Test facility development for testing of micro-thrusters at TU-Delft

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ABSTRACT

The development of highly integrated and compact micro-satellites and the need for a higher precision of positioning and attitude control in space missions has stimulated the development of micro-propulsion systems. At TU-Delft, investigations are focusing on non-chemical, thermal propulsion. TU-Delft is also collaborating with TNO and UTwente to develop a mini-propulsion system (T^3-μps) to be flown in 2011 as part of the MicroNed Nanosatellite Program. To complement these developments, the TU-Delft is developing test facilities and equipment for on ground testing of such systems. The most critical need is the ability to take thrust and impulse bit measurements with adequate accuracy and resolution. To this purpose, the TU-Delft has developed a thrust stand capable of measuring thrust levels in the range 100-1000mN and minimum impulse bit of 5mNs as well as a smaller stand capable of measuring thrusts ranging from 0.5-50mN and a minimum impulse bit of 0.05mNs. In collaboration with Universidad Politécnica de Madrid, we are currently investigating the development of a thrust stand capable of measuring thrust levels in the range 10-2000μN with an accuracy of ± 2μN and minimum impulse bit of 0.25μNs. In addition, for thruster testing under rough vacuum conditions, a Heraeus vacutherm oven has been successfully adapted.

This paper describes the test facility developments made at the TU-Delft as part of the MicroNed program. We will describe the design objectives, and the design methods used, provide an outline of the thrust stands and the vacuum facility and talk about their development status and how well they perform. Also test results will be presented to show the performances of the various thrust stands and the benefits of testing under rough vacuum conditions.

NOMENCLATURE

c	Damping coefficient [Ns/m]
F	Force amplitude [mN]
g	Gravity constant [m/s^2]
F_{ax}	Axial load [N]
k	Stiffness N/m]
m	Mass [kg]
n	Number of periods [-]
r	Frequency ratio [-]
T	Oscillation period [s]
t	Time [s]
x	Displacement [mm]
δ	Logarithmic decrement [-]
σ	Sample standard deviation [-]
ω_d	Damped frequency [Hz]
ω_n	Natural frequency [Hz]
ζ	Damping ratio [-]

INTRODUCTION

The last decade or two has seen a steady rise in interest in microsatellites. Typical missions for such satellites include Earth observation, low cost communications, research and developmental testing of new space hardware, materials and processes applicable to larger spacecraft, relaying amateur radio messages and a wide array of other uses [SSHP], [Bentum], [Moser]. This is because microsatellites are considered useful, affordable and fast to build. [Kasteren] also mentions that in some situations swarms of relatively simple small satellites could offer increased performance at reduced vulnerability as compared to today's large and complex spacecraft. An enabling technology in this respect is the propulsion system that provides the spacecraft with the capability to perform orbit transfer, on-orbit repositioning and formation flying.

A number of propulsion technologies are currently being explored with some very promising results. A good overview of some of these efforts is provided in [Micci]. At TU-Delft research focuses on the development of micro-propulsion systems in the thrust range below 1N. Some examples are the T^3 cold gas micro-propulsion system (T^3-μps), solar thermal thrusters and resistojets [Zandbergen], [Rycek], [Leenders].

Part of the development of such systems is to characterize their performance on ground. Interest is in both steady state and dynamic performances. For instance, the T^3-μps that is to be integrated on Delfi-n3Xt shall be able to provide a steady state thrust ≤ 6mN and a minimum impulse bit ≤ 0.1mNs

[Müller]. For performance testing of micro-thrusters on ground a dedicated thrust bench (stand) is necessary as the thrust levels are extremely small, which renders the measurements noise sensitive.

As a first attempt we modified an existing bench by replacing the load cell with one that is much better suited for thrust levels of up to 1000mN. This bench, referred to as Thrust Bench 1.0 (TB-1.0) was used in 2008 to test an engineering model of the T^3-μps [Zandbergen] as well as a range of other thrusters. Results though show a high noise content in the signal, necessitating measuring over long times (up to several tens of seconds).
Since 2008, work is conducted to extend measurement capabilities to lower thrust levels and also to small impulse bits. To this end the TB-1.0 has been rebuild using lighter materials, thereby greatly reducing the noise content in the signal. In addition a dedicated thrust bench has been developed to allow for accurate thrust measurements in the range below 50mN and we are currently investigating a new bench capable of measuring accurate thrust levels below 2mN. In addition, we have adapted a commercially available thermal vacuum oven for thruster testing under rough vacuum conditions. In this paper the results of these efforts are described.

AVAILABLE THRUST STANDS

TB-1.0

Thrust Bench 1.0 is a pendulum type of thrust stand, see Figure 1. It was originally designed for measuring thrusts ≤ 20N. It was adapted for the testing of micro-thruster by changing the load cell to one with a thrust range ≤ 1N. An overview of the bench's main characteristics can be found in the Table 1.

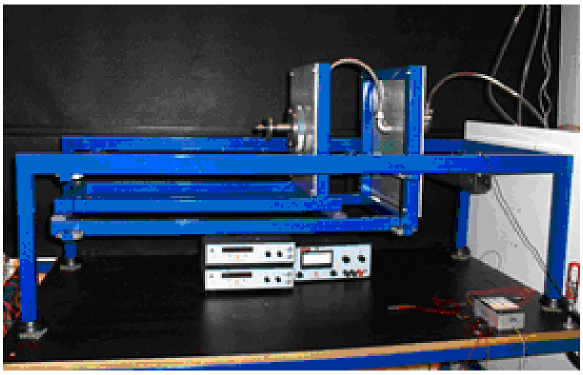

Figure 1: TB-1.0 pendulum type of thrust bench

The TB-1.0 though proved prone to environmental vibrations. Measurement results showed a noise amplitude of 90mN (3σ) which led to long integration times and hence a limited capability to measure small impulse bits. In addition, the system proved to be quite bulky and heavy with a total mass of 40 kg (without thruster).

TB-1.1

The TB-1.1 thrust bench, see Figure 2, is of a similar design as the TB1.0 except for the use of lighter materials and a reduced size. This allowed reducing the pendulum mass with about a factor 12 to 1.64 kg. As a consequence the noise level in the thrust signal was reduced to 5mN (3σ). In addition, the outer frame holding the pendulum was adapted to allow for better accessibility. Its main characteristics can be taken from the Table 1.

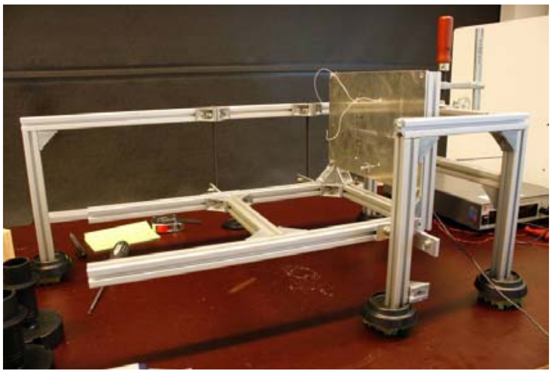

Figure 2: TB-1.1 pendulum type of thrust bench

TB-50m

This thrust bench is essentially a torsion balance type of bench using a lubricant-free, ball bearing in the rotary point. Through a mass symmetric design, using balance masses to balance the weight of the thruster, this design promises a much lower susceptibility to noise than the former two. It is equipped with a load cell capable of measuring thrust levels ≤ 100mN.

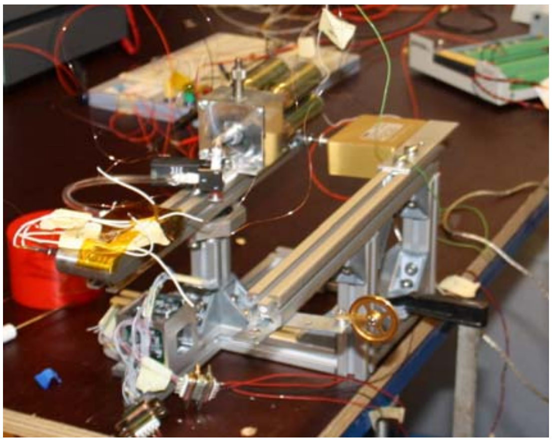

Figure 3: TB-50m torsion type of thrust bench

TB-2m

At present, we are developing a new thrust bench for measuring thrust levels in the range 10-2000 μN and impulse bits as low as 10 μNs. This work is done in cooperation with the UP Madrid. This bench, in contrast to the other three benches, is of the displacement measurement type allowing for adapting to different thrust ranges. A counter mass is incorporated in the design, thereby allowing for larger displacements at low thrust levels. Like for the

TB-50m this counter mass also serves as a balance mass. An important difference is that a vertical pendulum setup is used together with frictionless pivots and a torsion spring. A schematic of the design is given in the Figure 4.

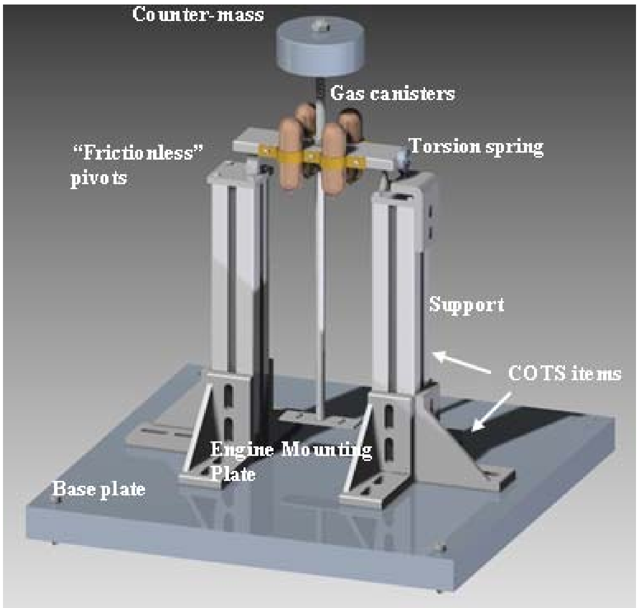

Figure 4: TB-2m vertical pendulum thrust bench (displacement measurement type)

A laboratory model has been built and is prepared for testing. Total mass including base plate (but excluding thruster) is 15 kg.

To allow for displacement measurement various non-contact options have been evaluated including a Linear Voltage Displacement Transducer (LDVT) and a laser-based optical system. Both options are feasible. The preferred solution for now is to use the laser-based optical system as it is not adversely affected by thermal drifts of the thrust stand. It can also be easily reconfigured to measure different deflection angles by simply changing the path length of the laser beam. The expected characteristics of the bench are given in the table 1.

DYNAMIC MODELLING

All facilities have been analyzed to determine the natural frequency, damping ratio and stiffness properties assuming that the benches behave as an under-damped second order system. The behaviour of the pendulum is generally described by

$$\frac{d^2x}{dt^2} + c/m \frac{dx}{dt} + k/m\, x = f(t) \qquad (1)$$

Here m is mass, c is damping coefficient, k is stiffness and x is displacement.

In case of absence of a drive force we may write:

$$\frac{d^2x}{dt^2} + 2\zeta\omega_n \frac{dx}{dt} + \omega_n{}^2 x = 0 \qquad (2)$$

Where ω_n is the undamped angular frequency of the oscillator and ζ is a constant called the damping ratio. It follows:

$$\omega_n = \sqrt{k/m} \text{ and } \zeta = c/2m\omega_n \qquad (3)$$

For an underdamped system, the solution can be written as:

$$x(t) = Ae^{-\zeta\omega_n t} \sin(\omega_d t + \phi) \qquad (4)$$

In this equation ω_d is the so called damped natural frequency given by:

$$\omega_d = \omega_n \sqrt{1-\zeta^2} \qquad (5)$$

Both damping ratio and damped frequency can be obtained from the response of the thrust bench to an impulsive load, see for instance the next figure as determined for the TB-1.0.

Table 1: Characteristics of TU-Delft micro-thruster thrust benches

Parameter	**TB-1.0**	**TB-1.1**	**TB-50m**	**TB-2m***
Thrust range	50-500 mN ± 1%	20-1000 mN ± 1%	1-50 mN ± 1%	10-2000 μN ± 10%
Thrust resolution	≤ 1 mN			≤ 2 μN
Minimum impulse bit	1-10 mNs ± 1%	1-10 mNs ± 1%	0.05 mNs	10 μNs ± 10%
Temperature sensitivity	≤ 10 mN/K	≤ 65 mN/K	≤ -0.32 mN/K	≤ 0.5 μN/K
Natural frequency	3.9 Hz	13.1 Hz	10 Hz	4 Hz
Damping ratio	0.0084	0.0286	0.037	0.0085
Stiffness	1.2 x 10^4 N/m	265.3 N/m	772.4 N/m	0.3 Nm/rad
Thruster mass	≤ 1kg	≤ 0.5 kg	≤ 360 gram	≤ 300 gram
Thruster dimensions	200x200x500 mm^3	≤ 100x100x150 mm^3	≤ 50x50x80 mm^3	≤ 30x100x100 mm^3

* Design values

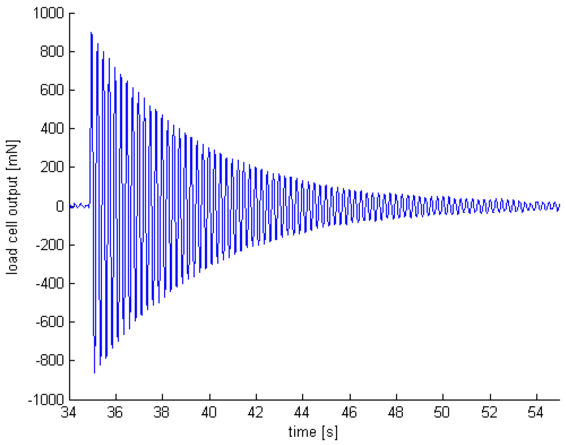

Figure 5: Measured response of TB1.0 to an impulsive load

The damped frequency is determined by applying Fourier analysis to the data obtained. For the TB1.0 this gives a damped frequency of 3.9Hz. The damping ratio is estimated from the logarithmic decrement δ using:

$$\zeta = \frac{\delta}{\sqrt{4\pi^2 + \delta^2}} \qquad (6)$$

From the Figure 5 follows a logarithmic decrement of 0.0525 which results in a damping ratio $\zeta = 8.4 \times 10^{-3}$. Typical values for the natural frequency and damping ratio as obtained from measurements for the various benches can be obtained from the Table 1.

Step response modelling

When a thruster is actuated to produce a steady state force, the pendulum starts oscillating about some new equilibrium position. It is interesting to find out the time needed for the oscillation to damp out sufficiently to obtain a reasonably accurate reading of the new equilibrium position (or force).

To study the response of the various thrust benches to a (step) loading of the bench, f(t) is modelled by the Heavyside function. In the absence of disturbances it follows for the measurement time needed to obtain a given measurement accuracy a:

$$t = \frac{\ln\left(a \cdot \sqrt{1-\zeta^2}\right)}{-\zeta \cdot \omega_n} \qquad (7)$$

For instance for an accuracy better than 1%, the required measurement time for the TB-1.0 is in excess of 20s and less than about 3s for the TB-50m. A shortening of the time needed can be achieved when averaging the thrust over the measurement time. In practice, this requires a high sampling rate, typically a factor 10 in excess of the damped frequency of the bench.

Response to an impulse bit of finite length

To determine the response of the various benches to an impulsive load f(t) is modelled by the Dirac delta function. This leads to the following relation for the displacement of the pendulum

$$x(t) = \frac{\hat{F}}{m\omega_d} e^{-\zeta\omega_n t} \sin(\omega_d t) \qquad (8)$$

At the first peak t = ¼T and sin $(\omega_d t)$ = 1. Substituting these values in equation 20 and after some rearrangement, results in

$$\hat{F} = x(t)\frac{m\omega_d}{e^{-\zeta\omega_n \frac{T}{4}}} = x(t)\frac{m\omega_d}{e^{-\zeta\frac{\pi}{2\sqrt{1-\zeta^2}}}} \qquad (9)$$

This then allows determining the impulse bit produced by measuring the amplitude of the displacement.

Figure 6 gives a typical response as calculated for the TB-50m to a pulse bit of duration 0.1s and thrust 10mN.

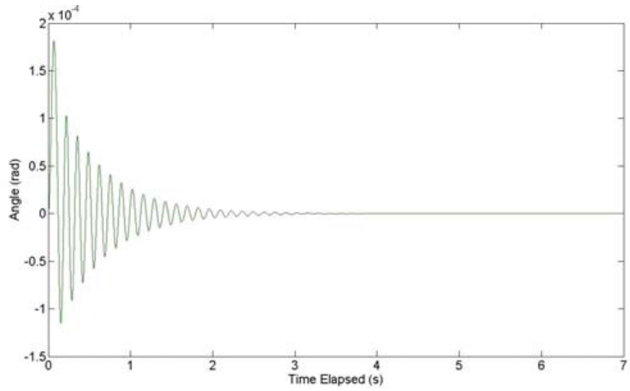

Figure 6: Simulated response TB-50m

Latest step in modelling is related to the development of the TB-2m and aims to generate the thrust curve from the measured displacement. Following [D'Souza], and [Rocca] a TRIM (Time-Resolved Impulse measurement) tool has been developed based on the general equation of motion of the system. This tool not only shortens the time needed to obtain a steady state thrust, but also allows determining impulse bits with varying thrust levels during the impulse bit. To test this tool, we also used Lagrangian mechanics to model the response to various impulse bits, but also to the mechanical vibrations coming from the environment. A typical example is shown in the Figure 7.

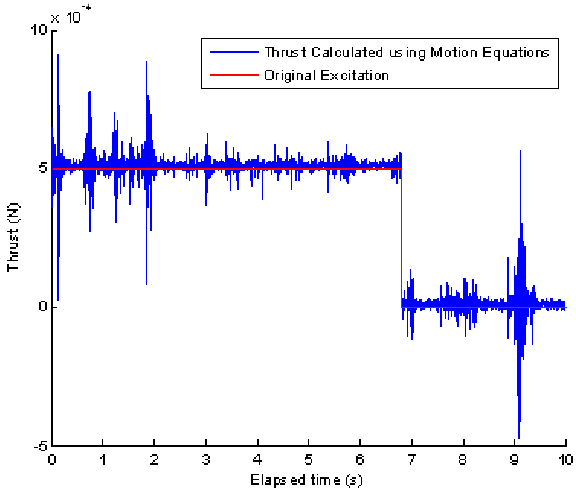

Figure 7: Impulse bit with noise

Next, the TRIM tool is used to reconstruct the original signal. The result after filtering, together with the original impulse bit, is shown in the Figure 8.

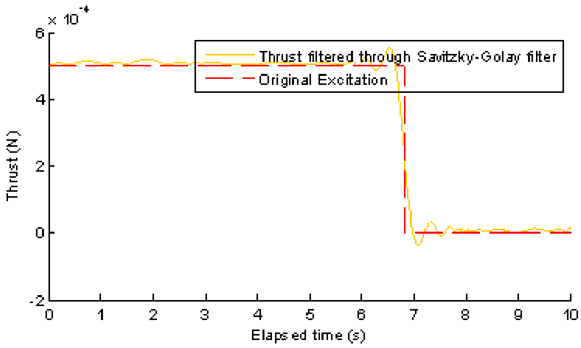

Figure 8: Reconstructed impulse bit

The result clearly demonstrates the capability of the TRIM tool together with the filtering to construct the thruster impulse bit. More on this work will be presented in more detail at the IAC 2010.

ACCURACY ANALYSIS

The various benches are all analysed for measurement accuracy. For the benches that use a load cell, the main error sources are the load cell it self and the Data Acquisition and Control System (DACS). For the TB-2m, the load cell is replaced by the displacement sensor and we need to include the errors made using the TRIM tool. A Monte Carlo type of analysis is used to determine the thrust measurement accuracy. Some results can be found in the Table 1.

CALIBRATION

To validate the thrust measurement, calibration methods have been devised thereby distinguishing between steady state force and impulse bit calibration

Steady state force calibration

Calibration is performed by hanging weights of the pendulum or balance with a pulley, also referred to as Weight-Pulley Calibration (WPC). According to [Polzin] the method is applicable for thrust levels in excess of 1mN and allows for a resolution down to 0.05mN. To take into account the effects of data wires, power cables, propellant feed tubes, etc. the calibration is performed with the thruster mounted on the bench and with all equipment connected as for the testing.

For vacuum calibration and to obtain experience with other calibration methods we use for the TB-50m an electromagnet to generate a small, controlled force. The electromagnet itself is periodically calibrated using WPC. Comparison showed a difference in force generated in vacuum and under normal atmospheric conditions of less than 0.5mN in the thrust range below 10mN. At higher force levels unfortunately a noticeably larger difference was found. This was found to be due to a change in temperature of the electromagnet which showed to be more pronounced in vacuum than under calibration conditions. Further development is necessary to allow for extending the force range to be handled.

Impulse bit calibration

Following [Wilson], calibration for impulse bit measurements is by using small metal balls that impact on the thrust stand. The balls are wire suspended from a tripod. Release is by de-activating an electromagnet. Momentum transfer is measured directly using a force transducer. The integration of the first force peak (quarter period) yields the applied impulse bit, see Figure 9.

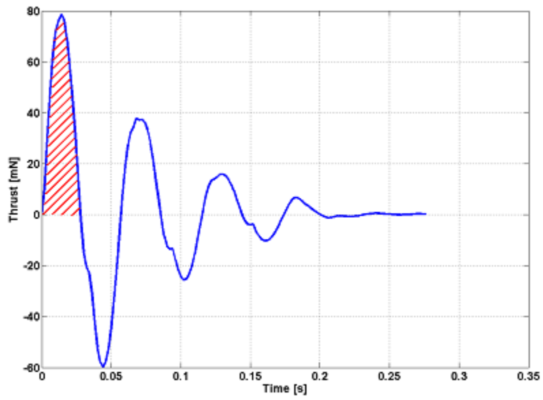

Figure 9: Response to ball impact

Typically 10 impact measurements are made to allow obtaining an average value and a sample standard deviation for each point in the calibration curve.

TEMPERATURE EFFECT

The Figure 10 shows the change in room temperature as experienced over a day as well as the effect of this change on the thrust measured for the TB-50m at zero load conditions.

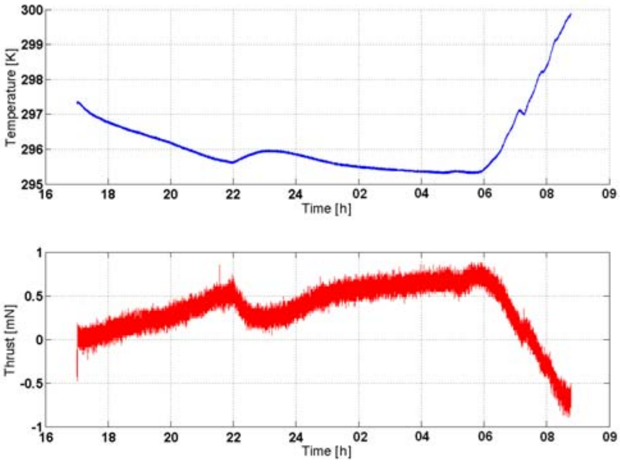

Figure 10: Temperature effect on TB-50m thrust measurement at zero load conditions

The top figure shows that the temperature in the laboratory varies about 5K over the period considered. The bottom figure shows the associated change in thrust. From these results a temperature sensitivity of -0.315mN/K can be calculated. The temperature effect is attributed due to differences in elongation between the various elements of the thrust bench related to a change in temperature.
Temperature sensitivity has also been experienced with the other benches. Typical data are provided in the Table 1. The higher sensitivity of the TB-1.0 and TB-1.1 is caused by the different construction of the benches as compared to the TB-50m. The higher sensitivity of the TB-1.1 is attributed to the use of aluminium as the main construction material as opposed to steel for the TB1.0. The latter material has a smaller thermal expansion coefficient.

VACUUM FACILITY

To allow for performing tests under (rough) vacuum conditions (vacuum pressure in the range of 10 mbar) we have recently adapted a Heraeus vacutherm VT 6025 thermal oven for micro-thruster development, with near-term focus on the TU-Delft, TNO and UTwente developed T^3-µPS as well as for the development of milliNewton hot/cold gas thrusters. The Figure 11 shows the vacuum chamber with TB-50m visible through a windowed door. The chamber has a volume of 352x386x424 mm^3. The window allows for monitoring the test status and measuring infrared transmissions, for instance for temperature measurements of heater chambers. In addition, access ports are available for pressure sensors and thermocouples as well as for providing command signals (2 9-pin connectors and 1 7-pin connector). A three stage totally oil free diaphragm pump provides a pumping speed of 1.3m^3/h with an ultimate pressure of 1.5mbar. Values obtained with a working nitrogen cold gas thruster in the chamber range from 10-90 mbar for a (nitrogen) mass flow rate in the range 10-30 mg/s.

Figure 11: Vacuum chamber with TB-50m

CONTROL AND MEASUREMENT SYSTEM

A PC-based data acquisition and control system (DACS) is available that is operated using LabVIEWtm, a graphical programming software package for measurement and control. The system makes it possible to measure the thrust, pressure, mass flow rate, and temperature and to control valves. Remote operation and monitoring are possible for these measurements and control systems using a local area network.

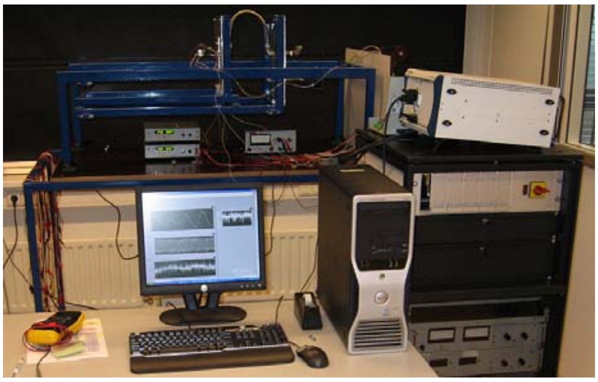

Figure 12: DARTS test facility.

NOISE

When using the TB1.0 bench for the first time, we were immediately confronted with a very high noise content of the signal. This is illustrated with the Figure 13.

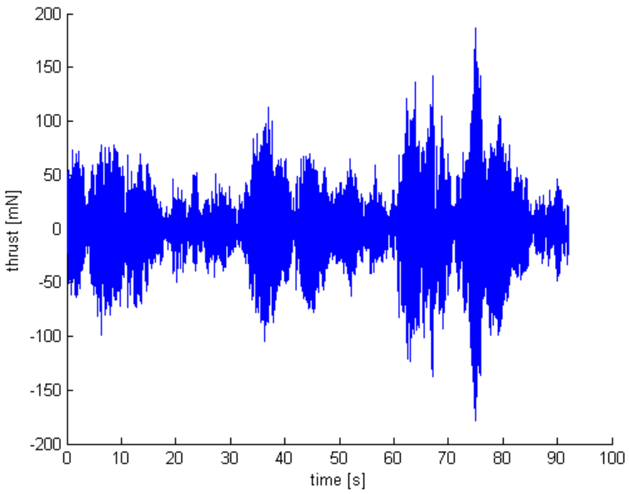

Figure 13: Zero-thrust measured by TB-1.0

To determine the mechanical noise coming from the environment (support motion), accelerometer measurements have been made in three orthogonal directions. The accelerometers were rigidly fixed on to the table stand supporting the thrust bench. The Figure 14 shows a typical result as measured parallel to the load direction of the load cell.

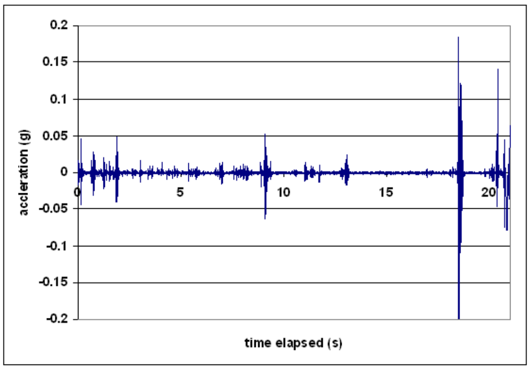

Figure 14: Mechanical disturbance environment

The figure shows acceleration levels measured over a period of 21s at a sampling rate of 500Hz; large peaks are attributed to doors closing, elevator movement and people walking by. Maximum acceleration measured is 0.26g. Standard deviation over the period is 1 x 10^{-2}g. Measurements also showed that in the evenings the noise level can be significantly less ($\sigma < 2.5$ x 10^{-3}g). Sensitive measurements are therefore made after 5 in the afternoon.

From the accelerometer measurements also the frequency of the environmental vibrations has been determined using Fourier analysis. Results show that the main frequency of the noise is ~70Hz.

The acceleration transmitted from the table support to the mass is estimated using [Paz]:

$$T_r = \frac{\sqrt{1+(2r\zeta)^2}}{\sqrt{(1-r)^2+(2r\zeta)^2}} \qquad (10)$$

Here r is the frequency ratio, which gives the ratio between the forcing frequency and the frequency of the pendulum. For the TB1.0 the acceleration transmissibility is 6.2 x 10^{-2}. For standard deviation in the forcing load of 2.5 x 10^{-3}g and a pendulum mass of 19.5kg this results in a thrust noise with standard deviation $\sigma \leq 27$mN, meaning that about 95% of all noise is in the range ±54mN.

For its successor TB1.1 the pendulum mass was considerably reduced (about a factor 12) to reduce the effect of the mechanical noise environment. As a consequence, the damped frequency of the bench is increased to 13.1Hz (about equal to the natural frequency), which gives an acceleration transmissibility of 0.240. Applying the same calculation as for TB-1.0, this would mean a reduction in thrust noise down to ±20mN (2σ range). The success of this approach is illustrated by Figure 15, which shows an even better result. The latter is probably associated with a further reduced noise environment due to measuring late in the evenings or an effect of the frame on the transmissibility.

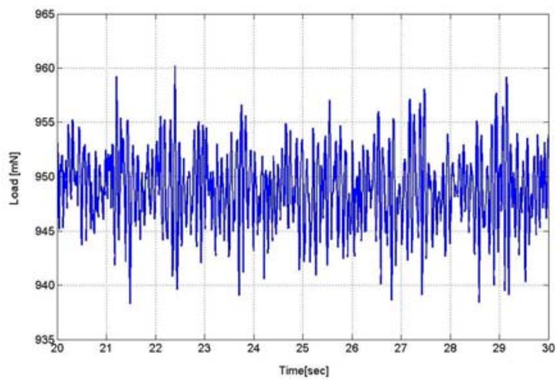

Figure 15: TB-1.1 thrust noise under steady state conditions

Noise levels for the TB-50m are much smaller than for the TB1.1. This is due to the mass-symmetric design of the TB1.1 that further reduces noise.

STEADY STATE THRUST

The next figure shows test results of a micro-thruster providing a steady state sea level thrust of about 10mN obtained with the TB1.0 test bench. Sampling rate is 100Hz. Top figure shows chamber pressure. At time t = 40s propellant start flowing in the chamber until after about 70s (t = 110s) the chamber is filled and equilibrium is reached. At time t = 270s the mass flow is stopped and the pressure returns to zero. The bottom figure shows recorded thrust values during this test. It clearly shows that the thrust signal is hidden under the high noise content.

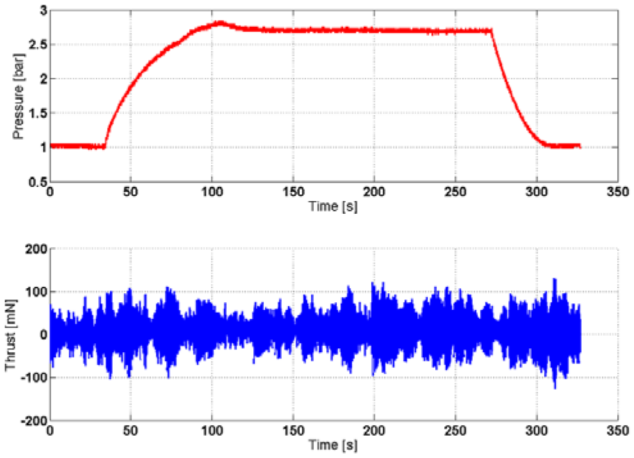

Figure 16: Pressure (top) and TB-1.0 measured thrust (bottom)

To remove the noise, simple averaging can be used. Another approach is by applying filtering techniques. As an example, the Figure 17 shows the filtered result of the measurement shown in the Figure 16. In this case filtering was applied using a Butterworth filter of the 5th order with a cut-off frequency of 0.2 Hz.

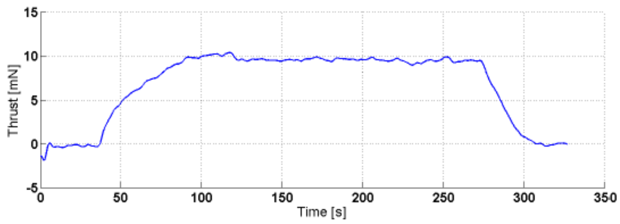

Figure 17: Filtered thrust

From the figure now clearly can be seen that after start up the thruster produces a steady state thrust of 10mN.

The same test has been repeated but now using the TB-50m thrust bench. The result, see Figure 18, is now directly visible without any data elaboration needed. This clearly stresses the importance of limiting the noise content in the signal.

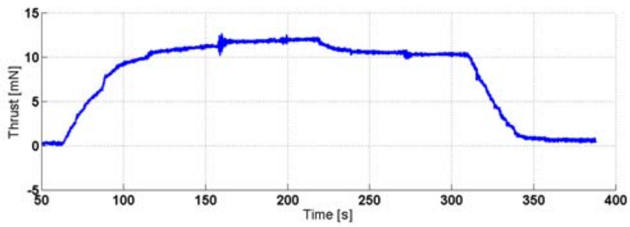

Figure 18: Thrust as measured by TB-50m

IMPULSE BIT MEASUREMENT

First impulse bit measurements have been made using the TB-50m and a 5mN micro-thruster. The result is shown in the Figure 19. Valve opening occurs at time 36.7s and closing at time t = 37.0s. This gives a pulse width of 300 ms.

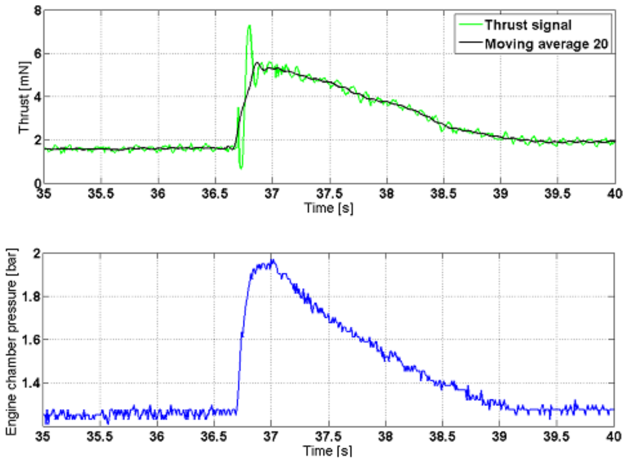

Figure 19: Impulse bit measurement

Filling of the thruster plenum is quite fast as is indicated by the steep rise in pressure at valve opening. The slower pressure decay after valve closing is associated with the large volume of the plenum and the limited outflow. The reason for the thrust to be different from zero at the start could later be traced back to a leaking valve. The double peak visible in the thrust curve at the onset of the impulse bit is associated with the valve opening, which introduces a vibration in the test bench. The total impulse bit that follows from integration is 4.6mNs.

CONCLUSION

Since 2004, various thrust benches have been developed at TU-Delft with as main aim to allow thrust and minimum impulse bit performance of micro-thrusters. The various benches have been used to measure the performances of various thrusters with thrust levels up to 500-600mN. Lowest thrust level measured is in the range 3-5mN. Smallest impulse bit measured so far is 1.36 x 10^{-3} mNs, but measurement capability allows for much lower levels to be measured, see the Table 1. However, this is still open for verification.

The validity of the thrust benches needs to be further verified, for instance by comparing the performances of other thrust benches applied to one and the same thruster. Also results should be compared with results in other facilities to find out if facility effects should be considered.

In the near future, the development of the TB-2m thrust bench will be finalized. Also care will be given to improving the vacuum calibration method as devised for the TB-50m to allow for higher thrust levels.

It is also foreseen to include a means of temperature control for the thrust benches to reduce/limit temperature sensitivity and to include some means of isolating the benches from the vibrations induced by the (mechanical) environment.

For the vacuum facility, it is considered to enlarge the pumping capacity and to improve the vacuum level to ≤ 1 mbar. This is considered essential to also allow for resistojet and solar thermal thruster measurements.

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