3.1. Chemical thrusters</td>
<td>6</td>
</tr>
<tr>
<td>2.3.2. Electric thrusters</td>
<td>7</td>
</tr>
<tr>
<td>2.3.3. Other thrusters</td>
<td>8</td>
</tr>
<tr>
<td>2.3.4. Thruster comparison</td>
<td>8</td>
</tr>
<tr>
<td>2.4. Vaporising Liquid Microthruster (VLM)</td>
<td>9</td>
</tr>
<tr>
<td>3. THRUST STAND</td>
<td>12</td>
</tr>
<tr>
<td>3.1. Resolution and Sensitivity</td>
<td>12</td>
</tr>
<tr>
<td>3.2. Types of thrust stand</td>
<td>13</td>
</tr>
<tr>
<td>3.2.1. Inverted pendulum</td>
<td>14</td>
</tr>
<tr>
<td>3.2.2. Long-period pendulum</td>
<td>14</td>
</tr>
<tr>
<td>3.2.3. Electromagnetic</td>
<td>15</td>
</tr>
<tr>
<td>3.2.4. Torsional balance</td>
<td>15</td>
</tr>
<tr>
<td>3.3. Thrust stand design</td>
<td>16</td>
</tr>
<tr>
<td>3.3.1. Equations of motion</td>
<td>17</td>
</tr>
<tr>
<td>3.3.2. Pivot</td>
<td>19</td>
</tr>
<tr>
<td>3.3.3. Damping system</td>
<td>20</td>
</tr>
<tr>
<td>3.3.4. Sensor</td>
<td>22</td>
</tr>
<tr>
<td>3.3.5. Electrostatic calibrator</td>
<td>23</td>
</tr>
<tr>
<td>3.3.6. Wirings</td>
<td>25</td>
</tr>
<tr>
<td>3.3.7. Levelling indicator and counter mass</td>
<td>26</td>
</tr>
<tr>
<td>3.4. Calibrations</td>
<td>26</td>
</tr>
<tr>
<td>4. LEVELING SYSTEM</td>
<td>28</td>
</tr>
<tr>
<td>4.1. Overview of levelling system</td>
<td>29</td>
</tr>
<tr>
<td>4.2. Proportional-Integral-Derivative (PID)</td>
<td>30</td>
</tr>
</tbody>
</table>
## LIST OF FIGURES

| Figure 2.1: | Types of microthruster | 6 |
| Figure 2.2: | Hydrazine monopropellant thruster | 6 |
| Figure 2.3: | Hall Effect thruster | 7 |
| Figure 2.4: | Schematic of VLM | 9 |
| Figure 2.5: | Setup of VLM | 10 |
| Figure 3.1: | Types of thrust stand: a) Inverted pendulum, b) Long-period pendulum, c) Electromagnetic, d) Torsional balance (top view) | 13 |
| Figure 3.2: | Design of torsional thrust stand | 16 |
| Figure 3.3: | Top view of torsional thrust stand | 17 |
| Figure 3.4: | Flexural pivot bearing cutaway | 20 |
| Figure 3.5: | Magnetic damping system: a) Setup, b) Without damping, c) With damping | 21 |
| Figure 3.6: | Types of sensor: a) Laser sensor, b) LVDT with proper setup | 22 |
| Figure 3.7: | Setup of electrostatic calibrator | 24 |
| Figure 3.8: | Wirings: a) Setup, b) Drift | 25 |
| Figure 3.9: | Bull’s eye indicator at horizontal position | 26 |
| Figure 3.10: | Flow chart depicting the calibration of torsional thrust stand | 26 |
| Figure 4.1: | Side view of torsional thrust stand with tilting (exaggerated view) | 28 |
| Figure 4.2: | Side view of torsional thrust stand with leveling system: a) slightly tilted, b) perfectly horizontal | 29 |
| Figure 4.3: | Block diagram of a PID controller in a closed loop | 30 |
| Figure 4.4: | Design of levelling system | 33 |
| Figure 4.5: | Picture of NI USB-6009 DAQ | 34 |
| Figure 4.6: | Output voltage of accelerometer | 35 |
| Figure 4.7: | Motor with the mass attached to the drive rod | 36 |
| Figure 4.8: | Block diagram of PID controller in leveling system | 37 |
Figure 5.1: Visible thrust (left), invisible thrust (right) 39
Figure 5.2: Power curve for a particular VLM 39
Figure 5.3: Setup of torsional thrust stand during thrust measurement 40
Figure 5.4: Algorithms of levelling system created using LabVIEW 41
Figure 5.5: Flow chart depicting algorithms of levelling system 42
Figure 6.1: Calibration results of torsional thrust stand 44
Figure 6.2: Uncertainties of torsional thrust stand 44
Figure 6.3: Displacement generated by VLM using method 2: a) 48μl/min, b) 60μl/min 47
Figure 6.4: Steady and unsteady flow in VLM 50
Figure 6.5: Hairline fracture in VLM 51
Figure 6.6: Response of levelling system 52

LIST OF TABLES

Table 2.1: Performance of various thrusters 8
Table 3.1: Specifications of torsional thrust stand 17
Table 3.2: Specifications of flexural pivot 20
Table 3.3: Specifications of various sensor 23
Table 4.1: Specifications of DAQ for analog side 34
Table 4.2: Specifications of accelerometer 35
Table 4.3: Specifications of motor 36
Table 6.1: Comparison between Method 1 and 2 48
Table 6.2: PID parameters obtained experimentally 52
LIST OF SYMBOLS

\( \alpha = \) Inclination angle

\( A = \) Area

\( B = \) Magnetic field

\( c = \) Damping coefficient

\( c_f = \) Half of fin width

\( d = \) Moment arm

\( \varepsilon_0 = \) Permittivity of air

\( e(t) = \) Error

\( f = \) Friction

\( F = \) Force

\( g = \) Acceleration due to gravity

\( g_f = \) Half of gap width

\( i = \) Current

\( I_0 = \) Moment of inertia

\( I_{sp} = \) Specific impulse

\( k = \) Spring constant

\( K_d = \) Derivative gain

\( K_i = \) Integral gain

\( K_p = \) Proportional gain

\( l = \) Length of bar

\( m = \) Mass

\( N = \) Number of fin pairs

\( \theta = \) Horizontal angular displacement

\( \Delta p = \) Change in momentum

\( r(t) = \) Set point

\( R = \) Length of linkage

\( R_s = \) Effective length of pendulum

\( S = \) Linear displacement

\( t = \) Time

\( T = \) Thrust

\( u(t) = \) Control action

\( V = \) Voltage

\( \omega = \) Frequency

\( W = \) Weight

\( \dot{W} = \) Weight flow rate

\( x_{cm} = \) Distance to center of mass

\( x_0 = \) Half of engagement length

\( y(t) = \) Measured variable
1. INTRODUCTION

Nowadays, with the rapid advancement in technologies, miniaturized satellites are getting more attention especially in many industrial, government and academic bodies around the world (Mueller, 2000). The simplified designs, small sizes and low weights of those satellites not only reduce the production and launch cost, but also increase their reliabilities (Khaymn, 2000). In addition, miniature satellites can be mass produced to form a constellation of satellites to perform missions which could not be accomplished by normal satellites. Some of those missions include using constellation for low data rate communication, using formation to gather data from multiple points and in-orbit inspection of larger satellites. Those satellites can be classified as microsatellite (10 to 100kg), nanosatellite (1 to 10kg), picosatellite (0.1 to 1kg) and femtosatellite (10 to 100g).

Microthrusters, which are small and light weight, will be needed in order for miniaturized satellites to perform more complex missions that require precise maneuverability. Those thrusters are able to generate thrust in the range of micro to millinewton and they can act as the primary thruster or perform various positioning functions such as attitude control, orbital transfer, station-keeping and even drag compensation (Khaymn, 2000).

Currently, there is no commercial available measurement system to measure the small thrust. Although there were numerous micronewton and sub-micronewton thrust stand being developed at institutions such as BUSEK Co. (Gamero-Castano and Hruby, 2001), US Air Force and University of Southern California (Ketsdever et al., 2001)
over the past few years, most of those thrust stands were specifically designed to cater for their testing program. Therefore, in order to measure the thrust generated by the microthrusters developed under the Undergraduate Satellite Programme (USP), there is a need to design a custom thrust stand that is capable of measuring small thrust.

1.1. Scope

This report will describe the development and testing of an improvised thrust stand design which is originally constructed from a torsional thrust stand. Subsequently, the thrust generated from the Vaporising Liquid Microthruster (VLM), which is developed by Cheah and Low (2014), will be measured in atmospheric conditions. The results will then be compared and analysed. Lastly, the design of a levelling system in attempt to improve the accuracy of the thrust stand will be discussed and developed.

1.2. Objectives

The objectives of the project are as follows:

1) Development and testing of the thrust stand
2) Calibration of the thrust stand
3) Measure and analyse the thrust generated by the VLM in atmospheric condition
4) Design and develop a levelling feedback control system for the thrust stand
1.3. Report outline

This report consists of three main sections, namely the microthruster, the thrust stand and the levelling system. Literature reviews on the microthruster, thrust stand and levelling system are provided at the first section of respective chapters (2, 3 and 4) to ensure a smooth flow of the report. In Chapter 2, various parameters and types of microthruster are first discussed followed by a detailed discussion of the microthruster’s design which is used in this project. In Chapter 3, various parameters and types of thrust stand are examined followed by a detailed investigation of the new thrust stand’s design and its calibration methods. The components, damping system and electrostatic calibrator, which are used in the thrust stand, are also presented in this chapter. In Chapter 4, the overview of the levelling system and the Proportional-Integral-Derivative (PID) control are introduced. After which, the development of the levelling feedback control system and its components used are investigated.

The operating procedures of the microthruster, thrust strand and the algorithm used by the levelling system are described in Chapter 5. The characteristics of the thrust stand, microthruster and levelling system, which are obtained experimentally, are discussed in Chapter 6. In addition, the post processing of the measurement results to reduce random noise is also discussed in this chapter. Lastly, Chapter 7 concludes this report with some recommendations for future work.
2. MICROTHRUSTER

Microthruster is a miniaturized propulsion system that is capable of generating thrust in the milli and micronewton range. Its small size and light weight allow it to be installed on miniaturized satellites without sacrificing the overall system mass and size. This section will look into the various parameters that characterize the microthruster followed by a brief introduction on the different types of existing microthruster. After which, the microthruster that is used in this project will be discussed in detail.

2.1. Specific impulse

Specific impulse (I_sp) is the change in momentum (Δp) per unit weight of the propellant (W) that is being expended. In other words, it is the ratio of the thrust produced (T) to the weight flow rate of propellant (Ẇ) as shown below (Hill and Peterson, 1991):

$$I_{sp} = \frac{\Delta p}{W} = \frac{T}{W}$$

Specific impulse has the unit of second and it is also a measure of the thruster efficiency. A thruster with a higher specific impulse will generate more thrust for a given propellant flow rate as compared to a thruster with a lower specific impulse. Hence, the higher the specific impulse, the greater the thruster efficiency. It should be noted that thruster efficiency should not be confused with energy efficiency, which is the ratio between useful energy outputs and total energy inputs. Electric propulsion thruster such as the ion thruster usually has high thruster efficiency and low energy efficiency due to the fact that large energy input is needed to produce the thrust. The specific impulses of various thrusters will be discussed in section 2.3.4.
2.2. Thrust to weight ratio

Thrust to weight ratio is the ratio of thrust generated by the thruster to the weight of the thruster or the vehicle propelled by the thruster (Hill and Peterson, 1991):

\[ Thrust \text{ to weight ratio} = \frac{T}{W} \]  

(2)

It is a dimensionless quantity and it is an indicator of the thruster acceleration. A thruster with a high thrust to weight ratio will give a higher acceleration and vice versa. Usually, the thrust to weight ratio of the thruster is used to determine the vehicle’s theoretical maximum acceleration since the weight of the thruster is often lower than the whole vehicle. Furthermore, the thrust to weight ratio based on the initial thrust and weight is commonly used in the comparison of the thruster performance. This is because the fluctuation of various factors such as leftover propellant weight, atmospheric density and thrust level will cause the instantaneous thrust to weight ratio to vary constantly during satellite operation. Therefore, microthrusters with a high thrust to weight ratio are ideally preferred in miniaturized satellite. This is to ensure that they have sufficient thrust to accomplish various mission. However, there is usually a trade-off between the specific impulse and the thrust to weight ratio in the current existing microthrusters and those trade-off will be discussed in section 2.3.4.
2.3. Types of microthruster

The propulsion systems of the miniaturized satellite are generally classified under three main categories as shown below:

![Figure 2.1: Types of microthruster](image)

2.3.1. Chemical thrusters

Chemical thrusters involve the conversion of the chemical potential energy stored in the propellant to the kinetic energy of the exhaust flow, which is the thrust. The propellants can be in the form of solid, liquid or gaseous state and they are usually heated up by chemical reactions such as combustion or decomposition. Generally, chemical thruster has high thrust to weight ratio but low specific impulse. One example is the hydrazine monopropellant thruster as shown in Figure 2.2, whereby the thrust is generated by decomposing the liquid hydrazine into its gaseous products.

![Figure 2.2: Hydrazine monopropellant thruster](image)
2.3.2. Electric thrusters

Electric thrusters involve the use of electrical energy to accelerate the charged propellant particles to generate thrust. The propellants used in those thrusters are usually inert material such as xenon or argon gases. Hence, there is a need to ionize the propellants first before accelerating those charge particle using either electrostatic, electromagnetic or electrothermal method. Generally, electric thruster has high specific impulse but low thrust to weight ratio. Hall Effect thruster as shown in Figure 2.3 is one example of the electric thruster which uses radial magnetic field and axial electric field to generate thrust. The radial magnetic field will trap orbiting electrons around the inner magnetic coil to ionise the propellant and produce an axial electric field due to Hall Effect. The axial electric field will then accelerate the ionised propellant particle, generating thrust (Martinez-Sanchez and Pollard, 1998).

![Hall Effect thruster diagram](image)

*Figure 2.3: Hall Effect thruster (McWalter, 2007)*
2.3.3. Other thrusters

Other type of space propulsion system include the solar sail. It is a form of propulsion system which uses radiation pressure from electromagnetic radiation to generated thrust. Radiation pressure is the pressure acting on any surface that is exposed to electromagnetic radiation. Generally, solar sail has infinite specific impulse as no propellant is needed to generate the thrust. However, a large surface is usually needed for solar sail to function effectively since the force per unit area generated by radiation pressure is very small (Macdonald and Mclnnes, 2011).

2.3.4. Thruster comparison

Table 2.1: Performance of various thrusters (Henry et al., 2007)

<table>
<thead>
<tr>
<th>Type</th>
<th>( I_{sp} ) (s)</th>
<th>Thrust to weight ratio</th>
<th>Power required</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chemical</td>
<td>200 - 400</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Nuclear</td>
<td>750 – 1500</td>
<td>High</td>
<td>Low</td>
</tr>
<tr>
<td>Electrostatic</td>
<td>300 - 1500</td>
<td>Medium</td>
<td>High</td>
</tr>
<tr>
<td>Electromagnetic</td>
<td>1000 - 10,000</td>
<td>Low</td>
<td>High</td>
</tr>
<tr>
<td>Electrothermal</td>
<td>2000 - 100,000</td>
<td>Low</td>
<td>High</td>
</tr>
</tbody>
</table>

The comparison of the performance of various thrusters can be seen in Table 2.1. Depending on the mission objectives, various types of thruster can be used in the miniaturized satellite. For example, a satellite which requires high thrust for orbital transfer could use chemical or nuclear thruster while a satellite with a long mission profile could use electromagnetic or electrothermal thruster for better thruster
efficiency in the long run. This project will focus on a chemical thruster whereby its thrust will be measured and investigated in the later section.

2.4. Vaporising Liquid Microthruster (VLM)

Vaporising liquid microthruster is a type of chemical thruster which involves the conversion of thermal energy into kinetic energy to generate thrust. In this project, a 33mm x 26mm x 80mm zirconia-based VLM, fabricated using Microelectromechanical system (MEMS) and high temperature co-fired ceramic (HTTC) technologies, will be used for the thrust measurement (Cheah and Low, 2014). Water will be used as the propellant in this study for simplicity and safety purposes.

![Figure 2.4: Schematic of VLM](image)
The VLM is made up of three layers sandwiched together as shown in Figure 2.4. The first and third layers contain the inlet and the microheater respectively while the second layer contains the inlet, channel, vaporising chamber and nozzle. The inlet allows the propellant to enter the VLM. The channel with 90° bends prevents the back-flow of the propellant during operation. At the vaporising chamber, the propellant will get heated to its boiling point by the microheater and become gaseous state. The hot gas will then accelerate through the nozzle generating thrust.

*Figure 2.5: Setup of VLM*

With reference to the setup as shown in Figure 2.5 above, the water propellant will be stored in the syringe which acts as a reservoir. A programmable syringe pump (Fusion 200, Chemyx) will be used to vary the propellant flow rate into the VLM. This will cause the VLM to produce different amount of thrust depending on the flow rate. A hypodermic needle will be attached to the inlet of the VLM and it will be connected to
the syringe using silicon tubing. A DC power supply will be connected to the VLM to supply current which will in turn heat up the microheater.

Previous studies done by Cheah and Low (2014) had found out that the vaporisation of water propellant using the VLM is made up of three stages. The first stage consists of warm water flowing out of the nozzle due to insufficient heating power. The second stage consists of a two-phase flow, which is made up of water vapour and water droplets, as the heating power is increased. The third phase contains purely water vapour if sufficient heating power is supplied. In addition, it was observed that rapid heating and cooling of the microheater would induced thermal stress on the VLM, causing it to fracture. Hence, this study will attempt to heat up the VLM gradually and measure the thrust generated using the newly developed thrust stand. The operating procedure of the VLM and its results will be discussed in section 5.1 and 6 respectively.
3. THRUST STAND

Thrust stand is a type of measurement system that is capable of measuring small thrust. Depending on the thrust stand design, it can measure forces in the range of nanonewton to millinewton. In this section, the parameters (resolution and sensitivity), which indicate the performance of thrust stand, will be discussed first followed by the review of the various types of thrust stand. Subsequently, the design of the new thrust stand and its components will be investigated in detail.

3.1. Resolution and Sensitivity

Resolution represents the degree to which a change can be measured. In other words, it indicates the smallest change in force that can be detected by the thrust stand and it is a relative quantity. In general, the lower the resolution, the smaller the force that can be detected by the thrust stand assuming other factors are constant.

Sensitivity represents the smallest absolute amount that can be measured. In other words, it indicates the amount of force per unit displacement of the thrust stand and it is an absolute quantity. In general, the higher the sensitivity, the greater the displacement of the thrust stand for a given force assuming other factors are constant. It should be noted that resolution and sensitivity have no relation to the accuracy of the thrust stand. However, in order to measure small force generated by the microthruster effectively, a thrust stand with a low resolution and high sensitivity is usually preferred. This will allow the thrust stand to produce a larger displacement for a given small force, hence enhancing the measurement readings.
3.2. Types of thrust stand

For the past decades, numerous thrust stand designs had been developed to measure small thrust. Almost all of the thrust stand designed to date measure thrust based on their displacement. Most of them can be categorized into four major groups which are mainly inverted pendulum, long-period pendulum, electromagnetic and torsional balance as shown in Figure 3.1 below:

Figure 3.1: Types of thrust stand: a) Inverted pendulum, b) Long-period pendulum, c) Electromagnetic, d) Torsional balance (top view) (Mirczak, 2001)
3.2.1. Inverted pendulum

Inverted pendulum thrust stand consists of a vertical arm (d) with the pivot located at the bottom of the arm. Microthruster will be mounted at the top free end of the arm and a small disturbance caused by the thrust (F) of the microthruster will produce a measureable displacement (S) which is given by:

\[ S = \frac{F d^2}{k - mgd} \]  

(3)

Although this type of thrust stand is simple to design, its sensitivity is limited by the spring constant of the pivot.

3.2.2. Long-period pendulum

Long-period pendulum thrust stand incorporates the effect of a very large pendulum in a compact size by using a combination of linkages (R). Microthruster, which is mounted on a connecting bar (l), will be positioned at the centre of mass of the whole system and the displacement (S) produced is similar to that of a simple pendulum of length \( R_s \) as shown below:

\[ S = \frac{F d^2}{k} \]  

(4)

\[ R_s = \frac{R}{2 \left( \frac{l}{2} - \frac{x_{cm}}{l} \right)} \]  

(5)

This type of thrust stand is usually used when the period of the pendulum thrust stand is shorter than the duration of thrust such as during impulse measurement. However, it is difficult to setup due to its complex design.
3.2.3. Electromagnetic

Electromagnetic thrust stand eliminates the mechanical contact between the microthruster and the thrust stand by levitating the microthruster using an electromagnet. A conducting ring will be attached to the bottom of the microthruster and the levitating force (F), which is produced by the magnetic field (B), will be proportional to the current (i), frequency (ω) and the enclosed area the conducting ring (A):

$$F \propto A^2 i^2 \omega$$  \hspace{1cm} (6)

A small thrust generated by the microthruster will cause the conducting ring to move downwards. The thrust can be measured by changing the levitating force until they are of the same magnitude, in other words, the conducting ring returns to its initial position. Unlike the pendulum type thrust stand, electromagnetic thrust stand can further reduce the vibrational noise experienced by the thrust stand during the measurement. Nevertheless, it is not widely used as special setup is needed to hold the floating microthruster in place.

3.2.4. Torsional balance

Torsional balance thrust stand consists of a horizontal arm with a pivot located at the center of the arm. Microthruster will be mounted at one end of the arm while a counterweight will be placed at the other end to balance the arm. A small thrust (F) will cause the arm of length d to produce a horizontal displacement (S):

$$S = \frac{Fd^2}{k}$$  \hspace{1cm} (7)
Torsional thrust stand is currently the most popular type of thrust stand as it produces less vibrational noise and is more stable than the inverted pendulum when its center of mass is perfectly balanced at the pivot. Furthermore, its ability not to be affected by gravity allows it to operate in any orientation and even in zero gravity.

### 3.3. Thrust stand design

By considering the characteristics of the various thrust stand as mentioned in the previous section, a 60cm long, aluminium torsional balance thrust stand is being designed. The torsional balance concept was chosen as a basis for the thrust stand design because it is simple to construct, has low vibration response and is independent of gravity effect. This will make it an ideal system to measure thrust accurately. The design and specifications of the thrust stand are shown in Figure 3.2 and Table 3.1 respectively. The equations of motion of the thrust stand and its components will be further discussed in this section.

![Figure 3.2: Design of torsional thrust stand](image-url)
### Table 3.1: Specifications of torsional thrust stand

<table>
<thead>
<tr>
<th>Material of balance arm</th>
<th>Aluminium</th>
</tr>
</thead>
</table>
| Dimensions of balance arm (cm)   | Length: 60  
                                      | Width: 11  
                                      | Height: 5  
                                      | Thickness: 0.3 |
| Cross sectional shape of balance arm | U-channel |
| Mass of balance arm (g)          | 300       |
| Distance of pivot/ Moment arm (cm)| 30        |
| Mass of VLM with mounting (g)    | 157.6     |
| Mass of electrostatic calibrator (g) | 86     |
| Counter mass (g)                 | 73        |

#### 3.3.1. Equations of motion

With reference to *Figure 3.3* above, the equations of motion of the thrust stand system can be written as:

\[
\ddot{\theta} + \frac{c}{I_{\theta}} \dot{\theta} + \frac{k}{I_{\theta}} \theta = \frac{Fd}{I_{\theta}}
\]

*Figure 3.3: Top view of torsional thrust stand*
where $\theta$ is the horizontal angular displacement, $I_0$ is the moment of inertia of the system, $F$ is the thrust generated by the microthruster, $d$ is the perpendicular distance from the pivot to the line of action of the thrust which is also known as the moment arm, $c$ is the damping coefficient and lastly, $k$ is the overall stiffness of the system which is assumed to be equals to the pivot spring constant. By assuming zero initial conditions and taking Laplace and inverse Laplace transformation, the steady state solution of equation (8) can be simplified to:

$$\theta(t) = \frac{Fd}{k} \quad (9)$$

Since the horizontal angular displacement is small, the linear displacement ($S$) can be approximate to be an arc of radius equal to the moment arm ($d$) as shown below:

$$S = d\theta \quad (10)$$

By substituting equation (10) into equation (9) and taking in to consideration of the friction ($f$) at the pivot and the tilting effect of the torsional thrust stand, the thrust generated by the microthruster can be calculated using:

$$S = \frac{(F - f)(d \cos \alpha)^2}{k} \quad (11)$$

$$F = \frac{Sk}{(d \cos \alpha)^2} + f \quad (12)$$

Where $\alpha$ is the inclination angle of the balance arm. A more detailed derivation of equation (12) can be found in appendix A.
It can be seen from the equation (12) that the thrust generated by the microthruster is independent of the damping coefficient and the moment of inertia of the system. In fact, the thrust will be directly proportional to the linear displacement of the thrust stand if the rest of the variables are constant. Those constants can be obtained using proper calibration methods and the thrust force can be calculated just by measuring the linear displacement of the moment arm as shown in section 6.

Furthermore, equation (11) also suggests that the sensitivity of the thrust stand is dependent on the moment arm, inclination angle, pivot spring constant and friction. A perfectly horizontal frictionless thrust stand with a long moment arm and a small pivot spring constant will have a higher sensitivity. In this project, a moderately long (30cm) moment arm was used to ensure that the thrust stand is able to fit into the vacuum chamber for future thrust measurements in vacuum condition.

3.3.2. Pivot

The pivot is the core component of the thrust stand. It is the only component that connect the rotating balance arm to the fixed base of the thrust stand. A double-ended flexural pivot from Riverhawk Company was chosen for the pivot of the torsional thrust stand. The flexural pivot not only allows rotational motion along the pivoted axis but it also provides the necessary spring constant for the thrust stand. In addition, the high loading capacities of the pivot allows the thrust stand to withstand multi-directional loadings and shocks, making it more durable. The picture and specifications of the flexural pivot are shown in Figure 3.4 and Table 3.2 respectively.
### 3.3.3. Damping system

The damping of the torsional thrust stand plays an important role in the time taken to reach a stable deflection of the balance arm during thrust measurements. Without damping, the balance arm will oscillate for a significant duration as shown in of Figure 3.5b, making it almost impossible to obtain an accurate thrust measurement. A magnetic damper will be used to provide a non-contact, passive damping system for the torsional thrust stand. This can be done by placing a strong neodymium magnet in close proximity to the underside of the aluminium balance arm as shown in Figure 3.5a. As the arm oscillates, the relative motion between the magnet and the arm will induce an eddy current in the arm. The induced current will then create an opposing magnetic field which will in turn produce a force acting in the opposite direction to the relative motion according to Lorentz force law. The force produced will be used to provide damping for the thrust stand. In addition, the amount of damping can be controlled by varying the distance between the magnet and the balance arm. The smaller the gap distance, the greater the damping of the thrust stand and vice versa. Hence, in order to achieve a suitable 2% settling time ($t_s$) of around 11s, a gap distance
of approximately 1mm will be used. Settling time is the time taken for the response to be within 2% or 5% of the final value.

Figure 3.5: Magnetic damping system
a) Setup, b) Without damping, c) With damping
3.3.4. Sensor

The function of the sensor is to detect the amount of linear displacement produced by the torsional thrust stand during thrust measurement. Initially, a linear variable differential transformer (LVDT) from the previous thrust stand experiment was intended to be reused for this torsional thrust stand. It is an electrical transformer which uses differential voltage to measure the linear displacement. Although the LVDT is a non-contact sensor, it is extremely difficult to ensure the moving probe is not in contact with the coil assembly as shown in Figure 3.6b. Incorrect setup of the LVDT will introduce friction in the thrust stand system, causing inaccuracies in the displacement reading. Therefore, a laser displacement sensor from Micro-Epsilon is used for the thrust stand instead. It is a non-contact sensor which uses laser triangulation principle to measure the linear displacement. Unlike the LVDT, the laser sensor is easy to setup and is less prone to errors. The picture and specifications of the laser sensor are shown in Figure 3.6a and Table 3.3 respectively.

![Figure 3.6: Types of sensor](image)

*a) Laser sensor, b) LVDT with proper setup*
3.3.5. Electrostatic calibrator

The function of the calibrator is to calibrate the thrust stand so that it is able to measure thrust accurately. It is necessary to calibrate the thrust stand due to the fact that the thrust stand’s overall stiffness does not solely depend on the pivot spring constant. The configurations of the wirings and tubing on the thrust stand might also contribute to the overall stiffness, causing the thrust stand to drift. This will be further discussed in section 3.3.6.

In this project, an electrostatic calibrator will be used for the calibration of the torsional thrust stand. It consists of a pair of electrostatic comb, each contains 36 fins and is mounted to one end of the balance arm and an external stand as shown in Figure 3.7. A power supply, which is connected to a step up transformer, will be used to supply the voltage to the comb pairs. By using a potential divider to vary the potential difference (V) between the two combs, different amount of electrostatic forces (F) can be generated. The magnitude of those forces can be approximated using the equation:

$$ F \approx 2N\varepsilon_0 V^2 \left[ 2.2464 - \frac{c_f + g_f}{\pi x_0} \right] $$

(13)
Where $N$ is the number of fin pairs, $\varepsilon_0$ is the permittivity of air, $2x_0$ is overlap distance between the fins which is also called the engagement length, $2c_f$ is the fin width and $2g_f$ is the gap width (Yan et al., 2009). Furthermore, the electrostatic force can be made independent of the engagement length by making $x_0 \gg (c + g)$ as shown below:

$$F \approx 4.4928N\varepsilon_0 V^2$$

(14)

This will greatly increase the accuracies of the calibration since the force produced is only a function of the voltage applied. The advantage of using electrostatic calibrator is that it is able to obtain a more accurate calibration over other types of calibration methods such as the impact pendulum. It should be noted that there should be no contact between the electrostatic combs and the applied voltage to the comb pairs is limited to a maximum of 900V to avoid electrical arcing. The calibration procedures of the torsional thrust stand will be discussed in detail in section 3.4.

![Figure 3.7: Setup of electrostatic calibrator](image)

*Figure 3.7: Setup of electrostatic calibrator*
3.3.6. Wirings

The wirings of the torsional thrust stand consist of the electrical wires and water tubing that are connected to the electrostatic comb and microthruster as shown in Figure 3.8a. Those wirings have their individual stiffness constant and their configurations on the thrust stand contribute significantly to the overall stiffness. This can be shown by the significant drift of the thrust stand from its initial position in Figure 3.8b. Hence, to tackle this problem, the positions of those wires are configured through experimental approach until the drift becomes negligible. Furthermore, thin electrical wires of low stiffness are used to further reduce the drift in order to achieve a more accurate calibration of the thrust stand.

![Diagram of wirings](image1)

*Figure 3.8: Wirings
  a) Setup, b) Drift*
3.3.7. Levelling indicator and counter mass

The levelling indicator and the counter mass will be placed on the balance arm of the torsional thrust stand so as to ensure that the arm is perfectly horizontal. A bull’s eye level will be used to indicate the arm’s inclination in two dimension plane while the electrostatic comb and a counter mass of 73g will be used to make sure the thrust stand’s centre of mass lies exactly at the pivot. This is to reduce the amount of friction at the pivot caused by non-uniform loading on the arm. The presence of friction will caused the the measured linear displacement to deviate significantly from its actual value and decrease the accuracy and sensitivity of the thrust stand as seen from equation (11) in section 3.3.1.

![Figure 3.9: Bull’s eye indicator at horizontal position](image)

3.4. Calibrations

This section will look into the calibration of the torsional thrust stand using the electrostatic calibrator mentioned in section 3.3.5. The calibration process basically consists of three main steps and those steps are summaries by the flow chart:

![Figure 3.10: Flow chart depicting the calibration of torsional thrust stand](image)
First of all, the electrostatic calibrator will be calibrated using an electronic balance. This can be done by placing one of the comb on an electronic balance and the other comb attached to a fixed stand. An electrostatic force will be generated when a potential difference is applied across the two combs. By varying the applied voltage using a potential divider, different amount of forces can be produced and the forces will be measured by the electronic balance. Those values will be recorded to obtain the relationship between the electrostatic force generated and the voltage applied.

After which, the electrostatic calibrator will be used to calibrate the thrust stand. This time, one of the comb will be placed at one end of the balance arm while the other is held by a fixed stand. By using different amount of forces generated by the calibrator, various linear displacement can be measured from the thrust stand. Those values will then be recorded to obtain the relationship between the displacement displaced and the voltage applied.

Finally, the graph of the force applied on the thrust stand against the linear displacement displaced by the thrust stand can be plotted by combining the two relationships obtained from the above calibrations earlier. The displacement against force graph plays a critical role during thrust measurements. It is used to determine the thrust value from a given thrust stand’s displacement by either interpolation or extrapolation. In addition, the graph is also used to characterise the thrust stand and this will be further discussed in section 6.1. The calibration data can be found in appendix B.
4. LEVELING SYSTEM

One of the common problem which exists in the torsional thrust stand is that the thrust stand would not remain perfectly horizontal. It will tend to tilt slightly due to the non-uniform loading on the balance arm as shown in Figure 4.1. This will increase the amount of friction in the system, especially at the pivot and the sensor (if a contact sensor is used). As a result, the measured linear displacement and the calculated thrust will have a larger deviation from actual value. In order to tackle this problem, a leveling system will be designed in attempt to improve the accuracies of the thrust stand. The overview of the leveling system will be first discussed in this section followed by an introduction of Proportional-Integral-Derivative (PID) control. After which, the components used in the system will be investigated in detail.

Figure 4.1: Side view of torsional thrust stand with tilting (exaggerated view)
4.1. Overview of levelling system

The basis of the leveling system is to shift the entire system's center of gravity to make the thrust stand perfectly horizontal. This can be done by moving a fixed mass back and forth along the beam, away or towards the pivot as shown in Figure 4.2. In order to do so, the leveling system need to be a feedback control loop consisting of an accelerometer which acts as the sensor to measure the inclination, and an actuator which acts as the plant to move the fixed mass. Since the tilting of the thrust stand is more significant about the lateral axis of the thrust stand, a single feedback control loop about that axis will be designed to ensure the thrust stand is perfectly horizontal during thrust measurements.

In addition, a PID controller will be used in the feedback control loop to provide the desired control actions in the system. In this case, the desired control action will be the
constant maintenance of the thrust stand in the horizontal position. A software called the Laboratory Virtual Instrument Engineering Workbench (LabVIEW) will be used to program the PID controller (National Instruments, n.d.). The advantages of using LabVIEW is that it offers a wide variety of PID controls and allows users to modify the algorithms to suit their system requirements.

### 4.2. Proportional-Integral-Derivative (PID)

The Proportional-Integral-Derivative (PID) controller is a type of feedback control loop system which is widely used in the industrial control system. It measures and attempts to minimise the error by varying the control inputs of the plant or process. The error \( e(t) \) is given by the difference between a measured variable \( y(t) \) and a desired set point \( r(t) \) (Ogata, 1996).

![Figure 4.3: Block diagram of a PID controller in a closed loop (Wikipedia, n.d.)](image)

The PID controller algorithm mainly contains three constant parameters: Proportional (P), Integral (I) and Derivative (D) values. By proper tuning the three parameters, the PID controller can provide control action \( u(t) \) designed for specific system requirements such as the responsiveness, overshoot and oscillation of the system. One example is the levelling of the torsional thrust stand in this report.
4.2.1. Proportional gain

\[ u(t) = K_p e(t) \] (15)

The proportional parameter produces an output signal which is proportional to the actuating error signals. In other words, it depends on present errors. The proportional response can be adjusted by multiplying the error signal with the proportional gain \((K_p)\). The main function of the proportional parameter is to shape the response. It can be used to obtain a faster transient response (which can be improved with constant damping ratio) and has a low steady state error. A high proportional gain will make the system more robust, that is, the system is more resistant to disturbance. However, a too high proportional gain can also cause system instability and saturation (output signal is higher than the maximum output of the system).

4.2.2. Integral gain

\[ u(t) = K_i \int_0^t e(\tau) d\tau \] (16)

The integral parameter produces an output signal which is the accumulation of the sum of the instantaneous error over a period of time. In other words, it is the accumulation of past errors. The integral response can be adjusted by multiplying the accumulated error signal with the integral gain constant \((K_i)\). The main function of the integral parameter is to decrease the steady state error by increasing the system type by 1. However, a high integral gain may cause system instability and lead to a more oscillatory response which is undesirable.
4.2.3. Derivative gain

\[ u(t) = K_d \frac{d}{dt} e(t) \]  

(17)

On the other hand, the derivative parameter produces an output signal which is proportional to the rate of change of the actuating error signal. In other words, it is a prediction of future errors. The derivative response can be adjusted by multiplying the rate of change of the error signal with the derivative gain \( K_d \). The main function of the derivative parameter is to increase the system stability by predicting future errors and initiate early corrections. In addition, it can also increase the damping of the system. This allows the use of higher proportional gain which in turn improves the steady state accuracy and system sensitivity. However, a pure derivative controller is seldom used in practice due to its inherent sensitivity to high frequency noise signal.

Based on the characteristics of the PID parameters as mentioned above, a suitable set of PID parameters will be obtained experimentally in section 6.5.
4.3. Design of levelling system

In this project, another torsional thrust stand, which was developed previously by a FYP student, will be used for the preliminary testing of the levelling system. This is to avoid any modification to the newly developed thrust stand during the testing phase. The design of the levelling system is shown in Figure 4.4 and the components which are used in the system will be further discussed in this section.

![Figure 4.4: Design of levelling system](image-url)
4.3.1. Data acquisition device (DAQ)

The NI USB-6009 from National Instruments will be used for the acquisition and generation of data in the levelling system. It is a USB based control device with analog/digital input and output and it is the most important component in the leveling system which link the hardware to LabVIEW. Since the hardware uses analog signals, only the analog side of the DAQ will be used. Some of the DAQ specifications are shown in Table 4.1.

<table>
<thead>
<tr>
<th>Input</th>
<th>Output</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of channels</td>
<td>8</td>
</tr>
<tr>
<td>Max. voltage (V)</td>
<td>10</td>
</tr>
<tr>
<td>Voltage range (V)</td>
<td>-10 to +10</td>
</tr>
<tr>
<td>Resolution (bits)</td>
<td>14</td>
</tr>
</tbody>
</table>

Table 4.1: Specifications of DAQ for analog side

Figure 4.5: Picture of NI USB-6009 DAQ
4.3.2. Sensor

A single axis accelerometer from Dytran will be used in the leveling system. It will detect the thrust stand’s inclinations by measuring the acceleration due to gravity and output voltages to the DAQ. In addition, its ability to operate in vacuum condition will allow future use of the leveling system in the vacuum chamber. The specifications and output voltages of the accelerometer can be found in Table 4.2 and Figure 4.6 below.

<table>
<thead>
<tr>
<th>Dimensions (mm)</th>
<th>25.4 x 25.4 x 21</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input DC voltage (V)</td>
<td>9 to 32</td>
</tr>
<tr>
<td>Frequency (Hz)</td>
<td>0 to 400</td>
</tr>
<tr>
<td>Sensitivity (mV/g)</td>
<td>1000</td>
</tr>
</tbody>
</table>

Table 4.2: Specifications of accelerometer

![Figure 4.6: Output voltage of accelerometer (Dytran, n.d.)](image-url)
4.3.3. Actuator

A high precision, direct drive motor from Piezomotor will be used as the actuator for the levelling system. The DAQ will output the necessary voltage to the motor driver, which will in turn commands the motor to move the mass back and forth along the beam, away or towards the pivot. It is to note that care must be taken to ensure the drive rod is not be subjected to any non-axial force or torque to avoid damaging the motor. In addition, the axial force acting on the drive rod must be within the operating range. Hence, the mass will be placed on the wheels in order to reduce the friction during operation. Similar to the accelerometer, the motor’s ability to operate in vacuum condition will allow future use of the levelling system in the vacuum chamber. The specifications of the motor can be found in Table 4.3 below.

<table>
<thead>
<tr>
<th>Dimensions (mm)</th>
<th>22 x 19.3 x 10.8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input DC voltage (V)</td>
<td>0 to 5</td>
</tr>
<tr>
<td>Force (N)</td>
<td>0 to 3</td>
</tr>
<tr>
<td>Resolution (nm)</td>
<td>&lt;1</td>
</tr>
</tbody>
</table>

Table 4.3: Specifications of motor

![Motor with the mass attached to the drive rod](image)

Figure 4.7: Motor with the mass attached to the drive rod
4.3.4. PID controller

The block diagram of the PID controller in the leveling system is shown in Figure 4.8 above. The PID controller parameters (\(K_p\), \(K_i\), and \(K_d\)) and the desired set point will be programmed in LabVIEW. The DAQ will acquire readings from the accelerometer to LabVIEW and generate signals from LabVIEW to the motor driver. The driver will then control the movement of the motor based on the signal received. In this way, a single feedback system is formed.

In this leveling system, the desired set point will be the initial accelerometer reading when the thrust stand is perfectly horizontal. The instantaneous error, which is the difference between the desired set point and the instantaneous accelerometer reading, will be multiply by the optimal proportional, integral and derivative gain so as to minimise the future error, in other words, it is to make the thrust stand horizontal. A more detailed explanation of how the levelling system works will be discussed in section 5.3.
5. METHODOLOGY

The procedures of thrust measurement and levelling system will be examine in this section. The operating procedures for the VLM will be discussed first followed by the torsional thrust stand. After which, the algorithms used in the levelling system will be examined.

5.1. For VLM

Before the start of any measurement, the power required to fully vaporise the water propellant at various flow rate must be obtained. This is to ensure the right amount of power is supplied to the VLM during thrust measurements. The VLM will be first pre-heated at 1W for 30 seconds to boil off any liquid water in the vaporising chamber. After which, water will be feed into the VLM using the syringe pump. The power supplied will be gradually increased until a steady thrust consists only of invisible water vapour is produced. This can be done by observing the visible thrust, containing a mixture of water droplets and water vapour, turn invisible as shown in Figure 5.1. The above steps will be repeated for various flow rate (12, 24, 36, 48 and 60μl/min). It should be noted that any voltage change to the VLM should be made gradual to avoid the formation of thermal fracture caused by the high thermal gradient in the microthruster. In addition, this power test should be done for every VLM prior to usage as their power required might differ slightly from one another. The graph of power required against flow rate for one of the VLM can be found in Figure 5.2.
After obtaining the power curve for the VLM, the measurement of thrust using the torsional thrust stand can be carried out. The whole setup will be placed inside a transparent casing as shown in Figure 5.3. This is to reduce the effects of air current on the measurements. Once the displacement of the balance arm is stable, the data recording will start first followed by the activation of the VLM. The VLM will be activated using the same procedure as the power test mentioned previously. The
recording will stop once the deflection is stable. This process will be repeated for the various flow rate to obtain the respective thrust generated by the VLM.

In order to validate the results, two measuring methods were being used. The first method (Method 1) is the normal method whereby the VLM is mounted on one end of the balance arm. The thrust generated by the VLM will be transferred to the arm, causing the arm to displace from its initial position. The displacement will then be captured by the laser sensor. The second method (Method 2) involves placing the VLM on an external stand and mounting an electrically heated metal plate on one end of the balance arm. The thrust generated by the VLM will impact on the metal plate. The transfer of momentum from the water vapour to the plate will cause the arm to deflect. The displacement will then be captured by the laser sensor. The function of the heated plate is to prevent water vapour from condensing into water droplet on the plate’s surface which will in turn affect the measurements. The results from the two methods will be compared and discussed in section 6.3.

*Figure 5.3: Setup of torsional thrust stand during thrust measurement*
5.3. For levelling system

The flow chart and the algorithms of the levelling system, which are created using LabVIEW, are shown below:

![Flow chart and algorithms of levelling system](image)

Figure 5.4: Algorithms of levelling system created using LabVIEW
With reference to Figure 5.4, starting from the algorithms in the blue block, the input voltage from the accelerometer will be passed through a “PID control input filter” to reduce random noise in the input signal. The PID input control filter is a fifth-order lowpass finite impulse response (FIR) filter with a cut-off frequency set at 1/10 of the input signal frequency. In addition, the signal will be further smoothen by rounding it to the nearest two decimal place.

After the signal is filtered, the error is obtained by subtracting the filtered signal from the desired set point which is given by the “level indicator”. The error will then be...
multiplied by the proportional, integral and derivative gains, which are set by the user, to give an output voltage. This can be seen in the green block.

Since the motor has a no move voltage of 2.5V and any voltage lower than 2.5V will cause the motor to move in one direction and vice versa, a constant value of 2.5 is added to the output signal in order for the motor to function properly. This is shown in the red block.

In order to prevent the DAQ from supplying voltages outside the operating range of the motor (0 to 5V), a case structure is being created as shown in the grey block. The DAQ will output the exact same voltage if the voltage is within the operating range and output a no move voltage of 2.5V if the voltage is outside the range.

In attempt to test the performance of the levelling system, an additional mass will be placed on one end of the balance arm to shift the thrust stand’s centre of gravity away from the pivot, causing it to tilt. The levelling system will need to react to make the balance arm to be horizontal again. The response of the system will be recorded and discussed in section 6.5.
6. RESULTS AND DISCUSSIONS

6.1. To find characteristics of torsional thrust stand

The experimental and theoretical calibration results and the uncertainty of the torsional thrust stand are shown in the graphs below:

*Figure 6.1: Calibration results of torsional thrust stand*

*Figure 6.2: Uncertainty of torsional thrust stand*
With reference to the graphs in *Figure 6.1*, it can be seen that the experimental calibration curve is almost linear as the coefficient of determination is close to 1 ($R^2=0.9942$). This coincides with the theoretical curve calculated using equation (12). However, the experimental curve has a different gradient than the theoretical curve. One reason is because the actual parameter values presented in the thrust stand might not be equal to the values assumed in the theoretical calculations. For example, the actual overall stiffness of the thrust stand might differ from the pivot spring constant due to the presence of wirings and friction in the actual experiment. Hence, the actual calibration curve will be scaled vertically and translated horizontally from the theoretical curve.

In addition, the sensitivity of the torsional thrust stand, which is given by the gradient of the calibration curve, is found to be 4.67N/m while the resolution, which is given by multiplying the gradient with the fluctuation of the measurements (1μm), is found to be 4.67μN. As seen in the experimental calibration results, the data point at (9.3, 29.43) lies quite far away from the best fit line as compared to the point at (14.1, 88.29). This shows that the torsional thrust stand might not be able to measure such a small force accurately. Although the experimental curve can be extrapolated to obtain thrust force below 88.29 μN, the result will not be as accurate as the thrust force of a higher value. This can be evident in *Figure 6.2* whereby a smaller thrust force being measured by the thrust stand will give a higher percentage uncertainty and vice versa. Therefore, it can be concluded that although the thrust stand is able to measure any thrust greater than 4.67μN, it should not measure thrust lesser than 46.7μN in order to limit its accuracy to be within 10%.
The experimental curve will then be used to obtain the corresponding thrust value from a given displacement either through interpolation or extrapolation. This will be shown in the section 6.3.

6.2. Post processing of results

During the experiment, it was observed that the thrusts generated by the VLM were quite small. Furthermore, the presence of external disturbances and the bubbling effect of liquid water in the vaporising chamber caused the measurements to fluctuate significantly. Some of the external disturbance include random noise, vibration and air current. This severely worsen the clarity of the results. In order to reduce those random noise while retaining a sharp step response, a moving average filter with a period of 23 points will be used in Microsoft Excel. It is an effective smoothing filter in time domain which decreases the amplitude of the random noise by averaging a number of points from the input signal. A period of 23 points is chosen to reduce the noise by a factor of 4.8 without sacrificing much of the response sharpness. Furthermore, the filter is simple to use and requires less time to compute as compared to its counterpart. However, it was found that the displacements produced using flow rate smaller than 48µl/min are too small to be measured by the thrust stand. Therefore, only thrust generated by the VLM, operating at a flow rate of 48 and 60µl/min, are being measured in this experiment. A comparison of the displacement graphs with and without the filter are shown in Figure 6.3 while the rest of the experimental results can be found in appendix C.
Figure 6.3: Displacement generated by VLM using method 2:
   a) 48µl/min, b) 60µl/min
6.3. To find thrust generated by VLM

The thrust and displacement results, which are obtained by the torsional thrust stand, using various flow rates and measuring methods are shown in the table below:

<table>
<thead>
<tr>
<th>Method 1</th>
<th></th>
<th>Method 2</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Flow rate (μl/min)</td>
<td>48</td>
<td>60</td>
<td>48</td>
</tr>
<tr>
<td>Displacement (μm)</td>
<td>2.25</td>
<td>4.1</td>
<td>1.2</td>
</tr>
<tr>
<td>Thrust (μN)</td>
<td>46.7</td>
<td>55.3</td>
<td>41.8</td>
</tr>
</tbody>
</table>

**Difference (μN)**

<table>
<thead>
<tr>
<th></th>
<th>4.9</th>
<th>4.2</th>
</tr>
</thead>
<tbody>
<tr>
<td>% Difference</td>
<td>10.5</td>
<td>7.60</td>
</tr>
</tbody>
</table>

With reference to the results in Table 6.1, it can be seen that a higher flow rate will generates a higher thrust. This is because more water vapour will be flowing out of the nozzle at a higher flow rate. Hence, both the water vapour and the VLM will experience a greater change in momentum and this will in turn increase the amount of thrust produced according to Newton’s third law of motion.

In addition, the thrust measured using Method 1 is generally higher than using Method 2 for all flow rates. The slight deviation of the thrust might be due to the fact that not
all of the water vapour hit the metal plate in Method 2. Hence, less momentum is being transferred from the water vapour to the thrust stand and this accounts for the low thrust in Method 2.

It was also noted that the thrusts generated by the VLM at both flow rates were lower than 88.29μN and they were obtained by extrapolation of the experimental calibration curve. Therefore the thrusts of the VLM obtained in this experiment will have a high uncertainty of around 10% according to the graph in Figure 6.2 and this might not reflect their true thrust values.

6.4. To find characteristics of VLM

Assuming the normal operating flow rate of the VLM is 60μl/min and all the water vapour transferred their momentum to the thrust stand, the specific impulse and the thrust to weight ratio of the VLM can be calculated as follows:

\[
I_{sp} = \frac{T}{W} = \frac{55.3 \times 10^{-6}}{(60 \times 10^{-6} \times 9.81)} = 5.64\text{s}
\]

\[
\text{Thrust to weight ratio} = \frac{T}{W} = \frac{55.3 \times 10^{-6}}{1.2 \times 10^{-3}} = 0.0461
\]

It should be noted that the above calculation for thrust to weight ratio uses only the weight of the VLM excluding the rest of it components such as tubing, reservoir and mounting.
With reference to Figure 6.4, it can be seen that the thrust of the VLM consists of both unsteady and steady flow during operation. When the VLM is just turned on, the microheater does not have sufficient heating power to fully vaporise the water propellant. Hence, the thrust generated consists mostly of two-phase flow, which is made up of water vapour and water droplets. This will produce an unsteady flow which will cause the thrust stand’s displacement to change non-uniformly. After the VLM is turned on for some time, the microheater starts to gain sufficient heating power to fully vaporise the liquid water into water vapour. This will produce a steady flow which will cause the thrust stand’s displacement to fluctuate about a fixed value. In this experiment, the steady flow was used for the thrust determination.
In addition, hairline fractures were detected on all the VLM after the experiment as shown in *Figure 6.5*. This might be caused by the high thermal gradient in the VLM despite great care were taken to heat them up gradually. As a result, water vapour might escape from the vaporising chamber, causing the thrust measured to be lower than the actual value. However, further experimenting of the VLM design is not done since it is not within the objectives of this project.

*Figure 6.5: Hairline fracture in VLM*
6.5. To find characteristics of levelling system

A suitable set of PID parameters and the response of the levelling system are shown in Table 6.2 and Figure 6.5 below:

<table>
<thead>
<tr>
<th>Proportional gain ($K_p$)</th>
<th>22</th>
</tr>
</thead>
<tbody>
<tr>
<td>Integral gain ($K_i$)</td>
<td>0</td>
</tr>
<tr>
<td>Derivative gain ($K_d$)</td>
<td>0</td>
</tr>
</tbody>
</table>

As seen in Figure 6.5, the thrust stand returns to its initial horizontal position ($V=0$) at $t=67s$ after an additional mass is placed on the balance arm at $t=18s$. A proportional gain of 22 is chosen for the system in order to achieve a fast transient response with a 2% settling time of 49s while retaining a zero steady state error. Since the response
has no overshoot or steady state error, there is no need to introduce derivative or integral gains into the system. Therefore, this shows that the levelling system developed in this project is able to make sure the thrust stand is perfectly horizontal at all times. This will minimize the introduction of additional friction in the pivot due to tilting, hence, improving the accuracy of the thrust stand.

In addition, any attempt to further increase the transient response by increasing the proportional gain will caused the system to be unstable. This called for the introduction of integral and derivative gains. However, it is quite time consuming to tune the parameters manually and it was found that the levelling system with a proportional gain of 22 still gives the best settling time. Although there are various methods available for PID tuning, they are not used in this project due to time constrain and the moderately fast transient response is sufficient to satisfy the preliminary testing of the levelling system.
7. CONCLUSION

To sum up, this report has successfully demonstrated the development of the newly designed torsional thrust stand and the levelling feedback control system. The thrust stand is equipped with a magnetic damping system and calibrated using an electrostatic calibrator. It was found from the calibrated results that the thrust stand is able to measure thrust levels between $46.7\mu N$ and $892.71\mu N$ with a resolution of $4.67\mu N$ and an accuracy of $10\%$ and below. This makes it an ideal measurement system to measure thrust generated by future microthrusters developed under the Undergraduate Satellite Programme (USP). Although the thrusts of the Vaporising Liquid Microthruster (VLM) lie outside the accurate measuring range of the thrust stand, they can be obtained through extrapolation of the calibration curve and its specific impulse and thrust to weight ratio were found to be $5.64s$ and $0.0461$ respectively. The low thrust value of the VLM might be due to the presence of thermal fracture on its surface, causing water vapour to escape from the vaporising chamber which in turn reduce the thrust generated. In addition, the levelling system, which is operated using a PID controller in LabVIEW, is able to rotate the thrust stand back to its horizontal position within $49s$ in the event it is subjected to any disturbance. This will effectively reduce the amount of friction presented in the thrust stand, especially at the pivot, and hence improve the thrust stand’s accuracy. Future research such as using the torsional thrust stand to measure a known thrust from a known microthruster in both atmospheric and vacuum condition can be done to further validate the accuracy of the thrust stand.
7.1. Recommendations for future work

1) Thrust stand

Measurement of the thrust using a known microthruster in both atmospheric and vacuum condition can be carried out in order to further validate the thrust stand’s accuracy. This is because the build-up of pressure in the transparent casing might affect the accuracy of the measurements too. It should be noted that some of the thrust stand’s components which is made of high-outgassing materials such as rudder might need to be replaced with a low-outgassing material such as aluminium to ensure proper operation of the thrust stand in vacuum condition.

2) Levelling system

The levelling system can be setup on the newly developed torsional thrust stand to further improve the thrust stand’s accuracy. Due to time and technical constrains, the levelling system was only tested on the old thrust stand. Furthermore, other PID tuning methods such as the Ziegler-Nichols or Cohen-Coon method can be tested to obtain an ideal set of PID parameters which might in turn gives a faster transient response.

3) VLM

The low thrust of the VLM generated during the thrust measurement might be caused by the hairline fractures due to the high localized thermal gradient around the microheater. As the result, the thrust measured does not reflect its true value. Hence, future investigation of the VLM design should be done to reduce the fracture.
REFERENCES


Appendix A: Derivation of equations of motion of torsional thrust stand

Without friction and tilting

With reference to Figure A1 above, the equations of motion of the thrust stand system can be written as:

\[ \sum M = I_\theta \ddot{\theta} = Fd - c\dot{\theta} - k\theta \]

\[ \ddot{\theta} + \frac{c}{I_\theta} \dot{\theta} + \frac{k}{I_\theta} \theta = \frac{Fd}{I_\theta} \]

(A1)

where \( M \) is the torque, \( \theta \) is the horizontal angular displacement, \( I_\theta \) is the moment of inertia of the system, \( F \) is the thrust generated by the microthruster, \( d \) is the perpendicular distance from the pivot to the line of action of the thrust which is also known as the moment arm, \( c \) is the damping coefficient and lastly, \( k \) is the overall stiffness of the system which is assumed to be equals to the pivot torsional spring constant. By taking the Laplace transformation and assuming zero initial conditions, equation (A1) can be reduce to:

\[ s^2 \theta(s) + \frac{c}{I_\theta} s\theta(s) + \frac{k}{I_\theta} \theta(s) = \frac{Fd}{I_\theta} \frac{1}{s} \]
\[
\theta(s) = \frac{Fd}{I_\theta} \frac{1}{s(s^2 + \frac{c}{I_\theta} s + \frac{k}{I_\theta})}
\] 

(A2)

It should be noted that equation (A2) represents the horizontal angular displacement of the thrust stand in the frequency domain. Therefore, in order to change it back to time domain, inverse Laplace transform of equation (A2) should be taken and it is found to be:

\[
\theta(t) = \frac{Fd}{k} \left[1 - \frac{1}{\sqrt{1 - \zeta^2}} e^{-\zeta W_n t} \sin(W_d t + \phi)\right]
\]

(A3)

\[
W_d = W_n \sqrt{1 - \zeta^2}
\]

\[
\phi = \tan^{-1} \frac{\sqrt{1 - \zeta^2}}{\zeta}
\]

Where the natural frequency \( (\omega_n) \) and damping ratio \( (\zeta) \) are related by:

\[
W_n = \sqrt{\frac{k}{I_\theta}}
\]

and

\[
\zeta = \frac{c}{2 \sqrt{kI_\theta}}
\]

At steady state \( (t \to \infty) \), equation (A3) can be simplified to:

\[
\theta(t) = \frac{Fd}{k}
\]

(A4)

Since the horizontal angular displacement is small, the linear displacement \( (S) \) can be approximate to be an arc of radius \( (d) \) as shown below:
\[ S = d\theta \]  

(A5)

By substituting equation (A5) into equation (A4), the thrust generated by the microthruster can be calculated using:

\[ S = \frac{F d^2}{k} \]  

(A6)

\[ F = \frac{Sk}{d^2} \]  

(A7)

With friction and tilting

One of the common problem which exists in the torsional thrust stand is that the thrust stand would not remain perfectly horizontal. It will tend to tilt slightly due to the non-uniform loading on the balance arm as shown in Figure A2. This will increase the amount of friction in the system, especially at the pivot and the sensor (if a contact sensor is used).

Figure A2: Side view of torsional thrust stand with tilting (exaggerated view)

Figure A3: Top view of torsional thrust stand (with tilting)
With reference to the side and top view of the thrust stand in *Figure A2* and *A3*, it can be seen that the effective moment arm length \( x \) after tilting is reduced to:

\[
x = d \cos \alpha
\]  
(A8)

Where \( d \) is the perpendicular distance from the pivot to the line of action of the thrust and \( \alpha \) is the inclination angle. By substituting the effective moment arm length into equation \( A6 \) and including the effect of friction \( f \), the linear displacement and the thrust generated are found to be:

\[
S = \frac{(F - f)x^2}{k} = \frac{(F - f)(d \cos \alpha)^2}{k} \quad \text{(A9)}
\]

\[
F = \frac{S_k}{(d \cos \alpha)^2 + f} \quad \text{(A10)}
\]
## Appendix B: Calibration data

<table>
<thead>
<tr>
<th>Voltage (V)</th>
<th>F (μN)</th>
<th>S (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td>29.43</td>
<td>9.30</td>
</tr>
<tr>
<td>250</td>
<td>88.29</td>
<td>14.10</td>
</tr>
<tr>
<td>300</td>
<td>127.53</td>
<td>21.40</td>
</tr>
<tr>
<td>350</td>
<td>166.77</td>
<td>28.05</td>
</tr>
<tr>
<td>400</td>
<td>215.82</td>
<td>36.30</td>
</tr>
<tr>
<td>450</td>
<td>264.87</td>
<td>46.40</td>
</tr>
<tr>
<td>500</td>
<td>323.73</td>
<td>57.60</td>
</tr>
<tr>
<td>550</td>
<td>382.59</td>
<td>71.00</td>
</tr>
<tr>
<td>600</td>
<td>451.26</td>
<td>84.00</td>
</tr>
<tr>
<td>650</td>
<td>519.93</td>
<td>99.00</td>
</tr>
<tr>
<td>700</td>
<td>588.6</td>
<td>114.90</td>
</tr>
<tr>
<td>750</td>
<td>667.08</td>
<td>133.00</td>
</tr>
<tr>
<td>800</td>
<td>735.75</td>
<td>151.00</td>
</tr>
<tr>
<td>850</td>
<td>814.23</td>
<td>169.00</td>
</tr>
<tr>
<td>900</td>
<td>892.71</td>
<td>190.50</td>
</tr>
</tbody>
</table>
Appendix C: Pre and post processing results

Method 1:

Graph of Displacement against Time (Method 1)

- 48μl/min
- 23 per. Mov. Avg. (48μl/min)

2.25μm

Graph of Displacement against Time (Method 1)

- 60μl/min
- 23 per. Mov. Avg. (60μl/min)

4.1μm
Method 2:

Graph of Displacement against Time (Method 2)

- 48μl/min
- 23 per. Mov. Avg. (48μl/min)

1.2μm

Graph of Displacement against Time (Method 2)

- 60μl/min
- 23 per. Mov. Avg. (60μl/min)

3.2μm