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Development of a counterbalanced pendulum thrust stand for electric propulsion

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ABSTRACT

We have designed and tested a thrust stand for RF plasma thrusters characterization. The balance is employed in the development of small and medium size RF plasma thrusters; it allows for a high number of tests per day with an accuracy in the order of 10%. The balance relies on the counterbalanced-type pendulum concept, which allows adjusting the instrument sensibility without changing the overall pendulum size. The range of thrust which can be evaluated depends on the mass of the prototype under test; e.g. for a 0.5 kg prototype the thrust can vary from 20 μN up to 50 mN. The system can be calibrated with both a calibration mass, and an electric calibrator. We have developed an algorithm which corrects the thermal drifts generated during thruster operation. We have compared the stand results against Faraday cup measurements, finding an agreement within 20%.

1. Introduction

Plasma-based propulsion systems are beginning to challenge the monopoly of chemical thrusters in space applications. The high specific impulse (which allows for a huge reduction in the propellant mass) and high thrust efficiency make the plasma thruster an attractive solution for space propulsion. Many plasma-based propulsion systems rely on a Radio Frequency (RF) systems for both plasma generation and acceleration:

- Radio Frequency Ion Technology (RIT) [1] is an ion thruster concept which relies on a Radio Frequency (RF) source for plasma generation. RIT technology was originally developed in the 90's by Astrium, and to the present day has been employed in successful space missions such as EURECA [2] and ARTEMIS [3].
- An Inductive Coupled Plasma (ICP) [4] source has been employed in the Busek Ion Thrusters (BIT) series [5]. A particularly interesting application of the BIT-3 thruster is for the cubesat propulsion, e.g. the LunarCube platform [6].
- Helicon Plasma Thrusters (HPTs), whose plasma-generation system is derived from high-density Helicon plasma sources [7]. HPTs are under study and development in some international research projects such as the American VASIMR [8], where a high-power Helicon source is coupled to a ion cyclotron resonance heating section to increase the specific impulse; the Europeans HPH.COM [9] in which a low-power (⩽100 W) system has been developed, and SAPERE-STRONG [10] that aims at the realization of a high-power (⩾1 kW) propulsive system to be employed in a space tug. Other research centers which have developed HPTs prototypes are ANU [11,12], MIT [13], Tokio University [14], Madrid University [15], and Washington University [16].
- Neutralizer-free ion thrusters [17] in which plasma is accelerated by means of a RF biasing of acceleration grids; this technology is under development at ThrustMe, a startup from the Ecole Polytechnique and the CNRS.

The force produced by an electric thruster can be estimated following two different methods. The first method is based on the measurement of ion current and ion energy distribution in the plume by means of a Faraday cup [18] and a retarding potential analyzer [19]; the ion current and energy distribution can be coupled to deduce the thrust and the specific impulse [20]. This method, even if simple to implement, leads to not very accurate thrust values, in particular if we are dealing with RF based plasma systems [21] (the error is between 30 and 40%). The other method is based on the measurement of mechanical displacements produced on a sensitive thrust stand or a pendulum, on which the thruster is fastened. This second method is more reliable but even the simplest concepts of thrust stand (e.g. simple

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pendulum configuration [22]) requires bulky hardware in the vacuum chamber and several expedients to reduce mechanical vibrations and interferences, since the thrust levels to be detected are very small (usually lower than $\ll 1$ N). Many thrust stand concepts have been adopted in order to meet specific requirements, e.g. measuring thrust in the nano-Newton range [23] or in the tens of Newton range [24], measuring the thrust in two directions [25], measuring the performances of hollow cathodes [26] or pulsed plasma thrusters [27]; nevertheless some of the most common typologies are:

- Conventional hanging pendulum [28,29], which is the simplest solution but could be some meters tall if designed to detect micro-Newton level forces, or involves original mechanisms for motion amplification [30]
- Double pendulum [31,32] which has similar features of the Conventional hanging pendulum but is particularly robust against disturbances.
- Inverted pendulum [33–35], which can be very accurate depending on the feedback control employed, but can hardly be adjusted to cover a wide range of thrust and weight due to its intrinsic instability.
- Torsional pendulum [36–39], which allows for an accurate thrust measurement but the horizontal asymmetric arrangement can be difficult to configure.
- Null-displacement systems, involving a feedback control loop [40,41], which allows for accurate measurements but may be prone to RF disturbance effects.

At the ESA propulsion lab at ESTEC [42] motors which produce thrust from 1 μN up to 20 N can be tested; a so wide range of performances can be covered relying on different stand typologies: inversed pendulum, load cells, or null-force pendulum.

We have developed a thrust stand (see Fig. 1) for RF plasma thruster characterization at the Center for Space Studies and Activities CISAS-“G.Colombo” of the University of Padova, in the frame of the Italian MIUR project SAPERE-STRONG. Considering the increasing number of plasma thruster concepts which rely on RF technology, the development of a thrust stand specifically conceived for being low affected by RF disturbances is particularly interesting in the field of the Aerospace Measurements. Our thrust balance has been designed in order to develop and optimize RF thruster prototypes at the CISAS facility [43], therefore it shall meet two fundamental requirements: (i) allowing for an high number of measurements per day; (ii) being highly insensitive to RF disturbances in order to produce reliable data. Additional requirements are the possibility of being housed within CISAS’s vacuum chamber, characterized by an inner diameter of 0.60 m, with minimum impact on the facility and the reduction of complexity and costs. In order to meet all these requirements we resorted to a reconfigurable counterbalanced-type pendulum, which allows for high sensitivity and linearity in a wide range of thruster mass and performance while maintaining a compact enough envelope. We decided to avoid a null-displacement system, since it may be affected by RF disturbances, relying on a laser displacement sensor instead, while the mechanical stability of the system is ensured by the equilibrium between the applied masses. Our thruster balance is able to carry thrusters with mass up to 10 kg, and can be accommodated in the CISAS cylindrical vacuum chamber. The interval of forces which can be measured by our balance is strongly dependent on the mass of the thruster under test; e.g. for a 0.5 kg prototype, forces can vary in the range from 20 μN up to 50 mN.

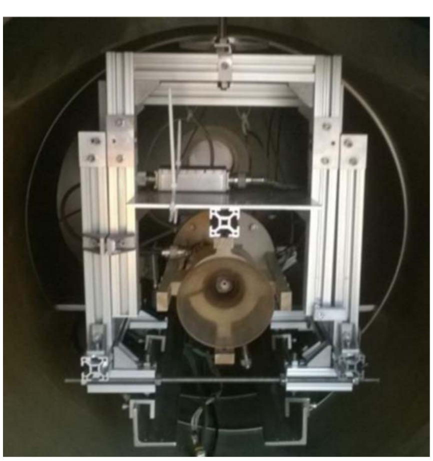

Fig. 1. Picture of the counterbalanced pendulum thrust stand installed inside the CISAS vacuum chamber. Non-optimized prototype of a 0.5 kg thruster fastened to the mobile arm.

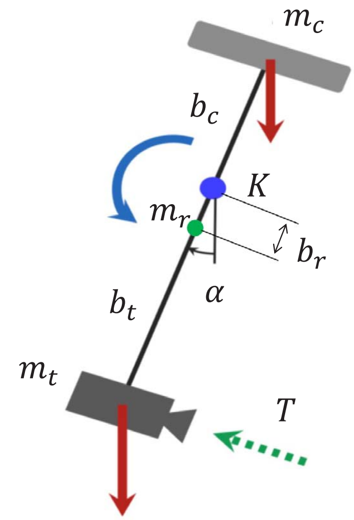

Fig. 2. Schematic of the counterbalanced pendulum thrust stand concept.

2. Design description

2.1. Thruster balance schematic

The schematic principle of our thrust stand is depicted in Fig. 2, the thrust T is correlated to the pendulum arm rotation angle α by means of the rotational equilibrium equation

$$K\alpha = Tb_t + g_0\sin(\alpha)(m_c b_c - m_t b_t - m_r b_r) \tag{1}$$

in which b_t is the distance between the thruster and the pivot, m_t is the thruster mass, b_c is the length of the arm between the counterweights and the pivot, m_c is the counterweights mass, m_r is the mass of the rotating arm, b_r is the distance of the baricenter of the rotating arm from the pivot, K is the torsional stiffness of the pivot, and g_0 is the gravitational acceleration at sea level. If we assume small angles, we have

$$\alpha = \frac{Tb_t}{K + g_0(m_t b_t - m_c b_c + m_r b_r)} \tag{2}$$

In our system rather than α we measure the horizontal displacement Δ_x of a point in the pendulum arm distant b_P from the pivot, therefore

$$R_T = \frac{\Delta_x}{T} = \frac{b_t b_P}{K + g_0(m_t b_t - m_c b_c + m_r b_r)} \tag{3}$$

where R_T is the instrument sensibility.

2.2. Thruster balance design

The thrust stand design is reported in Fig. 3, we have employed