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A voice coil based electromagnetic system for calibration of a sub-micronewton torsional thrust stand

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ABSTRACT

This paper presents the development of an alternative electromagnetic calibration system. Utilising commercially available voice coils and permanent magnets, the proposed system is able to generate linear, repeatable, and consistent steady-state calibration forces at over four orders of magnitude (30–23,000 μN). It is also capable of producing calibration impulse bits in the range of 12–668 μNs. The maximum uncertainty errors of the calibrator are evaluated as 18.48% and 11.38% for steady-state and impulsive forces calibration, respectively. Its performance is compared to other existing electromagnetic calibration techniques. Capability of the system is then demonstrated in calibrating a sub-micronewton torsional thrust stand.

1. Introduction

Nanosatellites (<10 kg) are finding new applications in various areas [1]. They are simpler and require shorter development time. Thus, they are inherently cost effective and ideal for demonstrating new and innovative ideas in outer space. In a nanosatellite, one of the desired sub-systems is micropropulsion system. The inclusion of microthrusters into nanosatellites is beneficial for improved operations in attitude control, station keeping, drag compensation, and orbital transfer [2]. Over the years, various microthrusters have been developed with the help of microelectromechanical systems (MEMS) [2–5].

Throughout the development campaign, the performance of a microthruster needs to be evaluated accurately. Since the forces produced by microthrusters are extremely low (in the order of micronewton), resolving them requires measuring instruments of high sensitivity. Pendulum thrust stand is widely regarded as the efficient and suitable method for measuring the micronewton forces [6]. Essentially, it is a mass-spring-damper system in which a structure holding the microthruster is supported by a torsional spring. The structure oscillates as forces are applied. By analysing the oscillation, the forces produced by microthrusters can be determined. There are three main configurations for pendulum thrust stand, i.e. hanging [7–9], inverted [10,11], and torsional [12–14], each with their own advantages and limitations.

Calibration is a necessary process for any measuring instrument. It establishes the relationship between the thrust stand response in terms of displacement and the forces applied. There are two categories of calibration techniques, namely contact and non-contact. Contact calibration techniques include string-pulley-weight system [7], impact hammer [15], and impact pendulum [16]. Although they are the earliest methods used in calibration and easy to set up, the calibration force is comparatively larger than the non-contact techniques [17], in the order of sub-micronewton and above. In addition, the contact nature of the techniques tends to induce zero drift on the thrust stand.

Non-contact calibration systems include gas dynamic [17,18], electrostatic (ES) [15,19–21], and electromagnetic (EM) [13,22,23]. Gas dynamic calibrators are reliable in producing calibration forces between nanonewton and sub-micronewton [18]. In contrast, ES calibrators are able to provide a wider range of calibration forces, typically between hundreds of nanonewton and thousands of micronewton [21]. Nevertheless, this versatile calibration technique requires high voltage for generation of sufficiently large calibration force. This results in the need of more costly equipment, e.g. high voltage amplifier. For EM calibrators, the reported calibration forces are sub-micronewton and above. They exhibit good consistency and repeatability. Besides, EM calibrators are easier to be implemented compared to gas dynamic and ES. They mostly consist of an electromagnet (solenoid) coupled

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with permanent magnet, current-carrying copper wire, or metal conductor. Unlike ES calibration system which is well established, 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 remain straightforward and simple, effective yet commercially available components can be implemented in order to innovate EM as an alternative technique for thrust stand calibration. In this study, we explore the feasibility of using commercially available voice coils as an alternative EM calibration system for a sub-micronewton torsional thrust stand. Due to the nature of its construction, voice coil acts as a small and light weight electromagnet that can be utilised as part of the calibration system. Combining with a coin-sized permanent magnet, this newly developed calibration system is very compact. Compact calibration system is beneficial for integration with small testing facilities, in particular the vacuum chamber, in which the setup cost is proportional to 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 calibration system is then implemented onto the thrust stand to showcase its performance as a calibrator for both steady-state and impulse forces. Lastly, the uncertainty error of the calibrator is evaluated and its performance is compared with other EM calibrators.

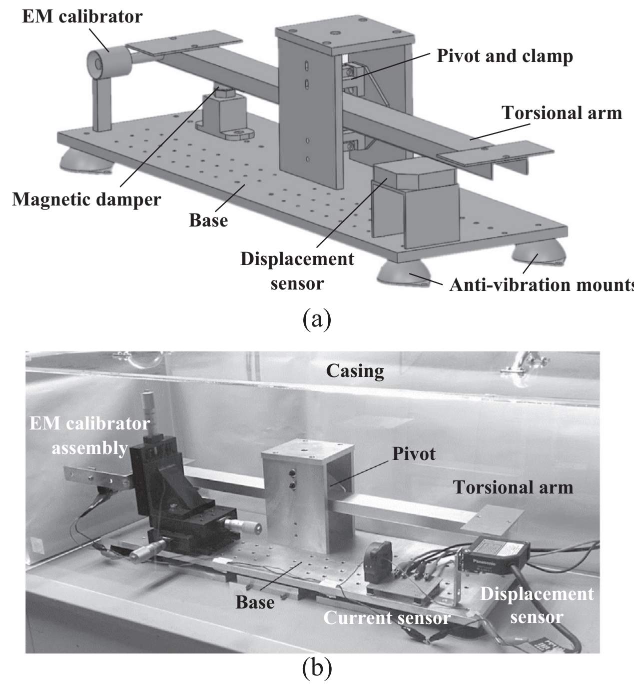

Fig. 1. (a): Thrust stand drawing and (b): Actual setup for existing study.

2. Torsional thrust stand setup

A thrust stand based on the working principle of torsional pendulum is designed and built in existing study. Generally, torsional pendulum thrust stand has good balance of high measuring and low vibrational noise sensitivities [6]. The dynamic motion of a torsional pendulum is described as:

$$J\ddot{\theta} + \lambda\dot{\theta} + k\theta = F_t r_t \tag{1}$$

where J is the moment of inertia about the rotational axis, *PleaseCheck* is the angular displacement of the pendulum, λ is the damping coefficient, k is the torsional elastic constant and F_t is the externally applied force at a distance of r_t from the rotational axis.

Our thrust stand consists of a 60 cm torsional arm made of U-shaped aluminium beam. It is light weight (210 g) yet sufficiently stiff to support external loadings mounted onto it. The torsional arm was supported by a single-ended flexural pivot (F-20, C-Flex) that acts as torsional spring. The pivot was clamped and connected to a heavy rectangular aluminium base (3 kg). Four anti-vibration mounts (126–3904, RS Pro) were installed to enhance its stability against external vibration. A strong permanent magnet was placed in close proximity under the torsional arm to induce an eddy current brake in order to dampen the oscillation of the arm. A high resolution (0.5 μm) laser displacement sensor (HL-G103-S-J, Panasonic) was positioned at one end of the torsional arm to measure its deflection. The EM calibrator was installed at the other end of the arm. The fluctuation of surrounding temperature and ambient air could affect the thrust stand response. The thrust stand was set up in an air-conditioned laboratory and enclosed with a transparent acrylic casing, where the temperature remains stable. The voice coil releases heat when excessively high current is applied. The electrical current was capped at 0.4 A and the voice coil was mounted externally. These precautionary steps minimise if not eliminate any significant heat transfer through the torsional arm that may cause undesired motion. The CAD drawing and actual setup of the thrust stand are shown in Fig. 1(a) and (b), respectively.

3. Electromagnetic calibration system

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, as shown in Fig. 2. Voice coil is commercially available in different sizes and commonly used in loudspeakers. It is essentially a solenoid, whereby an electromagnetic field can be generated when electrical current passes through the coil. Electromagnetic field strength of the voice coil, B, is governed by Ampere's Law:

$$B = \mu_0 n I \tag{2}$$

where μ_0 is the permeability of vacuum, n is the number of turns of wire per unit length, and I is the amount of electrical current flow through the coils.

In this study, electrical current of various levels were supplied to the voice coil in order to generate electromagnetic field of different strengths. The voice coil was then engaged to a permanent magnet to induce interactions between their magnetic fields. They were arranged in a way such that they repel each other. As a result,

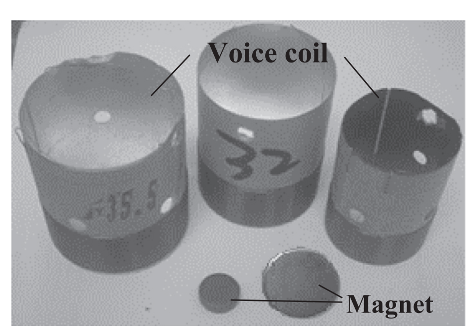

Fig. 2. Voice coils of various diameters and two different permanent magnets.