TRACEABLE, HIGH-ACCURACY THRUST MEASUREMENT FOR ELECTRIC PROPULSION

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High-accuracy, traceable, thrust and thrust noise measurement are becoming increasingly important with the demands being placed on electric propulsion systems for both scientific space missions and commercial applications. At the National Physical Laboratory (the UK's National Standards Laboratory) a number of thrust and impulse calibration systems have been designed and manufactured for various customers. These instruments cover the thrust range from less than 1 µN to 500 mN and impulse range 0.05 to 1 mNs. All the systems employ the design philosophy that a clearly identified and direct route to traceable calibration is inherent in the design, that sources of systematic uncertainty are minimised and that immunity to the influences of external noise sources is built-in.

In this paper, we briefly describe a number of thrust and impulse calibration devices giving particular emphasis to a recent calibration system developed for ESA's GOCE mission. The GOCE thrust balance requires a measuring range of up to 20 mN, a resolution of 3 µN, an accuracy of 20 µN and a measurement bandwidth of 10 Hz (rising to above 100 Hz for thruster step response measurement).

INTRODUCTION

The National Physical Laboratory (NPL) is the UK's National Standards Laboratory. As such, NPL is responsible for maintaining and disseminating the National Standards for the base units (*e.g.* kg, m, and s) within the International System (SI) of measurement, as well as derived units such as the newton. In addition to this nationally funded activity, NPL is unique among the major European National Measurement Institutes in that it is free to pursue third-party metrology-related research and development contracts. With over 600 scientists - experts in all fields of metrology - and world-class facilities, NPL is well placed to undertake demanding research and development activities in many fields.

One activity with which NPL is becoming increasingly involved is the development of instruments for characterisation and calibration of the force produced by a variety of electric propulsion devices. Over the last few years, NPL has developed a number of instruments, for ESA and other customers, to measure thrust and thrust noise for FEEP, ion and Hall-effect thrusters. Together, these instruments cover a measuring range from less than 1 µN to 500 mN and a measurement bandwidth of up to more than 100 Hz. Additionally, we have developed a simple device for measurement of impulse produced by micro-machined digital impulse devices.

DESIGN PHILOSOPHY

The philosophy behind the thrust balances produced by NPL has always been to produce a device with a traceable calibration (ie a calibration that can be compared to national standards by a series of well defined and documented steps), that has as high an immunity to tilt and vibration as possible and an electrical output directly proportional to thrust.

In order to achieve this, all the designs have been based on a force feedback nulling servo system, where a force of equal and opposite magnitude to the thrust is applied to the thruster by a force actuator. The output signal from the balance is then the electrical input to the nulling force actuator and this has been previously calibrated directly against fundamental International Standards.

Force feedback

Most of the thrust balances constructed by others[i, ii, iii, iv, v] have used either the deflection of a spring or of a pendulum, where gravity provides a restoring force, to measure the force generated by the thruster. This approach has several disadvantages:

- the system is dependant upon the linearity and reproducibility of a flexible member;
- the frequency response is, essentially, that of the pendulum or mass-spring combination *i.e.* low bandwidth with a strong resonance at the natural frequency;
- the system is tilt-sensitive.

At NPL we have used force feedback systems for our balance designs[vi, vii] that maintain the null deflection of a pendulum by applying a force to the thruster that is equal and opposite to the thrust. This has the following advantages:

- the motion detector is being used simply as a null detector, linearity *etc.* are irrelevant;
- the frequency response can be much higher as it is controlled by the feedback parameters;
- the natural resonance can be actively damped;
- high sensitivity can be achieved;
- the force feedback signal provides a convenient output signal that is directly proportional to thrust.

An important additional feature of the force feedback approach is that the force actuator applying the nulling force can be used as a transfer standard, *i.e.* as a means of transferring a traceable calibration to the instrument, and can be easily calibrated off the balance.

Force actuator

The force actuator is a key component in all the systems produced at NPL. It consists of a specially designed solenoid/magnet combination[viii] that has the following properties:

- the force produced by the combination is linearly proportional to the current applied to the solenoid;
- the force/current characteristic is reasonably insensitive to the relative position of the solenoid and magnet;
- the force/current characteristics can be *calibrated* directly using a suitable mass balance, thus providing *traceability;*

The force actuator (and its associated current source), therefore, forms a transfer standard that can be calibrated independently of the thrust balance.

The concept of a calibrated force actuator also provides a simple means of dynamically testing the response of the balance. By applying known, swept-frequency, test signals to the actuator, the frequency response of the complete closed-loop system can be easily measured. In this way, the suitability of the system to various dynamic measurement scenarios can be proven experimentally as well as predicted theoretically.

Since the system sensitivity is dependent only on the force actuator characteristics and the force actuator transfers its calibration to the balance, no *in-situ* re-calibration of the balance is required. However, an additional, calibrated, actuator can be fitted for confidence checking of the balance operation, if required.

Force Actuator calibration

Various methods of calibrating thrust balances have been reported in the literature, including empirical methods[v], methods using masses and pulleys generating 'known' forces[i] and impulses using ball bearings to impact the balance[ix]. All these methods, however, lack traceability and so cannot be claimed to be accurate. Oriaux *et al*[vii] used known masses attached to the balance in place of the thruster to calibrate their system. The balance is turned on its side and test masses added and 'weighed' by the force-feedback system. In this case the balance was designed for a very low mass thruster, so this approach is feasible. In general, however, the thruster mass is several orders of magnitude greater than the thrust level generated. To cater for traceable calibration, we introduce here the concept of a transfer standard – a means by which a calibration can be transferred from one calibration set-up to the measuring system. We use the force actuator as a transfer standard that can be removed from the thrust balance for calibration. Provided that the correct alignment of magnet and solenoid is maintained when the force actuator is returned to the balance, the calibration is valid.

To achieve direct traceability, our current source/force actuator combination is calibrated by placing the magnet assembly on a calibrated mass balance with a resolution of 2 μg (approximately 0.02 μN) and attaching a calibrated variable voltage source to the current source input. The solenoid is then mounted in the correct working position above the magnet. Applying a series of voltages to the input of the current source, within its working range, and observing the resulting apparent change in the mass of the magnet, together with the known value of the local acceleration due to gravity, gives a voltage/force calibration curve for the system.

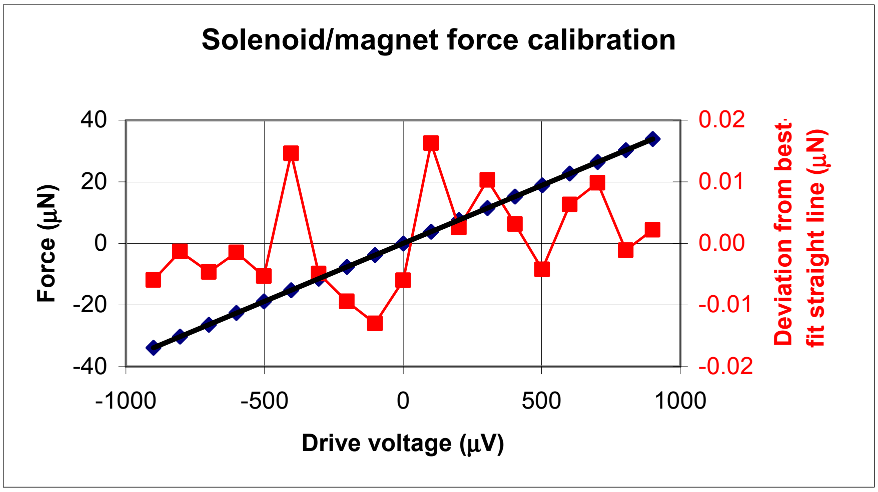

Figure 1, Typical calibration graph, showing linearity to within the measuring resolution (0.02μN)

Tests have been carried out to show the NPL designed force actuator systems are linear to within the resolution of the measuring equipment, and also, by mounting the solenoid on a moving stage, to quantify the variation of force with relative magnet/solenoid position. The knowledge gained in these tests has subsequently been used to modify the design of the magnet/solenoid combinations to ensure that the radial alignment tolerance is automatically guaranteed and the longitudinal alignment is easy to verify.

Tilt and vibration

A thrust balance based on a pendulum normally measures thrust by measuring the deflection of the pendulum relative to a 'fixed' frame. This type of instrument is, therefore, particularly susceptible to the effects of tilt due to seismic noise and movement of the test facility due to mechanical or thermal drift *etc.* because these effects cause a change of relative position of the pendulum and the 'fixed' frame. The apparent thrust produced by a tilt is proportional to the mass of the pendulum and the thruster supported on it and the sine of the angle of tilt. For example, for a total mass of 1 kg and a tilt angle of 1 second of arc, the apparent force generated is approximately 50 μN.

Similarly, vibration noise transmitted through the pendulum frame will cause motion of the pendulum relative to the frame – again appearing as noise on the output signal. The FEEP thrust balance developed at NPL and used by Nicolini[iv] and the Nanobalance[ii] developed at IMGC (Italy) used dual matched pendula to compensate for tilt and vibration. Whilst this method works well for tilt compensation, difficulty in getting an exact match in the dynamic response of both pendula limits the effectiveness of this technique for vibration cancellation, particularly at higher frequencies.

EXAMPLES OF NPL'S INSTRUMENTS

Impulse stand

This instrument was designed to measure the impulse from micro-machined digital explosive thrusters and takes the form of a ballistic pendulum. The thruster to be tested is mounted on the end of a light ceramic platform which is suspended by five silica fibres in such a manner that it can only move in one axis, the thruster being mounted in such a manner that this axis is parallel to the assumed direction of thrust. A magnet is attached to the rear of the platform, positioned within a stationary solenoid, and a moiré grating scale displacement sensor is attached to the side.

Control electronics monitor the position of the scale and apply a signal to the solenoid to keep the motion of the platform damped. Immediately prior to ignition of the explosive charge, the damping is turned off. The charge is then fired and the platform 'pendulum' is deflected. The control electronics then measures the magnitude of the peak of the deflection, and turns the damping control on again shortly after the peak. The platform is, therefore, returned, under control, to its initial zero position. Knowledge of the mass of the pendulum, the length of the pendulum support and the local acceleration due to gravity can then be used to determine the impulse from the magnitude of the swing of the pendulum.

The force per unit current generated by the solenoid/magnet combination was calibrated by direct comparison with a mass balance. This enabled the system to be calibrated since known impulses could be imparted to the platform by applying known magnitude currents to the solenoid for known periods of time.

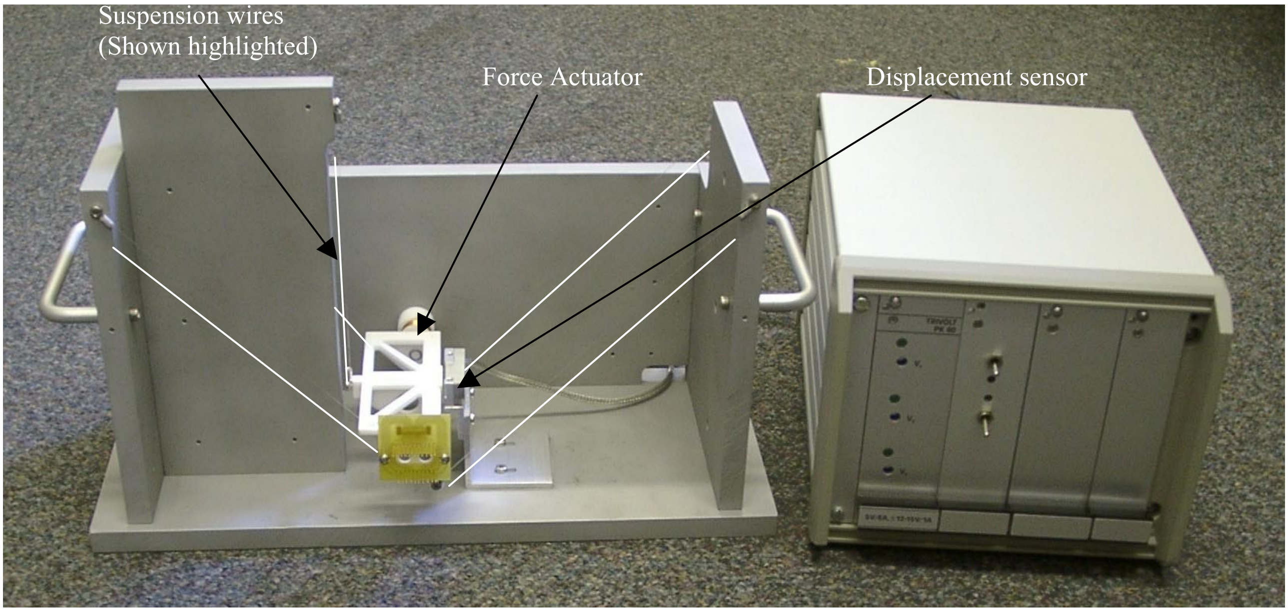

Figure 2, NPL Impulse stand.

FEEP thrust balance

The first thrust balance produced by NPL was based on the design concept of Franks *et al*[x] and was designed to measure the output from FEEP thrusters, with a maximum force of 100 µN, and a resolution of 1 µN. It consisted of a ceramic platform supporting the thruster, suspended by five silica fibres constraining the platform to move only in one axis (the assumed direction of thrust). A capacitance sensor provided position measurement for the servo control system that used a solenoid/magnet combination to provide a restoring force.

As this design was sensitive to tilt and vibration, a second, dummy, platform was provided that would be equally affected by tilt and vibration. The final output from the system, therefore, was the difference between the two platforms. Full details of this balance can be found in Nicolini *et al*[iv].

High thrust balance

This balance was designed to calibrate the thrust from high (500 mN) thrust, high mass (15 kg) thrusters. One of the chief design criteria, however, was the requirement for the balance to be capable of being lowered into the vacuum chamber from a load-lock, through a 20 inch (508 mm) diameter gate valve, whilst still being capable of testing an engine 350 mm in diameter and 300 mm long!

This balance took the concept of the use of a dummy to correct for tilt and vibration to a more sophisticated level than the FEEP balance described above. In this balance the two platforms are stacked vertically, to attempt to position them as close together as practicable.

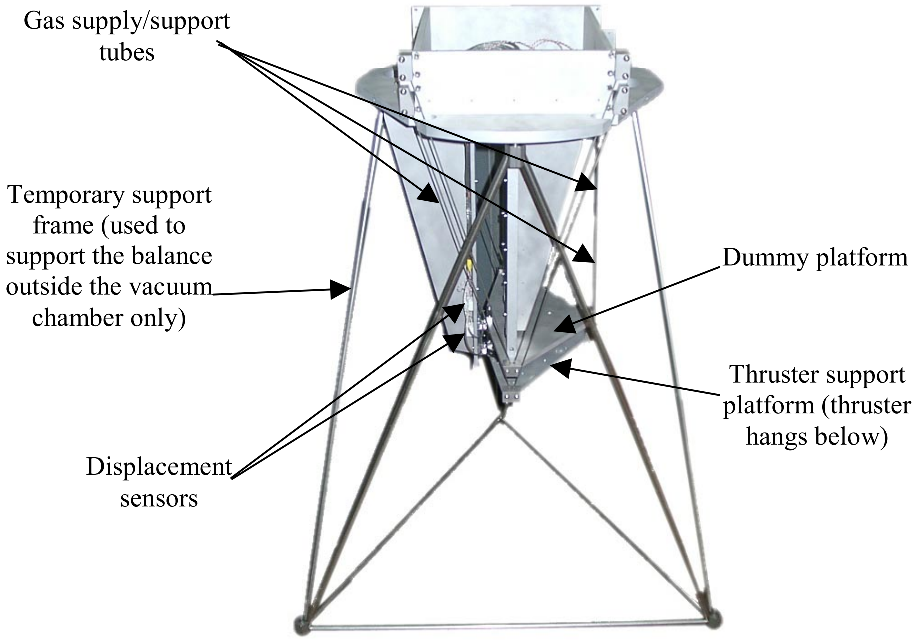

Figure 3, NPL's 500 mN thrust balance. In operation, the thruster under test would be suspended below the thrust support platform.

The thruster is hung from an aluminium platform, constrained to move only in the direction of thrust by a five-element support. This support is made from Invar® low expansion alloy tubing and also forms the gas supply lines feeding fuel to the engine. On one side of the platform is a moiré grating scale to measure the displacement of the platform with respect to a stationary frame and a solenoid/magnet combination is close to the centre line of the platform to supply an equal and opposite force to that of the thruster. A second, dummy, platform is positioned directly above the thruster platform and carries a mass equal to that of the thruster.

The entire balance is 496 mm in diameter and approximately 1 m long (including thruster). After being lowered through the gate valve in the top of the vacuum chamber, the balance locates kinematically in a ring hung by 6 adjustable length cables from the roof of the chamber. In this manner, the balance support can be adjusted to position the thruster exactly on the centre line of the chamber.

This balance has now been operating successfully for some time, providing better than millinewton accuracy on thrust up to 500 mN from thrusters up to 20 kg in mass.

GOCE thrust balance

The thrust balance presented below has been designed specifically to meet the performance requirements listed in Table 1. In particular, it has been designed to be tilt and vibration insensitive, to be easily calibrated with direct traceability, high sensitivity and dynamic range and to have controllable dynamics. This balance is also designed to use the same vacuum chamber mounting arrangement as the balance described above.

Measurement Parameter	Required Specification
Measurement range	up to 20 mN (minimum)
Measurement bandwidth	>150 Hz
Measurement resolution	2 – 3 µN
Measurement accuracy	20 µN
Drift	< 10 µN in 3 Hours
Dynamic range	10000

Table 1, Summary of Thrust Balance Measurement Specification.

The thrust balance consists of a parallel-linked, counterbalanced pendulum from which the thruster is suspended. An interferometric displacement transducer fixed to the reference frame and positioned on the thrust axis is used to sense the displacement of the pendulum with nanometre resolution. The output signal from the interferometer is fed to a servo control system with a force actuator that produces an equal and opposite force to return the pendulum to its null position.

The counterbalance mass enables the system to be tilt insensitive, since there is no gravitational restoring force. Additionally, the counter balancing eliminates the majority of the vibration sensitivity (the system remains sensitive to rotations parallel to the pivot axis). The pivots used consist of a series of 19 crossed thin metal strips which double as electrical connections, supplying power and control signals to and from the thruster.

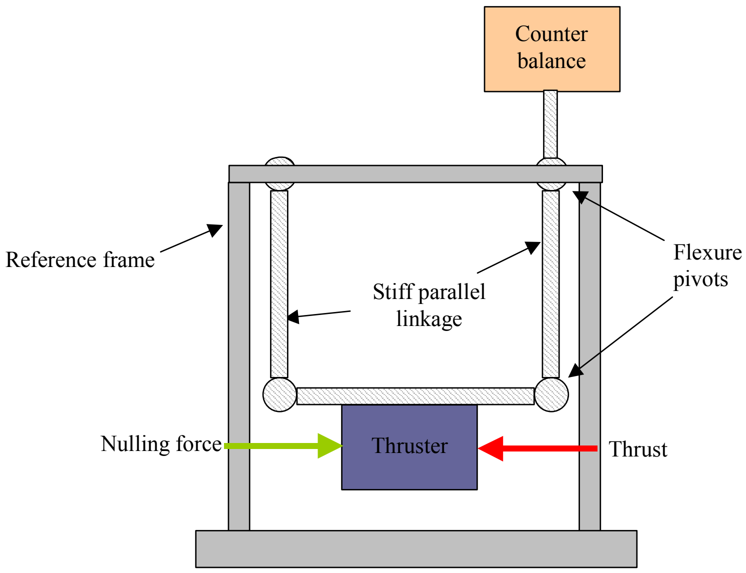

Figure 4, Schematic diagram of the thrust balance (displacement sensor and force actuator not shown for clarity).

The main structure of the parallelogram 'pendulum' is made from lightweight, low thermal expansion, fused silica tubing to produce a structure as light, stable and stiff as possible, thus attempting to move any structural resonances outside the critical operating bandwidth of the balance.

The force-feedback servo serves several purposes: firstly, it provides a means of generating an output signal that is proportional to thrust, secondly, it allows control over the dynamics of the pendulum and finally, it overcomes any non-linearities in the system that would otherwise be detrimental to the balances performance should the system be operated in open loop mode.

The counterbalance provides a means of offsetting the mass of the thruster, thus eliminating the gravitational restoring force on the pendulum. Without a gravitational restoring force, the system becomes insensitive to tilt. Additionally, the counter balance provides vibration isolation as vibration coupling into the system through the reference frame acts equally, but in the opposite directions, on the thruster mass and counterbalance. Thus the net torque on the pendulum is zero for most input vibration modes.

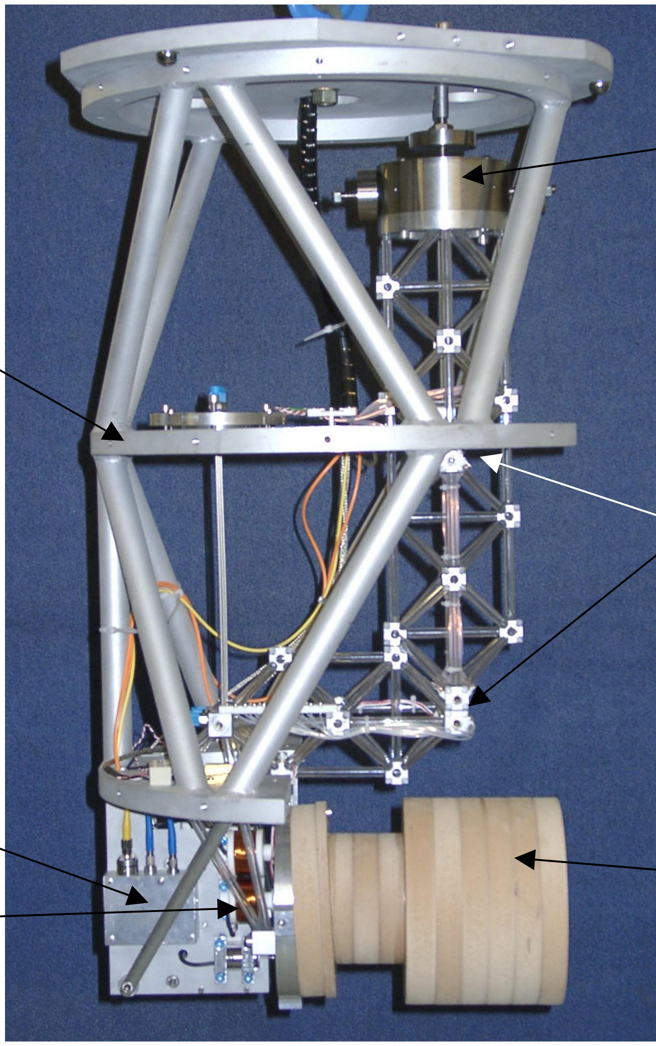

Figure 5, GOCE thrust balance

System Dynamics

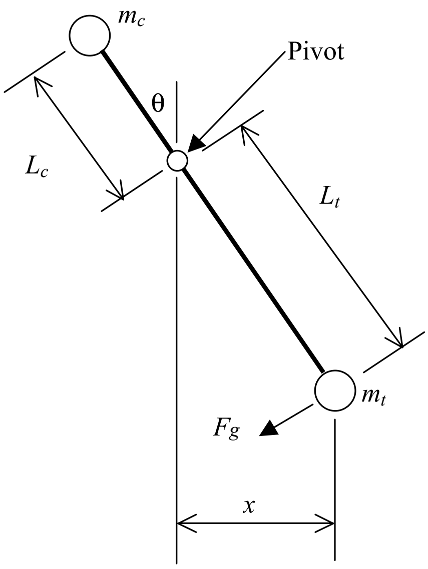

Figure 6, Model of the counterbalanced pendulum.

The mass of the thruster and counterbalance is, respectively, m_t and m_c, as shown in figure 6, and the distances of the centre of mass from the pendulum pivot are L_t and L_c. The net torque, F_g, on the pendulum due to gravity is,

$$F_g = m_t L_t - m_c L_c$$

Thus if $m_t L_t = m_c L_c$, the net torque is zero. Under this condition, the motion of the pendulum is affected only by the spring stiffness, λ, of the flexure pivots and the equation of motion becomes,

$$m \frac{\partial^2 x}{\partial t^2} + \lambda x = 0$$

The equation of motion can be re-written as a transfer function relating an externally applied thrust, T, to a displacement x giving,

$$\frac{x}{T} = \frac{1/m}{s^2 + \omega_n^2}$$

This is an un-damped second-order system with natural frequency, $\omega_n = (\lambda/m)^{1/2}$.

The force feedback control loop is shown in figure 7. It consists of an inner loop with velocity feedback and bandwidth control, and an outer loop comprising a PID controller.

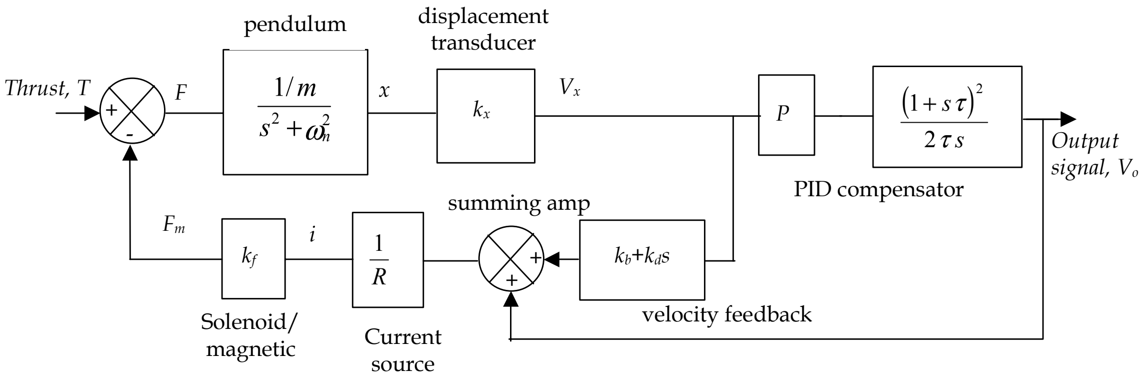

Figure 7, Block diagram of the force feedback control loop.

The closed-loop transfer function of the inner loop is,

$$\frac{V_x}{T} = \frac{k_x / m}{s^2 + \frac{k_x\, k_f\, k_d}{m\, R} s + \left(\frac{k_x\, k_f\, k_b}{m\, R} + \omega_n^2 \right)}$$

This is a second order system with damping and bandwidth controlled by feedback terms k_d and k_b respectively.

The PID compensator in the outer loop is included to eliminate steady state error thus forcing the feedback force, F_m to exactly match the applied thrust, T. The output signal, V_o, is related to the applied thrust, T, by the closed-loop transfer function,

$$\frac{V_o}{T} = \frac{P\, k_x (1 + s\tau)^2 / m}{2s\tau \left(s^2 + \frac{k_x\, k_f\, k_d}{m\, R} s + \left(\frac{k_x\, k_f\, k_b}{m\, R} + \omega_n^2 \right) \right) + P \frac{k_f\, k_x}{m\, R} (1 + s\tau)^2}$$

The thrust servo output is, therefore, dependent solely on the calibration of the force actuator and its current source since in the steady state,

$$i.e. \lim_{s \to 0}\left(\frac{V_o}{T}(s)\right),$$

$$V_o \to \frac{R}{k_f}T$$

INITIAL TEST RESULTS FOR THE GOCE THRUST BALANCE

Horizontal vibration isolation.

In order to demonstrate the effectiveness of the horizontal vibration isolation, an accelerometer was mounted on the interferometer's mounting bracket with its measurement axis aligned with the thrust balance axis. The output of the accelerometer was recorded together with the interferometer signal. The control loop servo was switched off. The noise spectra of the two signals are shown below in figure 8. The signal from the accelerometer has been scaled so that the peak at around 12 Hz matches that detected by the interferometer.

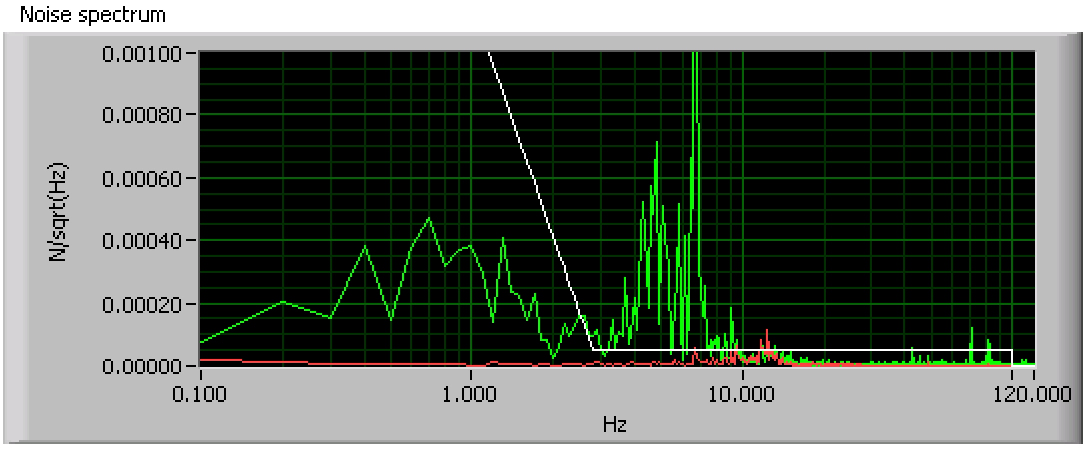

Figure 8, Red trace - interferometer signal spectrum. Green trace - accelerometer signal spectrum. (Ignore the white line).

From figure 8, it is clear that the accelerometer is detecting considerable vibration below 10 Hz. But the interferometer is not influenced by it. This demonstrates that the counterbalanced pendulum is isolating the measuring system from horizontal vibration.

Frequency response

The frequency response of the closed-loop system has been measured using a frequency response analyser. A swept-frequency sinusoidal signal was used to generate a simulated thrust using the test force actuator on the thrust balance. The Bode plot below shows the frequency response currently achieved. It is flat within 3 dB up to 10 Hz with a peak of 6 dB at around 13 Hz and a –3 dB point at about 17 Hz.

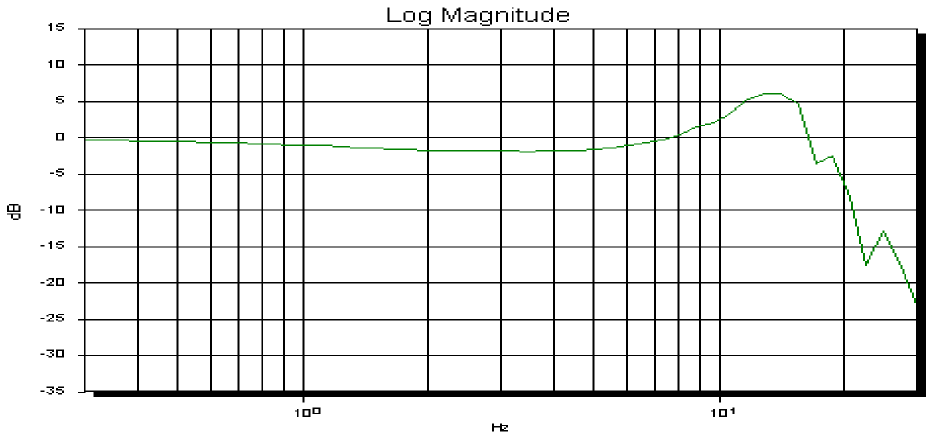

Figure 9, Bode plot showing frequency response to a swept frequency sinusoidal simulated thrust.

CONCLUSIONS

NPL has produced a range of thrust balances, with capacities ranging from 100 µN to 500 mN, capable of supporting thruster masses from 100 g to 20 kg and operating with bandwidths up to > 10 Hz. All these balances, however, share the same design philosophy of being nulling servo devices, where a force actuator, calibrated by a directly traceable method, is used to provide equal and opposite force to that generated by the thruster. The electrical output from the balance can, therefore, be directly related to the output of the thruster without the need for complicated in-vacuum calibration systems of dubious accuracy.

The accuracy, resolution and bandwidth these systems produce are, to the best of our knowledge, unparalleled.

ACKNOWLEDGEMENTS

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