

Configurations and Key Issues of Low Thrust Measurement for Microspacecrafts

Wei-jing Zhou¹, Ji-fei Ye¹, Nan-lei Li¹ and Hao Chang^{1,a}

¹State Key Laboratory of Laser Propulsion & Application, Space Engineering University, Beijing 101416, China

Abstract. Microthrusters on microspacecrafts are of interest and its output thrust must be characterized for a particular application. The technology of micro thrust measurement can evaluate the performance of microthrusters. The measurement principles of steady-state thrust, pulse impulse, average thrust and instantaneous thrust are introduced. The classical thrust stands at home and broad are summarized and they are classified into torsional arm type, balance type, hanging pendulum type and flexure vibration type according to their dynamics configurations. The characters, purpose, advantages and disadvantages are analyzed. The key problems, such as error influence factors and its countermeasure, calibration, and measurement automatization, are pointed out.

1 Introduction

Microspacecrafts can potentially reduce launch cost and can complete a variety of new space-based missions, so it has attracted much attention in recent years. And then, miniaturization of every component on the microspacecraft is required. Among all the components, microthruster, which can produce very small (on the order of μN or nN) and highly accurate thrust for stabilization, pointing and position keeping of microspacecraft is of current interest. Solid Propellant Microthruster (μSPT), Pulsed Plasma Microthruster (μPPT), Field Emission Electric Propulsion (FEEP), Colloid Thruster, Laser Ablation Microthruster (μLAT) and so on is generally recognized as potential microthrusters. But, the accurate measurement of their performance is the basic problem to be solved at first. And the most critical performance measurement is that of thrust. For the purpose of thrust measurement, many thrust measurement stands already exist. In this paper, the principles of thrust measurement are concluded. Several typical configurations of microthrust measurement system are summarized. And the key issues of microthrust measurement are discussed. The goal of this paper is to help users choose best configuration for a particular microthruster, and provide issues which are must pay attention to for particular micro thrust measurements.

2 Principles of Microthrust Measurement

Microthrusters can be classified into continuous thruster and pulse thruster according to the thrust output mode. For continuous thrust, the steady-state thrust is generally measured. For pulse thruster,

^a Corresponding author: changhao5976911@163.com

pulse impulse, average thrust and instantaneous thrust is generally measured. The measurement principles are summarized in Table 1.

Table 1. Measurement principles of micro thrust

Thrust	Measurement principle	Measurand	Measurement restrictions
steady-state thrust	Thrust is linear with the steady-state deflection angle of the executive unit.	steady-state deflection angle	—
	Thrust is compensated with feedback force in time.	deflection angle	The responsive bandwidth is low because of the inertia.
pulse impulse	Impulse is linear with the maximum deflection angle of the executive unit.	maximum deflection angle	Pulse width is several orders of magnitude smaller than the natural period of the thrust stand.
average thrust	Average thrust is linear with the average value of the quasi steady-state deflection angle of the executive unit.	quasi steady-state deflection angle	Pulse repetition frequency is several orders of magnitude higher than the natural frequency of the thrust stand.
instantaneous thrust	Thrust is linear with the deformation of the elastic element.	deformation	A compromise between the sensitivity and the responsive bandwidth are needed to take into count.
	Thrust is linear with the angular acceleration of the executive unit.	deflection angle	The precision is restricted by the sampling rate, the numerical differentiation algorithm, etc.
	Thrust is compensated with feedback force in time.	deflection angle	The responsive bandwidth is low because of the inertia.

3 Conclusion and Analysis of Classical Microthrust Measuring System

For the purpose of thrust measurement, many thrust measurement stands already exist. And they can be classified into torsional arm type, balance type, hanging pendulum type and flexure vibration type according to their dynamics configurations. Typical applications in various configurations are shown in Table 2 to Table 5. And test characteristics, advantages and disadvantages are analyzed in Table 6.

Table 2. Thrust stands based on torsional arm

Time	Research team	Application	Displacement/Angle measurement	Calibration method	Performance
1971 ^[1]	NASA Goddard Space Flight Center	Pulse Plasma Thruster	differential capacitance displacement transducer	Permanent magnet and multiturn coil	Range: 4.4μN~50mN Max error: 4.5%
1997 ^[2]	NASA Lewis Research Center	Pulse Plasma Thruster	LVDT	Steady-state force calibration: weight Impulse calibration: impact pendulum	Average thrust: 573μN Impulse bit: 266μNs
1999 ^[3]	C. R. Phipps team	Micro Laser Plasma Thruster	mirror and laser beam	—	Range: 20μNs Precision: 1nNs
2000 ^[4]	NASA Goldard Space	Colloid and Field Emission	autocollimator targeting a mirror	Measuring Natural frequency and	Range: 1~100μN Precision: better than 0.1μN

	Flight Center	Electric Propulsion thrusters		moment of inertia	
2004 ^[5]	University of Tokyo	Liquid Propellant Pulsed Plasma Thruster and Diode Laser Ablation Microthruster	LVDT	Impact pendulum	For LP-PPT, range: 20~80μNs, Resolution: 2.1μNs For μDLAT, range: 1~10μNs, Resolution: 0.7μNs
2006 ^[6]	C. R. Phipps team	msμLPT	Interferometer	Helmholtz coil	Force response: 1.25mN/rad Range: 100nN~500μN, Precision: 25nN
2012 ^[7]	Key Lab of Renewable Energy and Natural Gas Hydrate	MEMS micro nozzle chip	LVDT	Steady calibration: weights Impulse calibration: ball	Resolution: 0.1mN
2012 ^[8]	Institute of Mechanics, Chinese Academy of Sciences	—	light	Calibrating spring constant with period method	Range: 54~323μN Precision: 2μN

Table 3. Thrust stands based on balance

Time	Research team	Application	Displacement/Angle measurement	Calibration method	Performance
2005 ^[9]	University of Colorado	Pulsed Plasma Thruster	LVDT	Impact hammer	—
2011 ^[10]	University of Southern California	Micro Cathode Arc Thruster	LVDT	—	Impulse bit: 0.72±0.02μNs
2012 ^[11]	Beijing Aerospace Institute for Metrology and Measurement Technology	Micro Thruster	Displacement transducer	—	Range: 0.1~1mN Expend uncertainty: 0.05mN (k=2)

Table 4. Thrust stands based on hanging pendulum

Time	Research team	Application	Displacement/Angle measurement	Calibration method	Performance
1996 ^[12]	Princeton University	—	Laser interferometry	Force transducer	Range: 100μNs~10Ns Steady-state thrust: as low as 20μN Error: <2%

2004 ^[13]	NASA Marshall Space Flight Center	Electric Propulsion System	LGDT	Weights	Range: 100 μ N~1N
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Table 5. Thrust stands based on flexure vibration

Time	Research team	Application	Displacement/Angle measurement	Calibration method	Performance
2006 ^[14,15]	Johns Hopkins University Applied Physics Laboratory	Micro-scale Pulsed Plasma thruster	Interferometer	Ball	Min impulse bit: 0.3 μ Ns

Table 6. Characters of all types of thrust stands

Type	Characters	Measuring	Advantages	Disadvantages
Torsional arm type	The thruster is mounted on the arm. The arm response in horizontal plane by rotating about its axis. The restoring force is provided by elastic element or feedback force.	steady-state thrust pulse impulse average thrust	The restoring force is not influenced by the weight of the thruster or the arm. And the relationship between the restoring force and the deflection angle is not influenced by any nonlinear factors. And the structure is not sensitive to vertical vibration.	The spring constant can vary or the thermal deformation can happen as the temperature varies.
Balance type	The thruster is mounted on the arm. The arm response in vertical plane by rotating about its axis. The restoring force is provided by elastic element or feedback force.	steady-state thrust pulse impulse average thrust	Calibration is easy to carry out. And the ablation mass can be measured.	The thrust is not separated from the gravity.
Hanging pendulum type	The thruster is mounted on the pendulum. The pendulum response in vertical plane by rotating about its axis. The restoring force is provided by gravity.	steady-state thrust pulse impulse average thrust	The restoring force is not influenced by the temperature.	The restoring force is provided by the gravity so that the nonlinear effect exists. And the variation of the thruster can influence the restoring force.
Flexure vibration type	The thruster is mounted on the elastic element. And the elastic element vibrates when the thruster fires.	pulse impulse instantaneous thrust	The configuration is simple.	The noise interference is serious so that it is difficult to filter.

4 Key issues of Microthrust Measurement

(a) Error Analysis. Environmental factors that may have an impact on measurement are: (i) Vibration. Footsteps, passing vehicles, air flow and so on can cause measurement signal noise. So, firstly, the good testing environment, such as at night, must be taken into account. And then corresponding vibration reduction measures, such as vibration isolation foundations and vibration isolation platform, can be considered. At last, data processing model for noise reduction, such as the use of Fourier transform spectral analysis, adaptive filtering and so on, can be researched. (ii) Temperature. Temperature changing can cause changes in the spring coefficient of the elastic element. And this can affect measurement accuracy. So the characteristics of the impact must be studied. And the higher heat capacity and thermal conductivity material can be taken into account. Also, the spring coefficient can be calibrated before each experiment. (iii) Electromagnetic environment. Electromagnetic environment has a certain effect on some component (such as the electromagnetic dampers, coil permanent magnet) or thrusters (Pulsed Plasma Microthruster). Electromagnetic intensity can be monitored real-time so that the interference source can be checked out and removed. A certain amount of shielding measures can be carried out. Because of different configurations of thrust stand, the environmental interference factors must be analyzed specifically and then corresponding denoising measures is to be carried out.

(b) Automation Control. Thrust measuring system involves level control, zero control, calibration and so on. Because of particular measurement requirements in vacuum and the flexibility, the above operations had better automate as much as possible.

(c) Calibration. Calibration is the key issue in the validation of the measurement system. For thrust measurement, calibration commonly uses weights, electrostatic force and electromagnetic force. The friction caused by pulley can arouse error when the weight method is carried out. Electrostatic force and electromagnetic force has no mechanical contact, and can be controlled easily by program. But they are sensitive to electromagnetic interference. For pulse impulse measurement, calibration commonly uses ball falling method, the impact pendulum method and the force hammer method.

5 Summary

With the development of the microspacecraft, micro propulsion becomes a research field of current interest. The micro thrust measurement is very important for the performance validation of the microthrusters. But it is a complex and challenging technology. The working mode and the configuration of all kinds of microthrusters are different from each other so that the dynamical configuration of the measuring system must be chosen carefully according to the specific case. Interference is easy to be introduced into the measuring data. So denoising is the key technology to be solved all the time. And lastly, the implementation of the micro thrust measuring system is a complex and repeating work which needs patience and confidence.

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