B. TECH. PROJECT REPORT

On

Measurement of Thrust in small Rockets

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DISCIPLINE OF MECHANICAL ENGINEERING
INDIAN INSTITUTE OF TECHNOLOGY INDORE

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Measurement of Thrust in small Rockets

A PROJECT REPORT

Submitted in partial fulfillment of the requirements for the award of the degrees

of
BACHELOR OF TECHNOLOGY
in

MECHANICAL ENGINEERING

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December 2017

CANDIDATE'S DECLARATION

We hereby declare that the project entitled **"Measurement of Thrust in small rockets"** submitted in partial fulfillment for the award of the degree of Bachelor of Technology in 'Mechanical Engineering' completed under the supervision of **Dr. D.L. Deshmukh (Assistant Professor, Mechanical Engineering)** and **Dr. I.A. Palani (Associate Professor, Mechanical Engineering),** IIT Indore is an authentic work.

Further, we declare that we have not submitted this work for the award of any other degree elsewhere.

Signature and name of the student(s) with date

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CERTIFICATE by BTP Guide(s)

It is certified that the above statement made by the students is correct to the best of our knowledge.

Signature of BTP Guide(s) with dates and their designation

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Preface

This report on "Measurement of Thrust in Small Rockets" is prepared under the guidance of Dr. D.L. Deshmukh and Dr. I.A. Palani.

Through this report we have tried to give a detailed design of a device for measuring thrust in small rockets. We have tried to cover every aspect of the proposed design and its calculation. We fabricated the set-up and performed the experiments successfully which shows that the design is technically sound and feasible, and can have numerous applications in astronomical field.

We have tried to the best of our abilities and knowledge to explain the content in a pellucid manner.

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It is their help and support, due to which we became able to complete the design and technical report.

We would like to thank Discipline of Mechanical Engineering and in total IIT Indore for providing us the necessary equipment and funds for the fabrication process. We express thanks to **Mr. A. Petare**, **Mr. Rishiraj** and entire **workshop staff** for helping us in our set-up. We would like to extend our sincere regards to **Mr. Jayant Mohanta (Ph.D. Scholar)** and **Mr. Suryaveer (B.Tech, III year)** for helping us in lab activities. We are thankful to get constant encouragement support and guidance from B.Tech project evaluation committee.

Without their support, this report would not have been possible.

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Abstract

This Report deals with design and development of a thrust measuring pendulum stand capable of supporting testing of thrusters having a total mass of from 2kg to 5kg and producing thrust levels between 1N to 25N. The design features a conventional simple pendulum configuration which resulted in significant displacements and high resolution. Up to 45° of angular deflection was calculated under a force of 25 N theoretically. Angular Displacement of the arm is measured using the incremental angular encoder having 5000ppr. Thrust measurements will be carried out using a RC- Rocket fan that produces thrust around a fraction of Newton to 10N by varying its voltage. The thrusts of small thrusters used in spacecraft for attitude control and orientation of the camera in a specific direction can be measured using this method.

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CHAPTER 1: INTRODUCTION

Rocket propulsion systems are used in satellites so that they can be oriented in a particular direction for attitude control. This is necessary to ensure that the onboard camera is pointing towards the Earth, or that the solar arrays always face the Sun. That is why a satellite is equipped with a large number of small thrusters on its periphery. These thrusters are fired briefly when required so that the satellite starts to rotate slowly. When the satellite reaches its desired position, in order to stop the rotation thrusters are activated that fire in the opposite direction.

High specific impulse is provided by small rockets or thrusters, but low thrust, relative to large chemical propulsion systems. While chemical rocket thrust is generally measured using load cells, the low thrust levels associated with small thrusters lead to a device which more closely resemble sensitive laboratory mass scales, where physical displacement of one of the mechanical members in the balance system (in our case the balancing force is gravity) is used to infer the applied force.

The conventional simple pendulum is the most simple and is highly stable as compared to inverted pendulum when subjected to external perturbations. However, high sensitivity can only be attained with a long pendulum am, which may be impractical if the test facility (vacuum chamber) is small.

We describe in this work a thrust measuring stand design. This thrust measuring stand consists of a simple pendulum and an incremental angular encoder. When the thrust is applied to the pendulum, it moves till equilibrium position and the angle swept is measured using an angular encoder, the reading of which is recorded using a MATLAB program.

CHAPTER 2: METHODS FOR THRUST MEASUREMENT

2.1 Using capacitor

In this method, thrust can be measured by the change in the capacitance due to movement of the plates. In this method, plates will continue to move unless some opposing force is applied to counterbalance the thrust produced. To counteract the thrust, we can use springs but using springs will give an error in the readings as the spring constant may change due to the surrounding temperature and also may change due to the hysteresis and fatigue.

2.2 Inverted pendulum

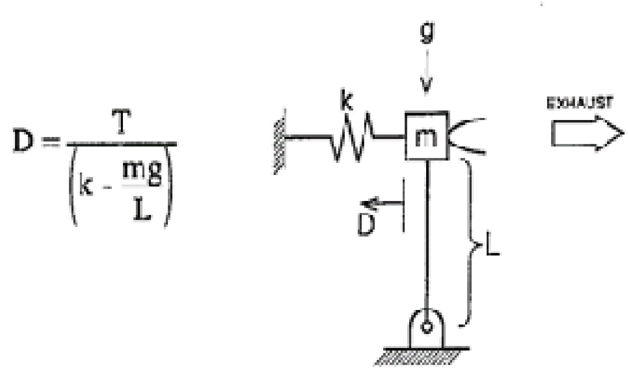


Figure 1: Inverted Pendulum

Thrust stand with magneto-plasma dynamic (MPD) thrusters used by Haag operate at powers up to 250 kW steady state has been tested. The stand was based on an inverted pendulum configuration which resulted in large displacements and high resolution. Deflection up to 50 mm was observed under a force of 5 N. This large range of displacement significantly reduced the effects of facility induced vibrations on thrust measurements. Calibrations showed that thrust measurements were linear and repeatable to within a fraction of 1%. Due to pump-down structural distortions of the vacuum facility were detected with an inclinometer located in the thrust stand base. Slope deviations as small as 10 arc sec could be compensated using a remotely controlled levelling motor. Early problems with magnetically induced tares caused by the thruster discharge current were reduced by re-routing high-current cables to decrease stray fields. The thrust stand was used with a water-cooled, applied field, steady-state MPD device at power levels up to 125 kW. By precisely maintaining a level thrust stand base, thermal drift was held to about 2% of the full scale reading over this period. The remaining thermal drift could be subtracted from the thrust measurement to further reduce systematic error. Tares caused by the applied magnetic field were similarly removed. By subtracting tabulated discharge current magnetic tares, thrust measurement uncertainty was reduced to approximately 2% of the measured value.

In this method also the measured values will be full with error due to use of the spring as due to different temperature conditions its stiffness will change thus producing error in the measurement.

2.3 LVDT

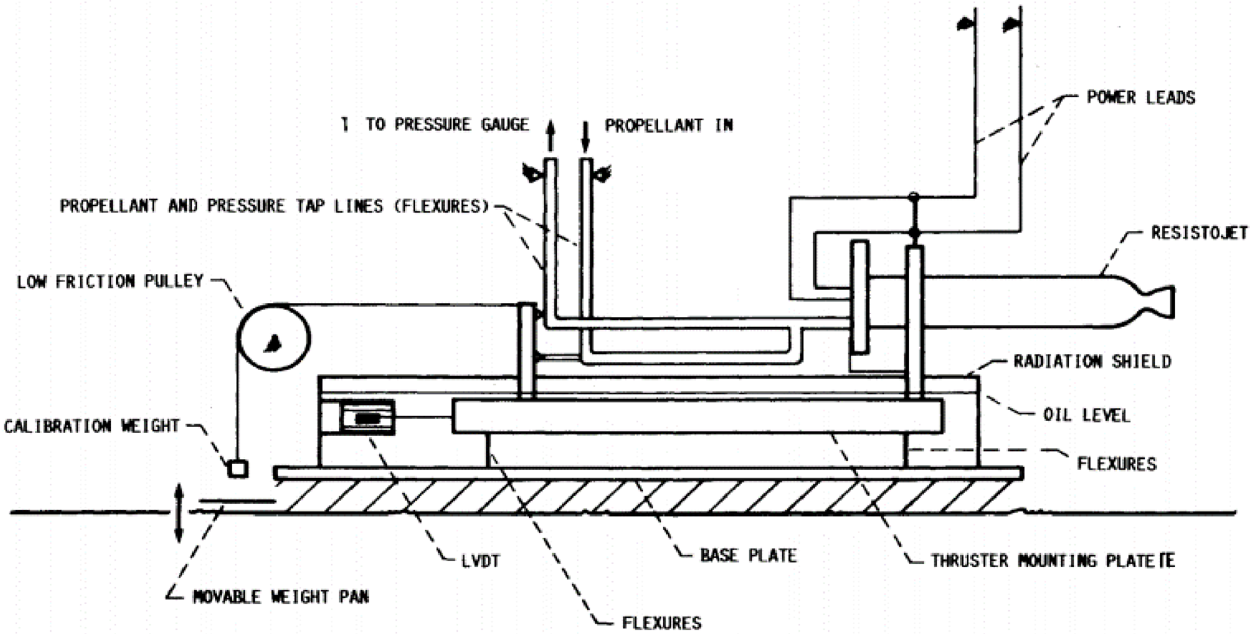


Figure 2: LVDT Thrust stand schematic

NASA reinstated a resistojet technology program to focus on material appraisal, fabrication methods, performance, plume evaluations, and life assessments of resistojet technology for space station application. The technology goals highlighted thruster life, reliability, and multi propellant capability rather than optimum performance. The design life goal is a minimum of 10,000 h for thrusters operating on hydrogen, helium, methane, water (steam), nitrogen, air, argon, and carbon dioxide at specific impulse and thrust levels of 100-500 s and 130-450 mN, respectively. The results of the material compatibility investigation, indicate that grain-stabilized platinum tubes are compatible with hydrogen, methane, steam, and carbon dioxide under the test conditions. Resistojet thrusters capable of operating for extended periods of time on a variety of propellant fluids have been base-lined at the low-thrust option for space station propulsion. Their benefits include simplicity, low cost, and the ability to provide drag makeup while disposing of fluids that would otherwise have to be removed from the space station via shuttle. All samples tested showed extrapolated lifetimes in excess of 10,000 h based on 10% mass loss as end of life. However, samples tested in ammonia at 1400°C showed severe pitting. Further tests showed that reducing the metal temperature to about 900°C (± 100°C) significantly reduced this material interaction. A laboratory model thruster fabricated from grain-stabilized platinum was subjected to a series of performance tests as well as a 2000-h, 2400-thermal- cycle endurance test Thrust levels observed varied from 90 to 420 mN at input power levels ranging from 140 to 240 W. The propellant inlet pressure ranged from 0.10 to 0.17 MPa during the endurance test, exerting a maximum hoop stress of 3.2 MPa on the outer wall of the heat exchanger, which is estimated to have operated at a maximum temperature of 600°C during most of the test. No degradation in the integrity of the heat exchanger/pressure vessel was observed.

Basically, what happens in this method when the thrust is applied the mounting plate supported by steel flexures will move in opposite direction and the dispplacement will be measured by LVDT.

2.4 Floating turn table

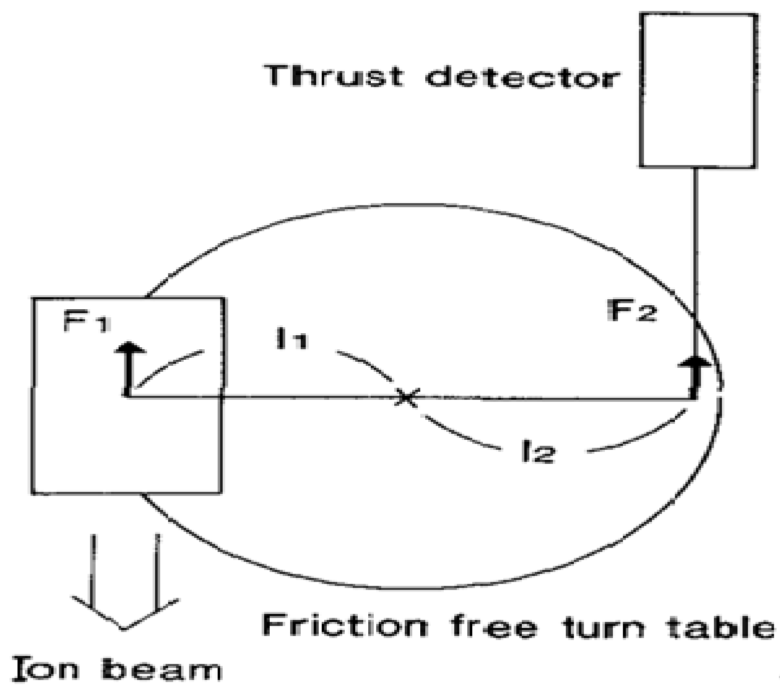


Figure 3: Floating turn table

H. Murakami et al designed and fabricated a thrust measuring device using gas bearing method. A direct thrust measurement of an ion engine using argon as a propellant was carried out in a vacuum chamber. All of the thruster components were placed on a floating turn table supported axially and radially by a gas bearing for friction free rotation. Theoretically, a thrust force of the ion engine can be calculated by production of an accelerating potential and a beam current. His paper presents results of direct thrust measurement using a thrust stand and a small light weight power supply unit. The measured thrust was 83% of the value calculated from the beam current and the accelerating potential. The difference between the measured thrust and electrically calculated one is considered to result from beam divergence, electron back streaming from the neutralizer, doubly charged ions and measurement error. It is not easy to make evaluation of above errors numerically.

The thruster will be mounted on a circular disc due to the thrust produced the table will rotate. The rotation will be measured by rotary encoder

Advantages:

- To realize a friction free condition the thruster system with necessary power supply units are isolated from measuring devices.

Disadvantages:

- The measured thrust was 83% of the value of calculated thrust
- Severe noise generation from the thruster and power supply unit.

2.5 Parallel Flexure balance

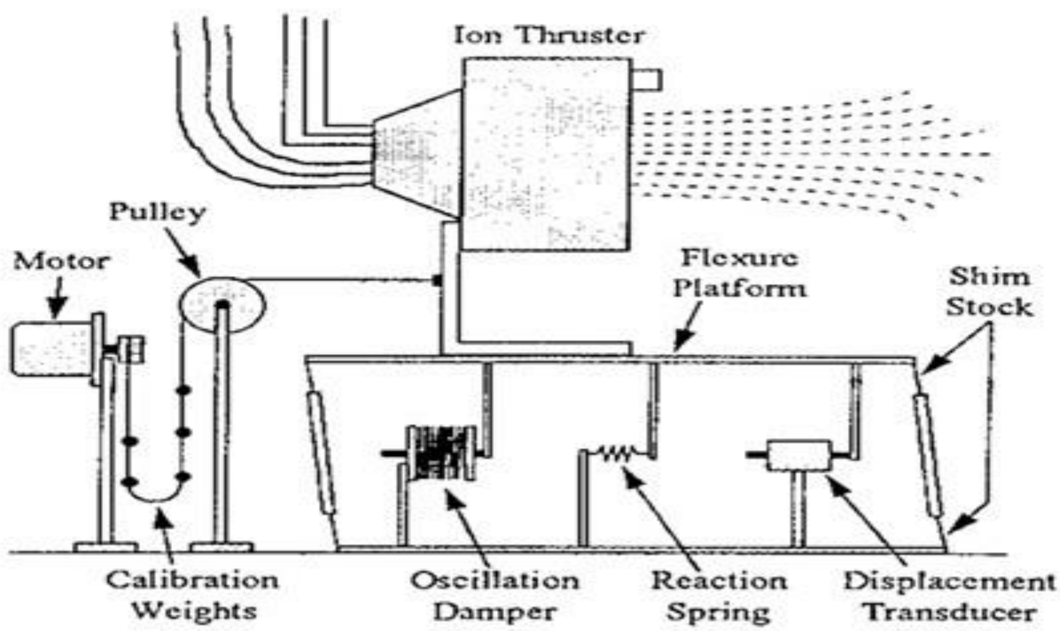


Figure 4: Parallel Flexure balance set-up

Pollard and Welle measured Thrust with a flexure balance for comparison with calculations based on the power supply current, beam divergence, and doubly charged ion fraction. After applying the known correction factors, the thrust balance result is at least 2%-4% lower than the calculated thrust, implying an unidentified loss mechanism. High resolution thrust observations directly reveal the effect of multiple ionization as a function of utilization efficiency. Ionization thrust losses are in the range of 1% - 6% depending on the propellant utilization efficiency. After applying the known correction factors, the thrust balance result is at least 2% - 4% lower than the calculated thrust, implying an unidentified loss mechanism. They measured thrusts in the range of 10-40 mN with a resolution of 0.3 mN.

The balance is configured as a hinged parallelogram with stainless steel shim stock for hinges. Its bottom plate is stationary, and its upper plate moves in response to a force while remaining parallel to the bottom plate. Engine thrust acts against a horizontal spring which resists displacement of the plates relative to one another.

Advantages:

- The flexure balance is enclosed in a grounded, water-cooled box, therefore very less possibility of thermal effects and electrical noise from the ion engine.
- To minimize thermal drift, the thrust balance is mounted on a framework that is thermally isolated from the ion engine and from the beam dump.

Disadvantages:

- Friction causes hysteresis that cannot be accounted for in the calibration process.

2.6 Simple pendulum method using LDS

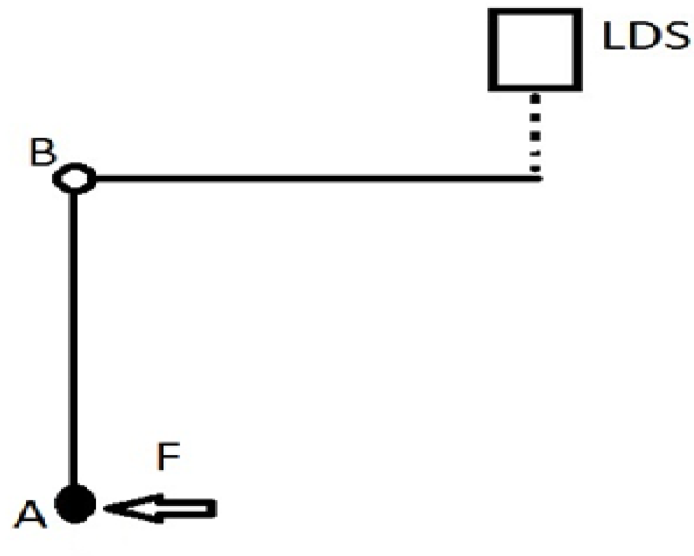


Figure 5: Simple Pendulum Method with LDS

In this method, laser displacement sensor is used to detect the linear displacement of pendulum arm, which can be used to determine its angular displacement. But it can only be used for small linear displacement, i.e. for small thrust.

2.7 Simple pendulum using Angular Encoder

The conventional hanging pendulum is the simplest configuration and is highly stable unlike the inverted pendulum. In this method angular encoder has been used to measure the angle rotated by the pendulum. The restoring force used in this method is gravity which is being acted on the bob of simple pendulum.

Advantages:

1. Most stable configuration as compared to the inverted and torsional pendulum configuration.
2. High Resolution.
3. It can measure the greater angular deflection from the equilibrium position which was not possible in the case of LDS.

Disadvantages:

1. Friction in the bearings cannot be neglected completely.
2. Small thermal effects will be present while using the actual thruster.

CHAPTER 3: SYSTEM DESCRIPTION

The system consists of simple pendulum connected to the angular encoder. Restoring force is the gravity acting on the thruster. Here we have used an electric fan as the thruster, as the weight of the fan wasn't enough to conduct an experiment, so the bob was used.

When thrust is applied, the pendulum rotates by some angle. This angle is measured by the encoder attached to the vertical support of the pendulum bob. Mat Lab software records the reading of the encoder.

Specification of the components used it the set up

3.1 Angular encoder

Specifications:

- Operating voltage 24VDC
- Load current 100mA
- 5000ppr
- Optical incremental encoder

Figure 6: Incremental Angular Encoder

3.2 Electric duct fan

Used in place of a thruster.

Specification:

- HL6408 2830-4500KV
- Fan motor is based on BLDC
- Diameter 64mm
- It produces different values of thrust on applying different potential across its terminals.
- It requires an esc (electronic speed controller) shown in fig.8 to run and control its rpm.

Figure 7: Electric duct fan with BLDC

Figure 8: ESC

3.3 LiPo Battery

Specifications:

- Power 2200mAh
- 11.1V
- 3 cells

Figure 9: LiPo battery

CHAPTER 4: DESIGN AND CALCULATION

4.1 DESIGN AND WORKING

Our final experimental set-up consists of a pendulum stand in which pendulum is hinged on the horizontal shaft which is supported by two ball bearings that are interference fit on a mild steel plate which is again welded on the two vertical square pipes. The incremental angular encoder is coupled using a coupling axially along the horizontal shaft on which the pendulum is welded. A 1.8kg mild steel billet is used as a bob to compensate for the mass of actual thruster which will be around 2kg as we are using an electric duct fan with BLDC motor as a thruster of approximately 125g. On supplying different voltages across the fan, it provides various values of thrust. The thrust force will rotate the bob up to some maximum angle. The angle turned by the pendulum will be equal to the angle rotated by the shaft on which it is welded, which will be recorded in the MATLAB software.

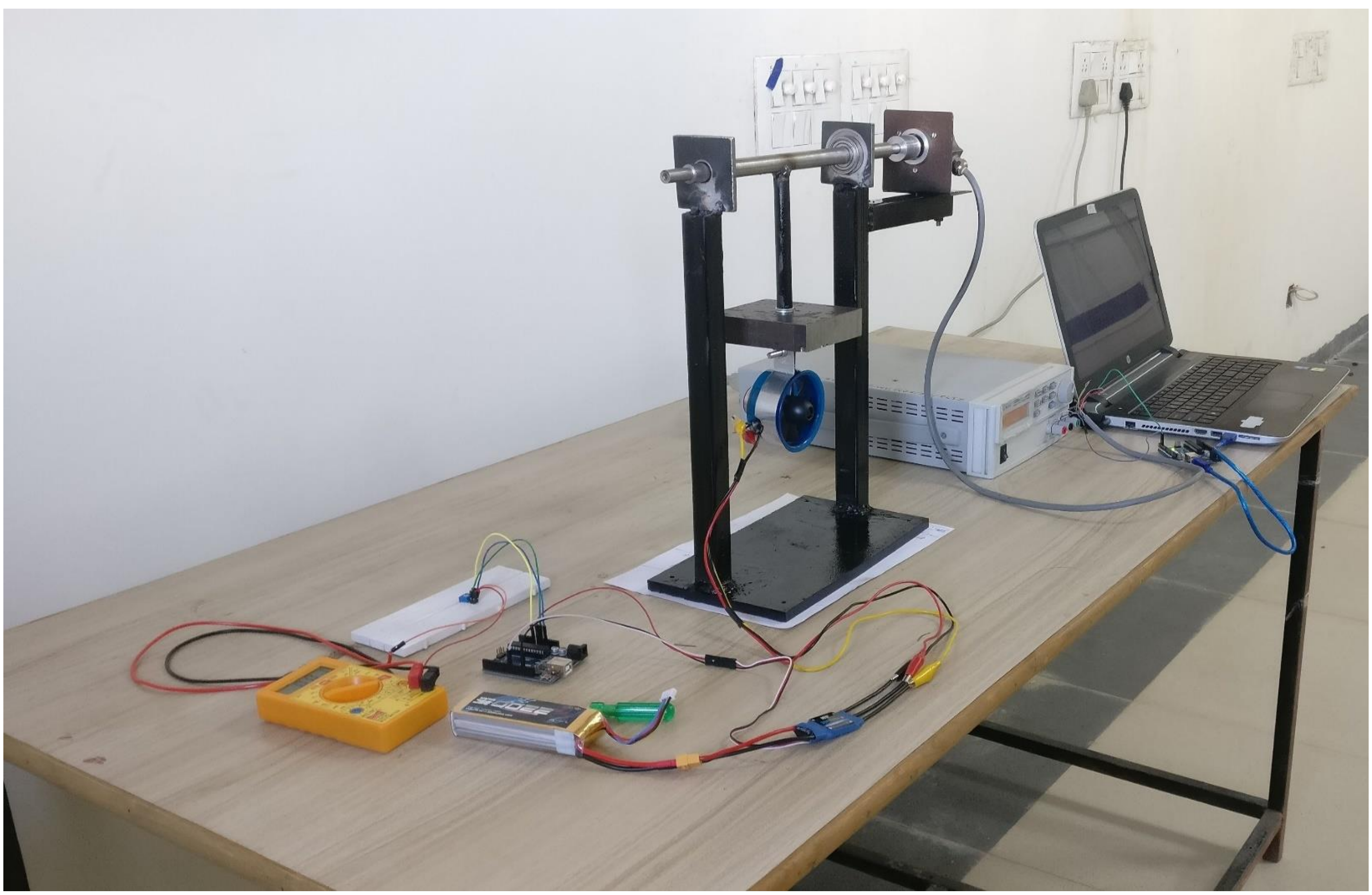


Figure 10: Experimental set-up

4.2 CALCULATION:

M_B= Internal moment due to hinge

Mass of Rod = 100g

Mass of fan = 125g

Mass of bob = 1.8kg

Center of gravity =14.23cm

k = torsional constant

Calculating moment about point B:

$M_B + mg(\sin\theta)*14.25 - F*20.75 = 0$

$\text{Sin}\theta = \frac{\boldsymbol{F*20.75-M_B}}{\boldsymbol{mg*14.25}}$

$F = mg(\sin\boldsymbol{\theta})*14.25 / 20.75 + \frac{M_B}{20.75}$

$M_B = k\,\boldsymbol{\theta}$

$k = 475\ N-cm/rad$

$F = \frac{\boldsymbol{mgsin(\theta)*14.25}}{\boldsymbol{20.75}} + \frac{475*\boldsymbol{\theta}}{20.75}$

Known values:

m = 2 kg

g = 9.81

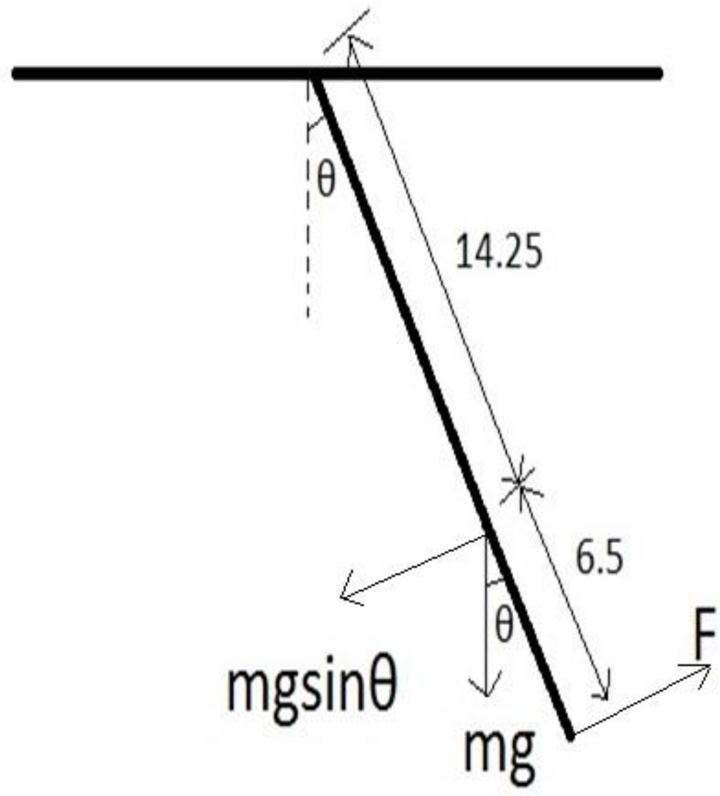


Figure 11: Force analysis

m/s^2

CHAPTER 5: RESULTS AND DISCUSSION

Table 1: ANGLE vs FORCE

ANGLE(in degrees)	Force (in N)
1	0.634125
2	1.268179
3	1.90209
5	3.169197
10	6.32948
15	9.472001
20	12.58805
25	15.66911
30	18.70695
35	21.69364
40	24.62165

Table 2: Force due to change in mass by +5%

ANGLE(in degrees)	Force(in N)
1	0.645865
2	1.291655
3	1.937295
5	3.227825
10	6.446289
15	9.646103
20	12.81812
25	15.9534
30	19.0433
35	22.07949
40	25.05407

Table 3: Force due to change in mass by -5%

ANGLE(in degrees)	Force(in N)
1	0.622385
2	1.244703
3	1.866885
5	3.11057
10	6.212671
15	9.297899
20	12.35798
25	15.38482
30	18.37059
35	21.30778
40	24.18923

Table 4: Force if length of pendulum changes by 10%

ANGLE(in degrees)	Force(in N)
1	0.615346
2	1.230618
3	1.845744
5	3.075259
10	6.141342
15	9.189143
20	12.20969
25	15.19424
30	18.13428
35	21.02168
40	23.84869

Table1 shows the variation of force with the angle swept by the pendulum calculated by the formula1 mentioned in the chapter 4. Table 2 and 3 shows the variation of force with the change in mass, as the thruster will continuously emit the thrust so its mass will kept on changing. Error due to change in mass by +5% is 1.845% and due change in mass by -5% is 1.85%   Table4 shows the variation of force with the change in length of pendulum arm, max error will be 2.45%. When mass and length both changes, we cannot calculate the error directly so it is calculated in terms of uncertainty.

Uncertainty due to 10% error in mass and length

Force = f (mass, length)

W_f = Uncertainty in force

W_l = Uncertainty in length

W_m = Uncertainty in mass

$$W_r = \left(\left(\frac{dF}{dm}\right)^2 * \omega_m{}^2 + \left(\frac{dF}{dl}\right)^2 * \omega_l{}^2\right)^{1/2}$$

$$W_f = \left((6.0147 * (\sin\alpha)^2) + \alpha^2\right)^{1/2}$$

$$\text{Percentage uncertainty} = \left(\frac{W_f}{F}\right) * 100$$

Uncertainty will be around 7.68% for all the angles ranging from 1.5º to 40º.

We did two experiments to calibrate our setup. The description of ducted fan that we used as a thruster is given i.e. on applying 10 volts across the fan current will be 27 amps and thrust will be 4.7 N and. on applying 11.1 volts across the fan current will be 31 amps and thrust will be 4.9 N.

Table5: Specification of ducted fan

Name	Volts	Amps	RPM	Thrust (g)
HL6408 2830-4500KV	10	27		480
	11.1	31		500
	12.6	36.2		596
	14.8	44		740

EXPERIMENT-1:

Voltage = 10V

Theoretical Thrust = 4.7N

Angle recorded by encoder (386 pulses out of 19500)

θ = 7.126 degree

From equation 1

K = 505 N-cm/rad

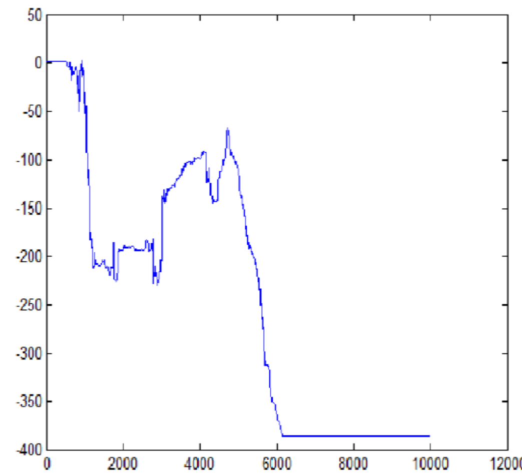


Figure 12

EXPERIMENT-2:

Voltage = 11.1V

Theoretical Thrust = 4.9N

Angle recorded by encoder (450 pulses out of 19500)

θ = 8.3 degree

From equation 1

K = 425 N-cm/rad

Average value of Torsional constant (K) from the two experiments

K_{avg} = 465 N-cm/rad

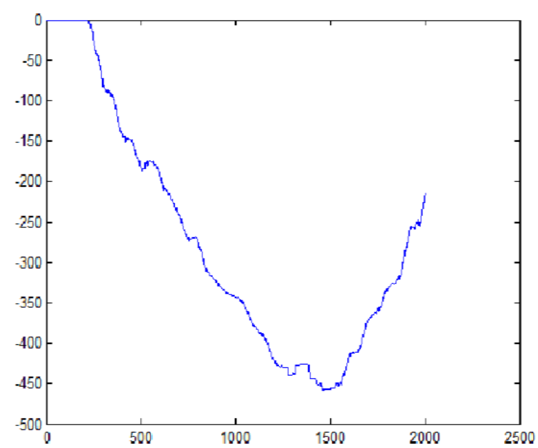


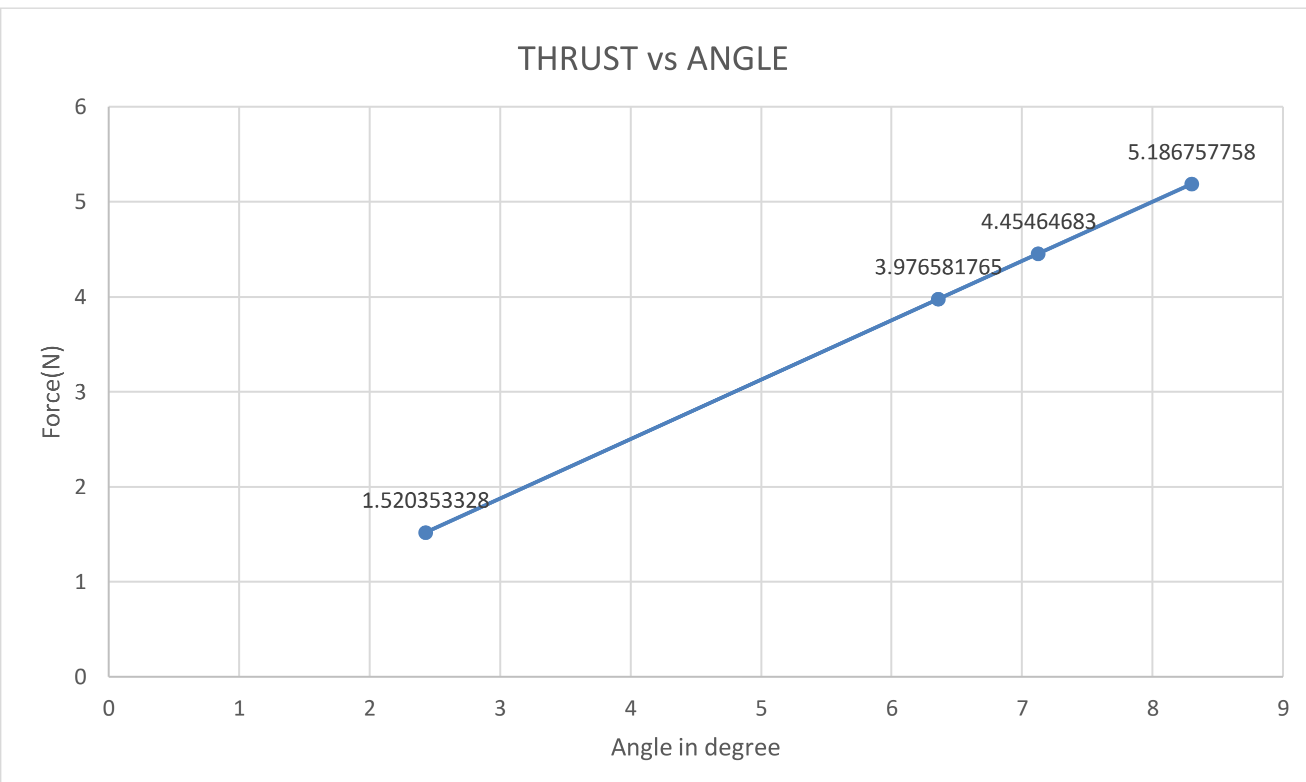
Figure 13

Therefore using this value of K, we can calculate the experimental value of Thrust

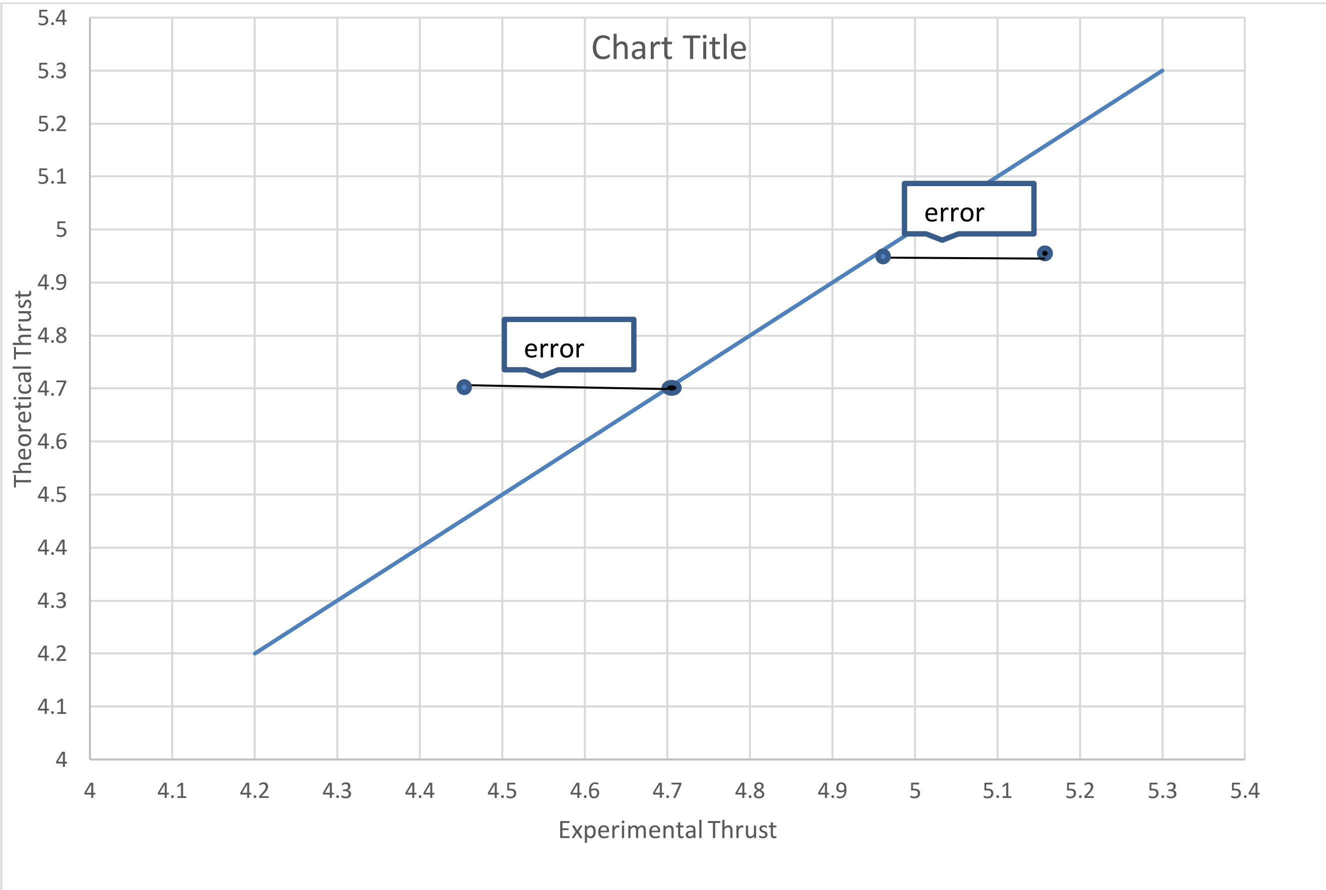
- For θ = 7.126° , Thrust = 4.4546 N, Error = 5.2214%
- For θ = 8.300° , Thrust = 5.1867 N, Error = 5.851%

Variation of thrust by varying applied Voltage across ducted fan

Volts(V)	Angle(degrees)	Thrust(N)
8.15	2.43	1.520353
9	6.36	3.976582
10	7.126	4.454647
11.1	8.3	5.186758



Variation of theoretical thrust vs experimental thrust



CHAPTER 6: CONCLUSIONS AND SCOPE OF FUTURE WORK

The report presents design and development of a thrust measuring device using simple pendulum for measuring of thrust ranging from 1N to 25N with a resolution of 0.1N. From above discussion we concluded that for measuring thrust in the range of 1N to 25N, angle recorded by angular encoder will be from 1.5º to 40º. Error due to change in mass will be 1.85% and due to change in length will be 2.45%. Uncertainty due to change in mass and length will be 7.68%. The value of torsional constant from the two experiments is 465 N-cm/rad. Resolution of Angular Encoder is 0.01846° so force resolution will be 0.011706 N. Error in actual thrust measurement is around 5.5%.

The above error can be reduced by reducing the diameter of bearing. Also the angular encoder we are using is very sensitive i.e. due to small vibration it's pulses fluctuates too much which is the major cause of error, so efforts can be made to reduce vibration or using alternative method to measure angle.

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