Research on Micro Impulse Measurement Technology for Micro Cathode Arc Thruster

IEPC-2019-A-560

Presented at the 36th International Electric Propulsion Conference
University of Vienna • Vienna, Austria
September 15-20, 2019

Xuhui Liu[1], Jinyue Geng[2], Yu Qin[3], Jun Long[4], and Yan Shen[5]
Advanced Space Propulsion Laboratory of BICE, Beijing, China

Beijing Engineering Research Center of Efficient and Green Aerospace Propulsion Technology, Beijing, China

Fei Li[6] and Xilong Yu[7]
Institute of Mechanics, Chinese Academy of Science, Beijing, China

Abstract: Micro cathode arc thruster is a new micro electric propulsion technology, which has the advantages of low impulse and simple structure. It is suitable for high precision attitude and orbit control of micro-nano satellites. In order to study this kind of micro-propulsion technology, the research of micro-thrust testing technology is carried out, and the performance evaluation of the thruster is carried out. A uN-level force measurement system is developed. The micro-thrust measurement system is based on the torsion pendulum structure and different types of displacement sensors, and a second-order damping system is formed. The high-precision displacement sensor is used to measure the torsion pendulum motion, and the impulse generated by the thruster is obtained. An electromagnetic calibration system is developed. The micro-force calibration is realized by utilizing the attraction force between the power supply coil and the magnet. To get the matching relationship between calibration current and micro-force, a high precision force-measuring balance is used , and the force-measuring accuracy is better than 0.05uN. The micro-thrust measurement system can measure force in a range of 1-1000 uN with the precision of 1 uN, and the maximum load of the test system is about 2 kg. The impulse of the micro cathode arc thruster is measured by the force measuring system. The average impulse range of the single pulse is 0.1~0.35uNs, and the impulse increases with the increase of discharge time. Under the same discharge time and inductance, the impulse bit decreases slightly with the increase of the working frequency of the thruster.

I. Introduction

It is difficult to measure micro-thrust for some propulsion system which is potential for microsatellite and nanosatellite. The main reason is the tiny thrust (~uN) and thrust-weight ratio which is about 10-6 or even less. It is almost impossible to measure it using traditional force sensor. Indirect force measurement method should be utilized.

---

[1] Senior Engineer, Advanced Space Propulsion Laboratory of BICE, xhliu99@163.com.
[2] Senior Engineer, Advanced Space Propulsion Laboratory of BICE, jinyuegeng@163.com.
[3] Engineer, Advanced Space Propulsion Laboratory of BICE, qinyu_502@126.com.
[4] Senior Engineer, Advanced Space Propulsion Laboratory of BICE, 18613889712@163.com.
[5] Professor, Advanced Space Propulsion Laboratory of BICE, shenyan7806@163.com.
[6] Associate Professor, LHD, lifei@imech.ac.cn.
[7] Professor, LHD, xlyu@imech.ac.cn.

For thrust less than 1 mN, thrust stand is used transfer the force and impulse to displacement and velocity. Researchers have invented variety of force measurement systems to solve this problem. For example, Andre.J.Jamison and E.P.Muntz [1] , H.Koizumi and K.Komurasaki [2], Denis Packans [3], S.Roy and J.Soni [4] etc. Those instruments have a great performed in steady force measurement. For impulse measurement of miniature cathode arc thruster (uCAT), a micro-thruster stand is developed. And vacuum tests show its great performance.

II. The thrust stand for micro-newton force measurement

A. The design of the system

For accurate measurement of micro-thruster, minimizing dependence on experimental operators, a torsional pendulum was developed. Different kind of displacement sensors, such as LVDT, the Michelson Interferometer, reflective laser displacement mete, were used for different force range.

Some issue should be solved for better practicality:

1. smaller spring constant can improve sensitivity, on the other hand, limiting and protecting device should be used to ensure the safety of the stand;
2. a suitable damping system should be used to restrain the disturb;
3. online real-time calibration should be developed;
4. suitable vacuum system for test, non-volatile substances and high exhaust material;
5. gas supply and power supply for thruster;
6. measurement and control system for damping, calibration and displacement sensor;

B. The mathematics model of forced vibration of torsional pendulum

When the pendulum is taking a small angle swing, the motion of the pendulum arm follows the simple harmonic vibration equation of the forced vibration. In this study it can be considered a small angle spread. Its control equation can be written as [5] [6]:

$$\mathrm{I}\frac{dx^2}{dt^2}+C\frac{dx}{dt}+Kx=f(t)L \tag{1}$$

let:

$$\zeta=\frac{c}{2}\sqrt{\frac{1}{IK}} \tag{2}$$

$$\omega_n=\sqrt{\frac{K}{I}} \tag{3}$$

$$\omega_d=\omega_n\sqrt{1-\zeta^2} \tag{4}$$

finally:

$$\frac{dx^2}{dt^2}+2\zeta\omega_d\frac{dx}{dt}+\omega_n{}^2x=f(t)\frac{L}{I} \tag{5}$$

where x represent displacement function, L is displacement between pivot center and thrust action point. I ($\mathrm{kg}\cdot m^2$)is the moment of inertia of the pendulum, C($\mathrm{N}\cdot\mathrm{S}\cdot\mathrm{m}$) is damping coefficient, K($\mathrm{N}\cdot\mathrm{m/rad}$) is the elasticity coefficient. $\zeta$is attenuation coefficient, $\omega_n$is natural frequency and the $\omega_d$is damping vibration frequency.

For steady thrust measurement, as shown in eq.(1), the pendulum is static, and its velocity and acceleration are zero, thus steady displacement is $x_s = F\cdot L/k$, force can be deduced using the calibrated elasticity coefficient

For impulse measurement, the actuation duration of the impulse force is much less than the natural period of the stand. Therefore, $F(t) = I_{bit}\delta(t)$, it has analytic solutions for eq.(1), the required impulse can be described as $I_{bit} = \dot{x}(0)\cdot I/L$. The impulse can be deduced using the calibrated parameters of the pendulum as well as the initial velocity.

C. The physical construction of the torsional pendulum

Similar to former references [7][8], torsional pendulum is the key part the measurement system. Figure 1 is a schematic diagram of the force measuring system of mechanical parts. The mechanical part has several important parts, they are: pivot axis, torsional pendulum arm, calibration coil, damper and displacement sensor. The main parameters of this system are: at the quasi-static force the measurable range is1~3000 μN and the measurement precision is 1 μN.

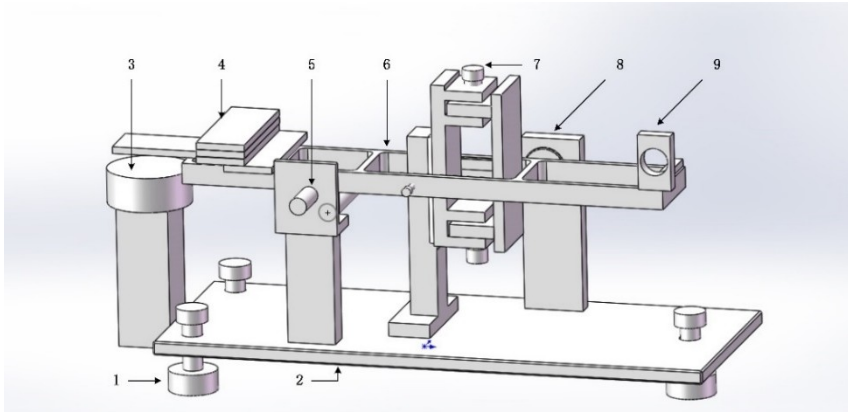


Figure 1 The torsional pendulum system
1.Leveling bolt, 2.Base plate, 3.Damping magnet, 4.Conuterweight and part-time damping plat, 5.displacement sensor, 6.Oscillating arm, 7.pivot axis(a couple up and down), 8.calibration system, 9.thruster's tray.

Pivot axis is to restoring torque, to balance the thrust. The torsional pendulum arm is to transition the thrust into deflection and offset gravity. Calibration system's [9][10][11] structure is one permanent magnet and a coil on the opposite of the magnet, and this coil connect with the high-precision source, the calibration range of this calibration system is 1~10000μN, and its accuracy is higher enough. The damper theoretical basis is Lenz's law, it's structure is a group of circle permanent magnets and a copper plate (counterweight plate), its aim is to make the torsional pendulum station keeping and revert to the equilibrium position from moving, during the experimentation. Displacement sensor is one of the most important Subsystem in this micro-thrust balance system, the parallel plate capacitance displacement sensor was choired. It's measurable range is 100μm, the accuracy is 1nm. The other part of the micro-thrust balance system is control Subsystem, it's including software part and hardware part, to control the thruster's work or not, and record the deflection data.

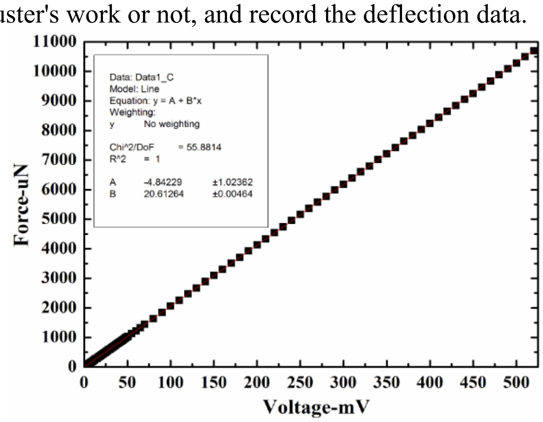


Figure 2. The results of the calibration coil

The moment of inertia I(kg • m2), damping coefficient C (N • S • m) and stiffness coefficient K(N • m/rad) can be calibrated. The specific process will be told in sec 3.2. To product the displacement a suitable device for generating external excitation is important. The calibration device includes two important parts: one is the mechanical part, it is including one flat cylindrical, high magnetic energy density, rubidium nickel alloy permanent magnet that has a circular hole in the magnet's core, it's superficial magnet filed intensity are about 4000 Gs, and on the opposite of the magnet a coil is there, the distance between the magnet and the coil is about 300 μm. The center point of the coil is coincidence with the center of the magnet.

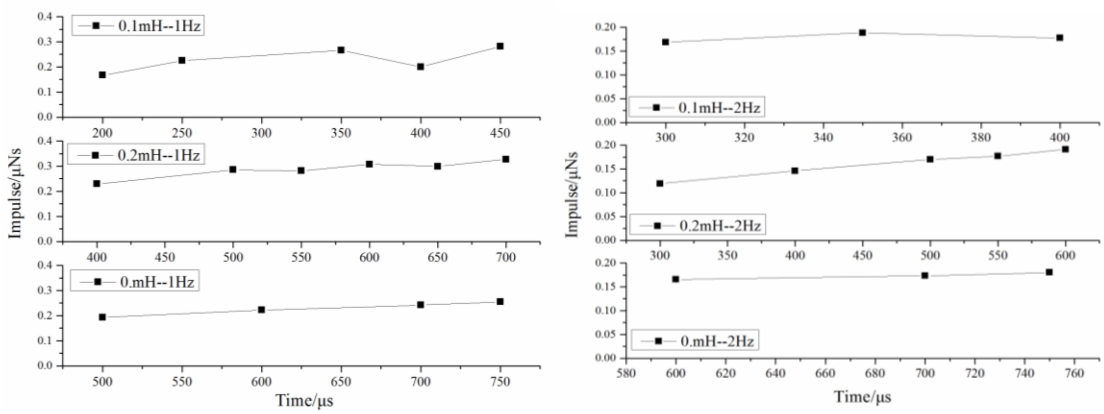
This device is calibrated first using a High Precision Force Balance using standard counterweight with accuracy better than 0.05 uN. Figure 2 shows the typical calibration curve which indicates the excellent linearity of this calibration method. Force with range of 10-100000 uN can be exert on the pendulum. Consider the arm of force, this measurement system can provide force range of 1~3000 uN with uncertainty about 1 uN.

III. Results for uCAT

Both the impulse and the average thrust of one uCAT thruster were measured using the stand. Changing the discharge duration, inductance intensity (one main parameter of the thruster) as well as the repetition rate of the discharge, the uCat can provide different impulse. The measured average impulse as shown in figure 3. Figure 3(a) gives the results at 1Hz discharge with inductance intensity of 0, 0.1 and 0.2mH. Figure 3(b) gives the results at 2Hz discharge. As can be find impulse can alter from 0.1 to 0.35uNs, which increase with the discharge duration. Single impulse slightly decreasing with repetition rate at same discharge duration and inductance intensity.

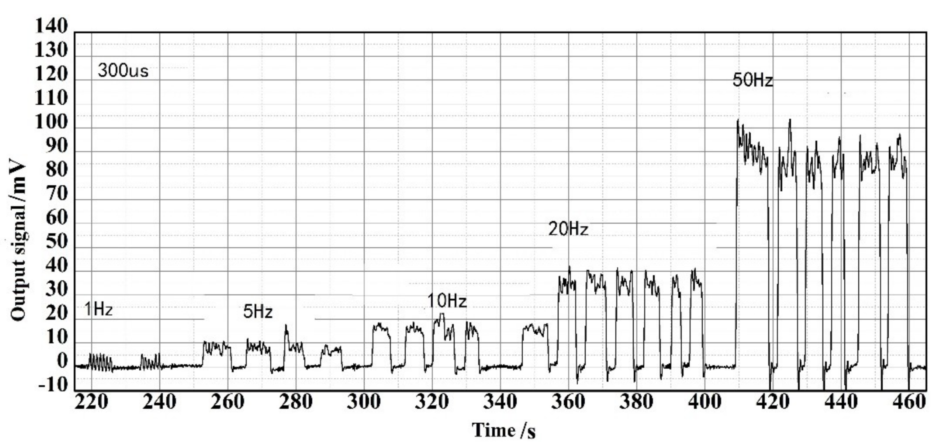
Due to the pendulum's low natural frequency, equivalent average thrust can be measured when the continuous ignition for 5-10s at different discharge repetition (i.e. 5Hz). At high repetition rate, this pendulum can come to the equilibrium position after several vibrations. This displacement of equilibrium position can be used to deduce the average thrust as well as the impulse.

Figure 4 shows the stand response at 1,5,10,20,50Hz discharge repetition and 300/330us discharge duration. The thrust-signal coefficient is 0.1uN/mV. As can be seen, for 300us discharge duration, average thrust is about 10uN at 50Hz. It means the impulse is about 0.2uNs. It is similar for other repetition rate. Impulse at 300us discharge duration is 15% smaller than 330us. For 1Hz repetition rate which is close to the pendulum's natural frequency, the pendulum would sustain vibration which means the average thrust cannot be deduced for this case.

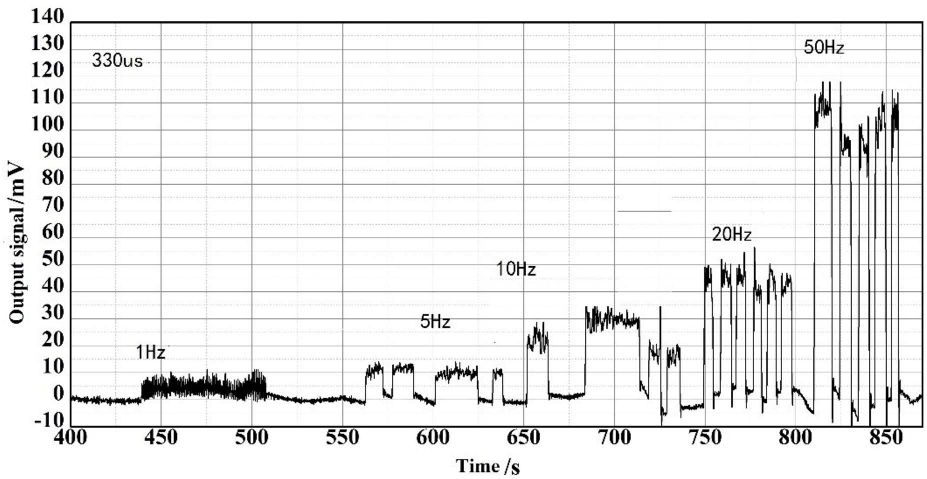


(a) Repetition of 1Hz (b) Repetition of 2Hz

Figure 3. Measured impulse for different cases



(a) Discharge duration of 300us



(b) Discharge duration of 330us

Figure 4 average thrust for different cases

IV. Conclusion

One micro-thrust measurement system was developed based on torsional pendulum. Its measurement range is about 1~3000 uN with 1uN measurement precision. Both impulse and average of a miniature cathode arc thruster is measured at different discharge duration, inductance intensity, and the repetition rate of the discharge. The range of the measured impulse is 0.1-0.35uNs for the given cases.

References

[1] Andrew J. Jamison Andrew D. Ketsdever Gas Dynamic Calibration of a Nano-Newton Thrust Stand, REVIEW OF SCIENTIFIC INSTRUMENTS VOLUME 73, NUMBER 10 OCTOBER 2002

[2] H.Koizumi K.Komurasaki Y.Arakawa Development of thrust stand for low impulse measurement from microthrusters, REVIEV OF SCIENTIFIC INSTRUMENTS VOLUM 75, NUMBER 10 OCTOBER 2004

[3] Denis Packan Thrust Measurements with the ONERA Micronewton Balance Conference Paper ·No. 102-108 January 2007.

[4] J. Soni and S. Roy Design and characterization of a nano-Newton resolution thrust stand, REVIEW OF SCIENTIFIC INSTRUMENTS 84, 095103 (2013).

[5] Daeban Seo1, Jongkwang Lee2 and Sejin Kwon The development of the micro-solid propellant thruster array with improved repeatability J. Micromech. Microeng. 22 (2012) 094004 (11pp)

[6] Keiji Hagiwara1, Hitoshi Yonamine2, and Hideyuki Horisawa Control of thrust measurement system for cw laser thrusters The 32nd International Electric Propulsion Conference, Wiesbaden, Germany September 11 – 15, 2011

[7] Md. Emdadul Hoque and Takeshi Mizuno Magnetic levitation technique for active vibration control Magnetic Bearings, Theory and Applications

[8] M. Benedettia,d,n, D. Bortoluzzi, L. Baglivo S. Vitale An optimal two-input approach for impulse measurements in the nano Ns range produced by contact forces, Mechanical Systems and Signal Processing 25 (2011) 1646–1660

[9] S Rocca,CMenonand D Nicolini FEEP micro-thrust balance characterization and testing, MEASUREMENTSCIENCE ANDTECHNOLOGY 17(2006) 711–718.

[10]]M Masuda，M Sasakiand A Araya A torsion balance for probing a non-standard force in the sub-micrometre range, CLASSICAL ANDQUANTUMGRAVITY 24(2007) 3965–3974

[11] Hui Xie and St´ ephane R´ egnier development of impulse measurement techniques for the investigation of transient forces due to laser-induced ablation, J. Micromech. Microeng.19(2009) 075009 (9pp)