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Electromagnetic calibration system for sub-micronewton torsional thrust stand

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Abstract. It is critical for a micropropulsion system to be evaluated. Thrust stands are widely recognised as the instrument to complete such tasks. This paper presents the development of an alternative electromagnetic calibration technique for thrust stands. Utilising the commercially made voice coils and permanent magnets, the proposed system is able to generate repeatable and also consistent steady-state calibration forces at over four orders of magnitude (30 – 23000 μN). The system is then used to calibrate a custom-designed torsional thrust stand, where its inherent ability in ease of setup is well demonstrated.

1. Introduction

Small satellites have found increasing applications in communications and space weather study [1]. This is because they are simpler, can be developed in shorter time frame and inherently cost effective [2]. In particular, nanosatellites (typically <10 kg) have gained more interests. They can be developed and launched into space within only two years, which is highly advantageous for demonstrating new and innovative ideas in outer space exploration. One of the major sub-systems in a nanosatellite is the micropropulsion system. It makes use of microthrusters to perform tasks like attitude control, station keeping, drag compensation and orbital transfer [3]. Throughout the years, various microthrusters have been developed with the help of microelectromechanical systems (MEMS) that have been proven as a promising approach [4].

In light of this, the accurate and precise performance characterisation of a microthruster becomes critical [5]. As the forces produced by microthrusters are extremely low (in the order of micronewton), resolving them requires highly sensitive measuring instruments. The pendulum thrust stand is widely regarded as the more efficient and suitable method to measure constant and impulsive thrust forces produced by the microthrusters [6]. Essentially, it is a spring-mass-damper system in which a structure holding the microthruster is supported by a torsional spring. The structure will oscillate as the forces are applied. By analysing the oscillation, the forces produced by the microthrusters can be determined. There are three main configurations for pendulum thrust stand, i.e. hanging [7, 8], inverted [9, 10] and torsional [11–13], with each of them having their own advantages and limitations.

As a measuring instrument, it is necessary for the pendulum thrust stand to be calibrated. Basically, the calibration establishes the relationship between the thrust stand response in terms of displacement (measured by the sensor) and the forces applied. There are two categories of calibration techniques: contact and non-contact. The contact calibration techniques include string-pulley-weight system [7], impact hammer [14] and impact pendulum [15]. These are older methods that have become obsolete

[16] as their performance pales in comparison to that of the modern non-contact methods. Non-contact calibration systems include gas dynamic [16, 17], electrostatic (ES) [14, 18–20] and electromagnetic (EM) [12, 21–22]. The gas dynamic calibrators are reliable in producing calibration forces between nanonewton and sub-micronewton [17]. In contrast, ES calibrators are able to provide a wider range of calibration forces, typically between hundreds of nanonewton and thousands of micronewton [20]. As for EM calibrators, though the reported calibration forces are sub-micronewton and above, they also exhibit good consistency and repeatability. Besides, EM calibrators are much easier to be implemented compared to gas dynamic and ES. They mostly consist of an electromagnet (solenoid) coupled with permanent magnet, current-carrying copper wire, or metal conductor.

This study explores the feasibility of using the commercially available voice coil to develop EM calibration system for a sub-micronewton torsional thrust stand. The developed calibration system is very compact as the voice coil is rather small in size. This is highly beneficial for integration with small testing facilities, in particular the vacuum chamber, in which the setup cost is proportional with the overall size. The selected voice coil is first tested with different permanent magnets to investigate the characteristics of the EM calibration force generated. The system is then implemented onto the thrust stand to demonstrate its performance as a calibrator.

2. Torsional Thrust Stand Setup

A thrust stand is designed and constructed based on the working principle of a torsional pendulum [6]. Generally, the torsional thrust stand has a good balance in measuring high and low vibrational noise sensitivities. The existing thrust stand consists of a 60 cm torsional arm made of U-shaped aluminium beam. It is lightweight (210 g only) yet sufficiently stiff to support external loadings mounted onto it. The torsional arm is supported by a single-ended flexural pivot (F-20, C-Flex) that acts as the torsional spring. The pivot is clamped and connected to a heavy rectangular aluminium base (3 kg). Four anti-vibration mounts (126-3904, RS Pro) were installed underneath the corners of the base to enhance its stability against external vibration. A strong permanent magnet is placed in close proximity under the torsional arm to induce an eddy current braking force in order to dampen the oscillation of the arm. A high resolution (0.5 μm) laser displacement sensor (HL-G103-S-J, Panasonic) is positioned at one end of the arm to measure the deflection of the torsional arm. The EM calibrator is installed at the other end of the arm. A transparent acrylic casing is used to enclose the entire assembly in order to minimise the effect of ambient disturbance on the thrust stand response. This setup is shown in Figure 1.

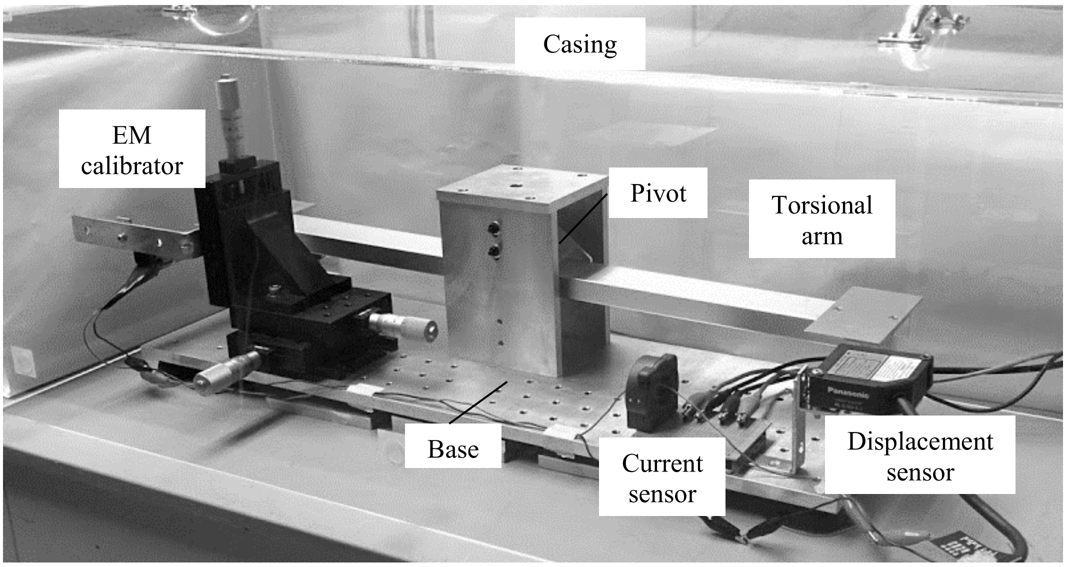

Figure 1: Setup of the torsional thrust stand for existing study

3. Electromagnetic Calibration System

Unlike ES calibration system, which is well established and proven, EM calibration for torsional thrust stand is a relatively new idea. It can be further improved in terms of performance as well as simplified for its implementation. While the fundamental working principles of EM calibrators remain the same, effective yet commercially available components can be utilised in order to further innovate EM as an alternative technique for thrust stand calibration.

3.1. Voice Coil and Permanent Magnet as Electromagnetic Calibrator

The EM calibration system used in this study consists of a voice coil and a permanent magnet. Voice coil, as shown in Figure 2, is readily available in different diameters and is often used in loudspeaker. It is essentially a solenoid, whereby an electromagnetic field is generated when the electrical current passes through the coil. Operation of voice coil is governed by Ampere's Law as stated in Equation 1, where B is the electromagnetic field strength, μ is the permeability of vacuum, N is the number of turns of wire and I is the amount of current flow.

$$B = \mu NI \tag{1}$$

In this study, electrical current of various levels are supplied to the voice coil in order to generate electromagnetic field of different strengths. The voice coil is then engaged to a permanent magnet to induce interactions between their magnetic fields. They are arranged in a way such that they repel each other. As a result, it produces the electromagnetic force needed for the calibration of the thrust stand.

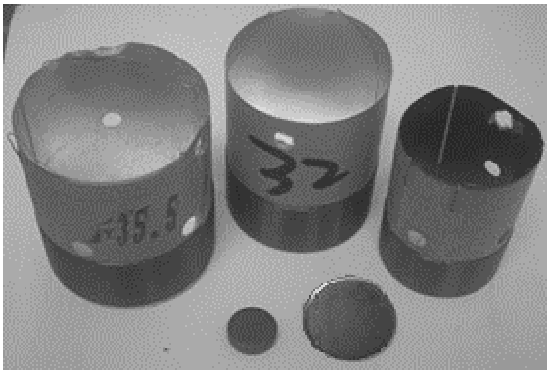

Figure 2: Voice coils of various diameter and two different permanent magnets

3.2. Electromagnetic Force Measurement using Weighing Balance

The amount of electromagnetic force generated by the EM calibration system is first measured through an experiment. After a few trials, a 25.5 mm diameter voice coil is selected as it provides the range of calibration force required for this study. A voice coil of this size is compact, thus it is easy to be set up. Two different types of permanent magnet, i.e. ferrite disk magnet (weaker magnetic field strength) and neodymium disk magnet (stronger magnetic field strength) are utilized. By using magnets of different levels of magnetic field strength, the range of forces generated is wider. As such, the torsional thrust stand can be calibrated to suit different types of micropropulsion systems.

The setup for electromagnetic force measurement is shown in Figure 3 and Figure 4. A weighing balance (HR250AZ, A&D Weighing) with a resolution of 0.1 mg (0.981 μN) is applied to measure the electromagnetic force generated. The permanent magnet is fixed onto the weighing balance while the voice coil is fixed externally to the mechanical stage (PT3/M, Thorlabs) for position and engagement adjustment. A power supply (MP303-3, Meguro) is used to supply electrical current to the voice coil. A current sensor (CTSR1-P, LEM) with a resolution of 10 mA and a digital oscilloscope (DS1102E, Rigol) are used to measure the amount of current that flows through the coil. Electrical current ranges from 0.01 A to 0.4 A are supplied and the corresponding readings from the weighing balance are then recorded.

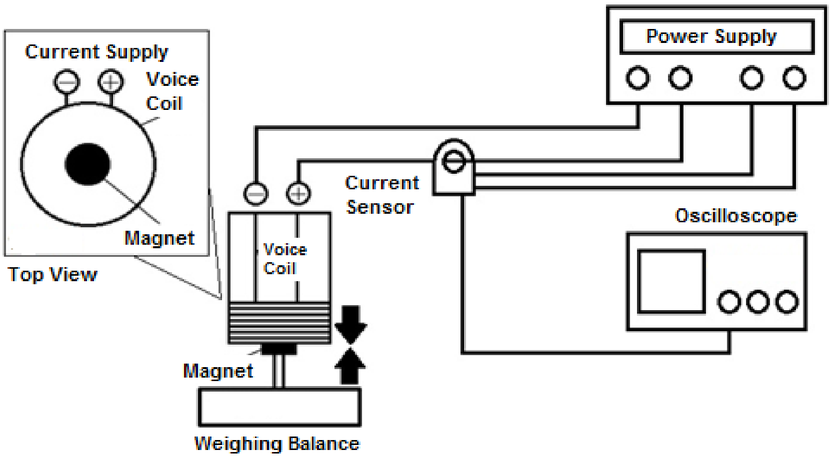

Figure 3: Schematics of EM force measurement setup and arrangement of voice coil and magnet

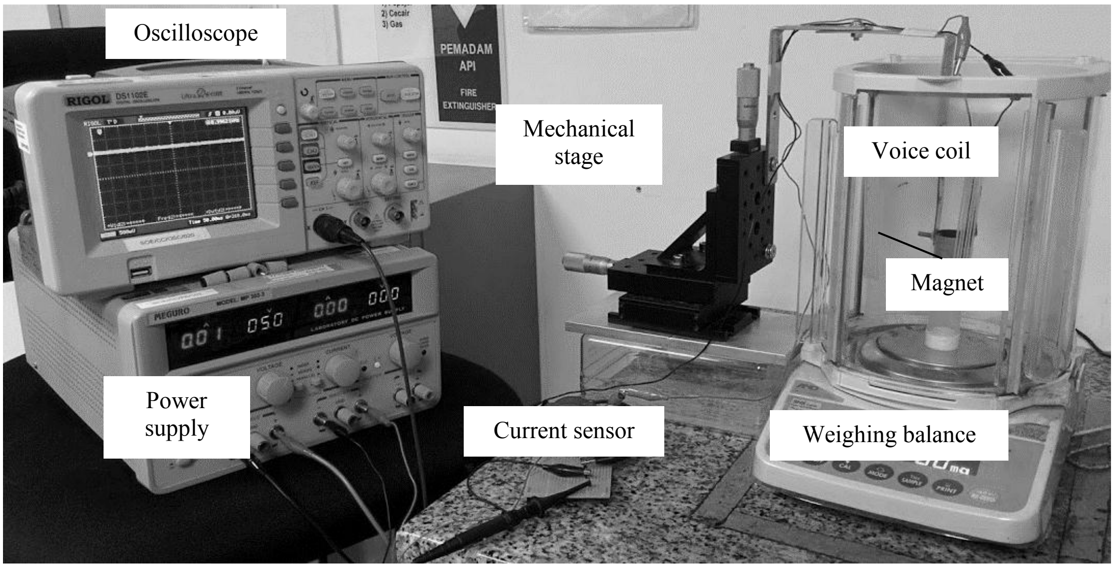

Figure 4: Actual experimental setup for EM force measurement

The effect of the engagement distance between the voice coil and the magnet on the stability of the electromagnetic force is studied. This is to identify the acceptable range of engagement distance for generation of consistent and repeatable electromagnetic force. For this purpose, the current is fixed at three distinct levels (0.1 A, 0.25 A and 0.4 A), which represents low, mid and high range of forces, respectively. The engagement distance is varied from -5 mm to 5 mm using the mechanical stage. Similarly, the corresponding readings from the weighing balance are recorded.

3.3. Implementation onto Thrust Stand

After the force measurement, the EM calibrator is installed onto the thrust stand as shown in Figure 5. The permanent magnet is fixed to the other end of the torsional arm as opposed to the end with the laser displacement sensor. The voice coil is placed externally and its positioning and engagement to the magnet are adjusted using the mechanical stage. The measured electromagnetic forces are applied to the torsional arm and the deflections of the arm are recorded using the linear displacement sensor.

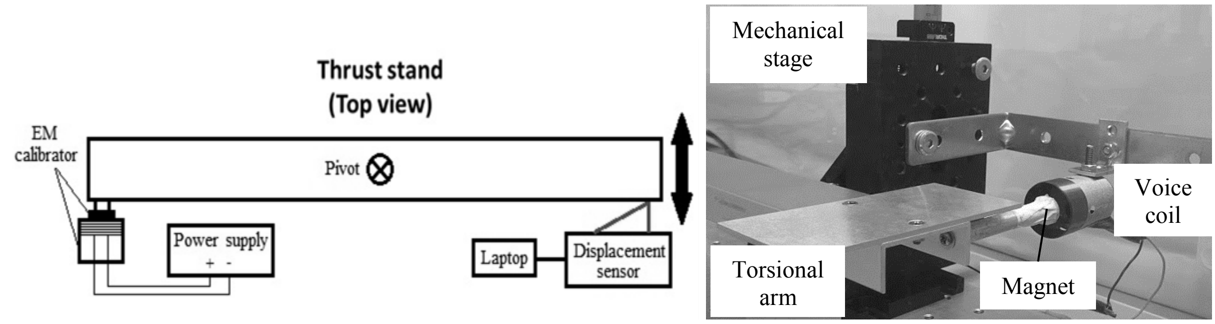

Figure 5: Schematic (left) and actual (right) installation of EM calibrator onto the thrust stand

4. Results and Discussion

4.1. Electromagnetic Force Measurement

Figure 6 shows the electromagnetic forces generated by the EM calibration system at varying levels of the electrical current. Overall, the neodymium magnet based system generates much higher force than that with ferrite magnet. This is predominantly due to the difference in their magnetic field strengths. Neodymium magnet is well known for its strong magnetism. Thus, given the same amount of current through the voice coil, the magnet with stronger field strength repels harder, leading to a higher force generated, and vice versa.

It can be noted that the relationship between electromagnetic force generated and electrical current supplied is linear and directly proportional, as dictated in Equation 1. Such relationship indicates that the electromagnetic force generated using the proposed EM calibrator is predictable and reliable. This is crucial for its applications onto the torsional thrust stand later on.

The combination of these two magnets has an extended range of electromagnetic forces that cover four orders of magnitude, i.e.30 – 2200 µN and 920 – 23000 µN, for ferrite magnet based and neodymium magnet based calibrator, respectively. This is advantageous as the thrust stand can be calibrated to suit a wider range of applications.

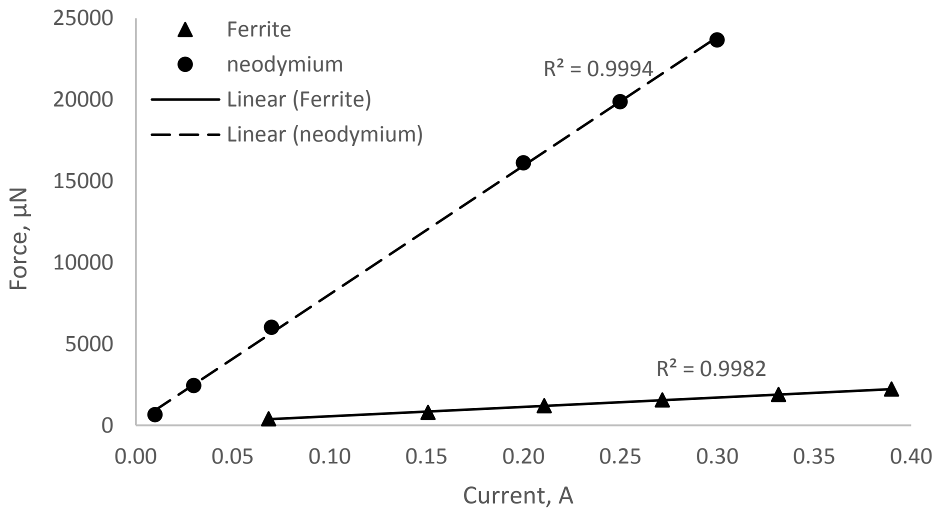

Figure 6: Electromagnetic force generated by ferrite and neodymium magnets at varying currents

Meanwhile, Figure 7 shows the change in the electromagnetic force with the engagement distance for both ferrite magnet based (top) and neodymium magnet based (bottom) calibrators. It should be noted that 0 mm engagement distance represents that the magnet is placed at the edge of the voice coil; whereas positive engagement distance means that the magnet is moved further away from the voice coil, and vice versa for negative engagement distance. Regardless of the polarity of the engagement distance, the electromagnetic force generated decreases as the magnet moves away or into the voice coil. The decreasing trends are due to the reduced magnetic field interaction between the voice coil and the magnet as the engagement distance changes. However, the order of deviation is different. The experimental measurement shows that the electromagnetic force decreases in a less drastically manner as the magnet is moved further away (positive engagement distance) from the coil.

Existing study reveals that beyond the range of ±2 mm of engagement distance, the electromagnetic force generated has decreased too much (~14 %) which has a negative impact on its repeatability and consistency. The effect is more apparent when the electrical current is at the higher level. The obtained results serve as an important guideline for installing the EM calibrator onto the thrust stand. The engagement distance should be kept within ±2 mm for reproducible and consistent calibration force generation.

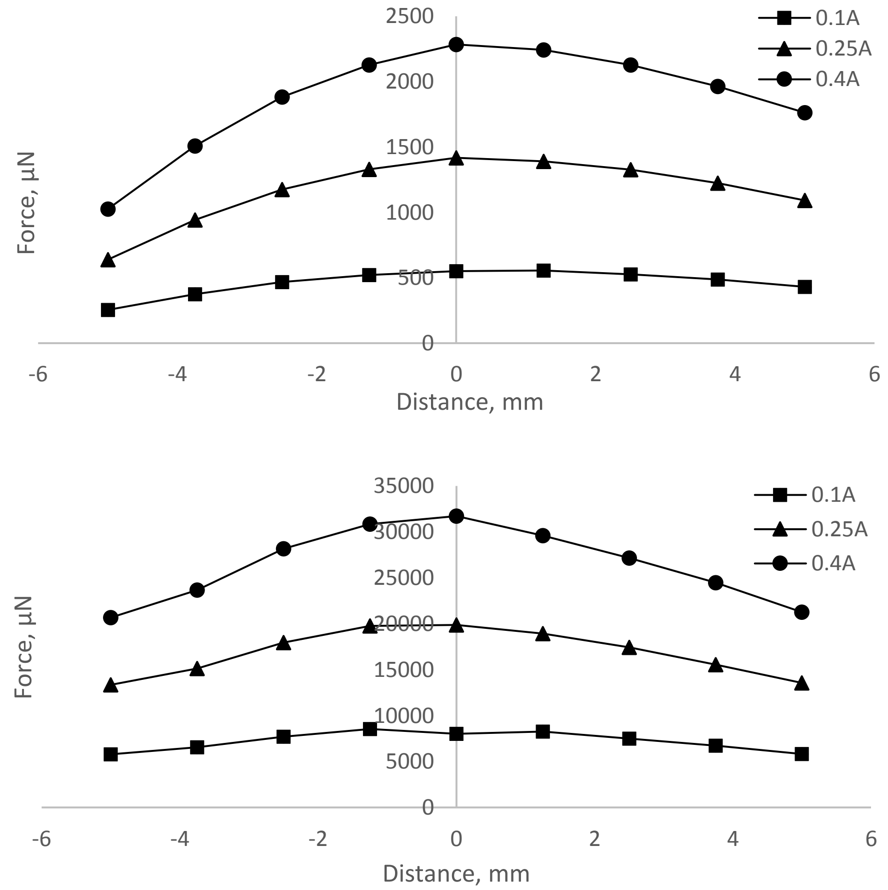

Figure 7: Electromagnetic force generated by ferrite (top) and neodymium (bottom) magnets corresponding to varying engagement distances at three current levels

4.2. Calibration for Steady-state Force

After the EM calibrator is installed, steady-state (constant) electromagnetic forces are generated and applied to the torsional arm. A similar range of electrical current (0.01 A to 0.4 A) is supplied and the corresponding deflection of the arm is recorded. Figure 8 depicts the sample response of the torsional arm due to the force applied.

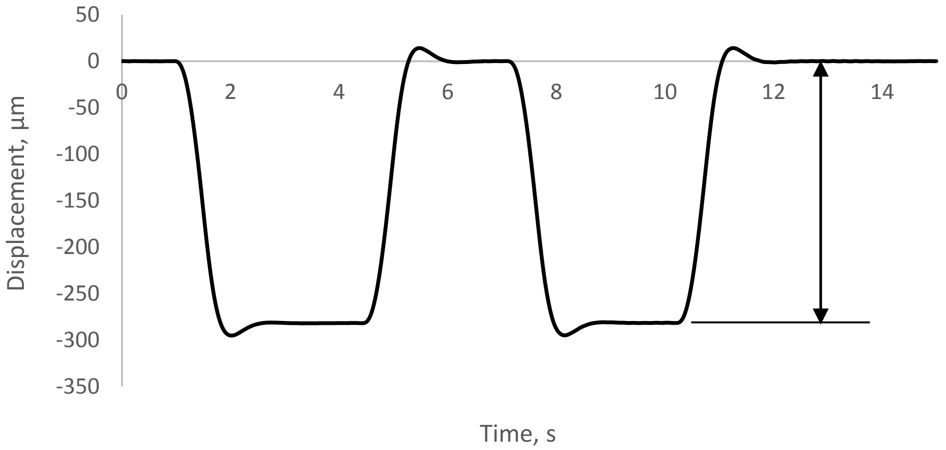

Figure 8: Displacement of the torsional arm due to the force generated by the ferrite magnet based EM calibrator at 0.25 A. Pointing arrow indicates the steady state deflection.

As observed, the torsional arm reached steady deflection at 282 μm in this case. Damping of the response can also be observed i.e. at ~2 s, ~5.5 s, ~8 s, and ~11 s. This shows that the damper installed is effective. It can also be noted that as the force is removed, the displaced arm returned to its initial position, indicating that the system is stable without zero drift. A calibration curve as shown in Figure 9 is then plotted based on the deflection data collected. Here, the electrical current applied is mapped to its equivalent amount of electromagnetic force using Figure 6. This curve can be directly used for measuring the amount of force produced by the micropropulsion system.

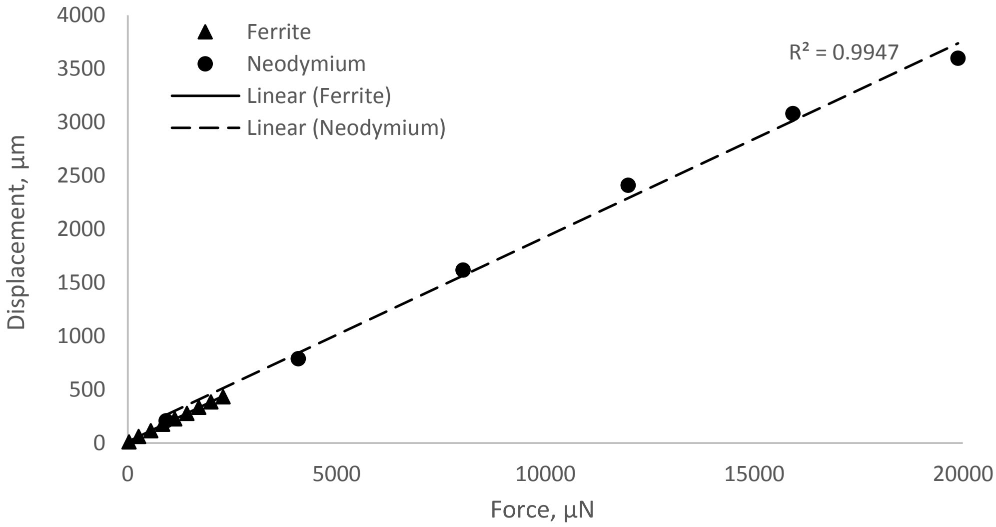

Figure 9: Calibration curve for steady-state force measurement

By using the combined ferrite and neodymium magnet based EM calibrator, the thrust stand has been calibrated to be able to resolve steady-state forces at four order of magnitude i.e. 30 – 23000 μN. From Figure 9, it is also observed that the two calibrators overlap at ~920 – 2200 μN, in which more in-depth study is needed for this overlapping region to obtain accurate calibration results.

5. Conclusion

The proposed EM calibrator is considered feasible as an alternative thrust stand calibration technique. With the combination of commercially available voice coils and various magnets, calibration force over four orders of magnitude ranging at 30 – 23000 μN is produced. Furthermore, the existing EM calibration system also exhibits good repeatability and linearity in generating the forces. The system is also inherently compact, thus easy for set up. Nevertheless, more detailed analysis of EM calibrators are in the pipeline and more extensions of its utility such as producing impulsive calibration forces are to be carried out.

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