

Research on Thrust Noise Characteristic of 1.35kW Hall Thruster

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Abstract: The rapid advancement of contemporary global satellite communication and navigation has led to a growing significance for accurate orbit prediction and real-time orbit control capabilities. This gives rise to higher standards for thrust resolution and precision in propulsion systems. Since Hall thrusters is among the most common used electric thruster types, increasing its thrust accuracy is meaningful to meet the latest requirements.

In this research, by parameter fitting of the performance test results, the thrust characteristic of the 1.35kW hall thruster with regard to the anode voltage and current is firstly developed. Secondly, the observed anode voltage and current are used to determine the thrust fluctuation trend and noise characteristic. It is demonstrated that xenon flow variation has the largest relative noise level, which infers that it is the main source of thrust noise. Thirdly, the thrust noise power spectrum density is evaluated and the results indicate that the noise level is largest in the low frequency band resulting from long-term drift of anode current, and it is less than 0.1 mN/Hz^{1/2} in the frequency band higher than 10⁻³Hz.

Keywords: Hall thruster; thrust noise; parameter fitting; wavelet decomposition; power spectral density

1 Introduction

1.1 Application background of high precision Hall thrusters

At present, with the gradual maturity of Hall electric propulsion technology, the application of Hall electric propulsion has expanded from the initial GEO satellites to deep space probes, MEO satellites, LEO satellites and their constellations, ultra-low orbit (VLEO) spacecraft, manned spaceflight, on-orbit maintenance and other areas^[1].

In the planning of the new generation of navigation satellites, China's Beidou navigation system, the Global positioning system of the United States, and the Galileo satellite navigation system of the European Union are demonstrating the use of electric propulsion instead of chemical propulsion lightweight system solutions.

The orbit control of navigation satellite is of great importance to the service continuity and availability of the system. If the orbit can be directly extrapolated according to the thrust, it can provide accurate orbit control and forecast for the orbit maintenance of GEO navigation satellites, and ensure the continuous navigation mission during orbit control^[2].

In addition, ultra-low orbit satellite "real-time resistance compensation", low-orbit high-density constellation "precision formation", low-orbit Internet communication satellite "precise orbit control" and high-resolution remote sensing satellite "moving imaging" are also the potential application scenarios. To ensure that the satellite can stably perform high-precision observation tasks, and realize inter-satellite strict and accurate

formation, we should eliminate the impact of thrust noise of the propulsion system on the satellite orbit determination accuracy.

1.2 Thrust noise source analysis of hall thruster

In order to achieve the error requirements of GEO navigation satellite autonomous orbit control position error less than 1m and orbit user ranging error less than 0.2m, the propulsion system needs to achieve a thrust accuracy index of better than 0.2%^[2]. At present, the thrust accuracy of electric propulsion is only 5%, as a result it cannot meet the demand for thrust accuracy of the new generation of navigation satellites for the time being. Following are several possible sources of thrust noise for the thruster.

For factors outside the thruster, 1) The thrust is proportional to the propellant flow, so the propellant supply accuracy directly determines the thrust accuracy. In order to achieve high precision of thrust output, the accuracy of flow control must be better than that of thrust output^[3]. Although the storage and supply system are developing towards high precision, it is still difficult to completely eliminate the deviation; 2) For the Hall thruster, its PPU not only needs to supply power to the anode, cathode and electromagnetic coil, but also needs power to drive the valve and other parts of the propellant storage system^[4]. In order to further improve the thrust output accuracy of the propulsion system, it is necessary to ensure that both the drive control and the power supply have high-precision and high-stability output capabilities, which puts forward extremely high requirements on the drive control technology and power processing technology.

For the thruster itself, 1) There are discharge oscillations and mode conversion in the working process of the thruster^{[5]-[8]}, which affect the stable output of thrust; 2) During the working process of the thruster, the change of space environment temperature and the discharge heat production of the thruster will affect its working temperature^[9], resulting in the change of discharge characteristics and thrust output characteristics; 3) Because the thruster is stored in atmospheric conditions, some gases are absorbed in ceramic structures. During the experiment in a vacuum tank, the absorbed gases in ceramic structures will gradually precipitate^{[9],[10]}, affecting the output thrust; 4) On a longer time, the change of the thruster wall morphology will also affect the thrust output value^{[11]-[12]}.

1.3 Background of thrust noise characteristic research

The thruster used by the GOCE satellite is the T5 ion thruster developed by the British company QinetiQ. The thrust is measured indirectly by measuring the beam current and voltage^[13].

The LISA pathfinder system was designed by ESA, and the micro-thrusters use FEEP thrusters. Indium^[14] and Cesium^[15] are used as propellants respectively for FEEP thrusters. The thrust noise was measured directly by the Nano balance thrust balance., and the thrust is also calculated based on the formula with beam current and voltage.

In the ground test stage, the thrust of the ST7-DRS system is measured by the torque balance, and the difference between the measured thrust and the average thrust is calculated to obtain the thrust noise^[16]. During the space test phase, the thruster noise is obtained by calculating the difference between the thrust force and the thrust command based on the measured electron beam current and voltage.

Cui Kai^[17] from Harbin Institute of Technology conducted experimental tests on the thrust noise and thrust dynamic response process of the μN class and micro-Newton class curved-type Hall propulsion system respectively. It can be seen that the thrust can be calculated from the ion current information in the plume region and the ion acceleration voltage information, in which the ion current can be measured by the Faraday probe and

the ion acceleration voltage can be measured by the RPA (Retarding Potential Analyzer) probe. The comparison of the thrust noise level is shown in TABLE I.

TABLE 1 Thrust noise level comparison of different thrusters

Thruster	Estimation Approach	Thrust/mN	Noise/ $\mu\text{N} \cdot \text{Hz}^{-1/2}$	Relatively Noise/ $\text{Hz}^{-1/2}$
T5 ion thruster ^[13]	Calculation	8.3	10	0.0012
FEEP (Indium) ^[14]	Thrust balance, Calculation	0.008	0.02	0.0025
FEEP (Cesium) ^[15]	Thrust balance, Calculation	0.01	0.06	0.006
Colloidal Thruster ^[16]	Thrust balance, Calculation	0.02	0.03	0.0015
Cusped Field Thruster ^[17]	Probe	12	40	0.00125

1.4 Content of the paper

In the second chapter, the thrust characteristic of the 1.35kW Hall thruster is established through parameter fitting of the performance experiment result. In the third chapter, the variation trend and thrust noise characteristic in time domain are computed using the measured anode voltage and current during experiment. In the fourth chapter, an evaluation of the thrust noise power spectrum density in frequency domain is performed and the importance of different factors is analyzed.

2 Mathematical Model of Thruster Performance

The performance characteristic of hall thruster (Fig. 1) is tested by changing the main working parameters of the thruster, including discharge voltage, xenon flow rate and magnetic field. The design working parameters of the thruster are adjusted up and down based on the default values, and the variation of the thruster discharge current and thrust are measured. Three-thread torsion balance (Fig. 2) was used for measurement.

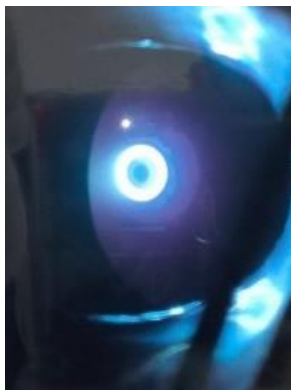


Fig. 1 Performance test of hall thruster

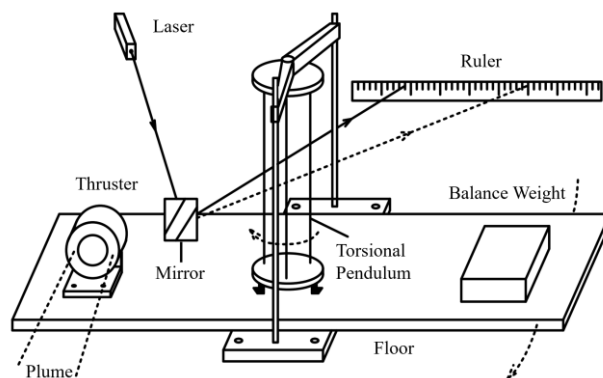


Fig. 2 Three-thread torsion balance

Assume that the position of the thruster working time marker is x , the position of the thruster not working time marker is R_0 , and the position of the weight hanging up and pulling the thruster time marker is R_1 . Then the thrust can be calculated using following formula.

$$T = \frac{x - R_0}{R_1 - R_0} m_f g$$

Where, m_f is the weight mass, g is the acceleration of gravity, which is 9.8 m/s^2 . The measured current and thrust are shown in Fig. 3.

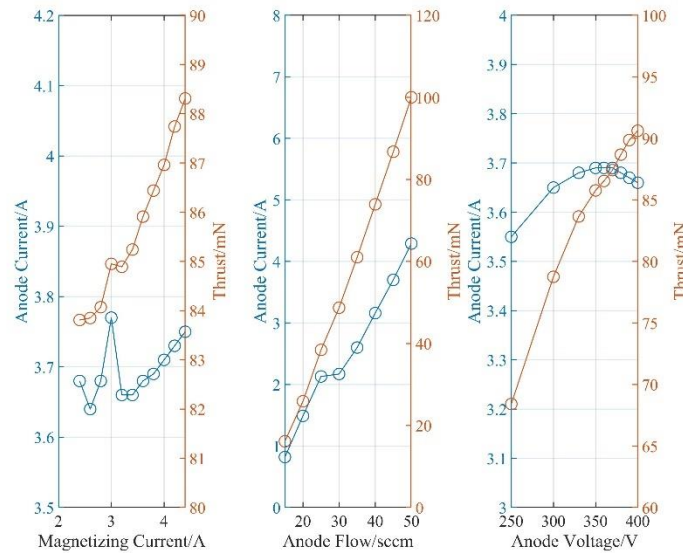


Fig. 3 Performance test result of 1.35kW hall thruster

As a device works by plasma discharge, the thruster working condition can be expressed by anode voltage U_d and anode current I_d measured by power source system, and the output thrust T is closely related to these parameters.

In order to further analyze the relationship between working parameters and output thrust noise, this paper first draws on the thrust calculation method proposed by Hey F G of TU Dresden^[18], and establishes the input and output model of thruster $T = f(U_d, I_d)$. In ideal condition, assuming that the ion current $I_i \approx I_d$, the working medium entering the thruster is completely ionized and accelerated, the plume only contain Xe^+ ion, and all of them are ejected along the thruster axis. The thrust force T generated by the thruster under completely ideal working condition with parameters I_d and U_d is as follows.

$$T = \dot{m}v_i = \frac{I_d}{e} M \sqrt{\frac{2eU_d}{M}} = I_d \sqrt{\frac{2MU_d}{e}}$$

Where, v_i is the axial velocity of xenon ion, e is electron charge and M is the mass of xenon atom.

However, in the actual working condition of the thruster, the actual output thrust value will be less than the ideal thrust value obtained by formula due to the factors such as the different between discharge current and beam current, the incompleteness of the ionization and acceleration of the working medium, the existence of multivalent xenon ion and the loss of plume divergence. Therefore, dimensionless thrust coefficient $C(U_d, I_d)$ is defined here to represent the influence of actual factors. The resulting thruster input and output model is

$$T = C(U_d, I_d) I_d \sqrt{\frac{2MU_d}{e}}$$

Since the electron charge and the atomic mass of the xenon are all constants. The thrust coefficient $C(U_d, I_d)$ is related to the working state of the thruster under the input conditions at that time and will change due to changes in the input parameters. Therefore, the thrust coefficient is obtained in this section according to the steady-state thrust measurement data in the thrust adjustable range experiment. And based on cubic polynomial fitting algorithm, the functional relationship between thrust coefficient $C(U_d, I_d)$ and parameters

anode voltage U_d and current I_d is established.

$$C(U_d, I_d) = C_0 + \sum_{i=1}^2 C_{1,i} p_i + \sum_{i=1}^3 C_{2,i} p_1^{3-i} p_2^{i-1} + \sum_{i=1}^4 C_{3,i} p_1^{4-i} p_2^{i-1}$$

$$p_1 = \frac{U_d}{U_{d0}}, p_2 = \frac{I_d}{I_{d0}}$$

Where U_{d0} and I_{d0} is the nominal working voltage and current, p_1 and p_2 are the dimensionless parameter. The comparison of measured and estimated thrust is shown in Fig. 4. It is computed that the standard deviation of fitting error between measured and calculated thrust is 0.33mN.

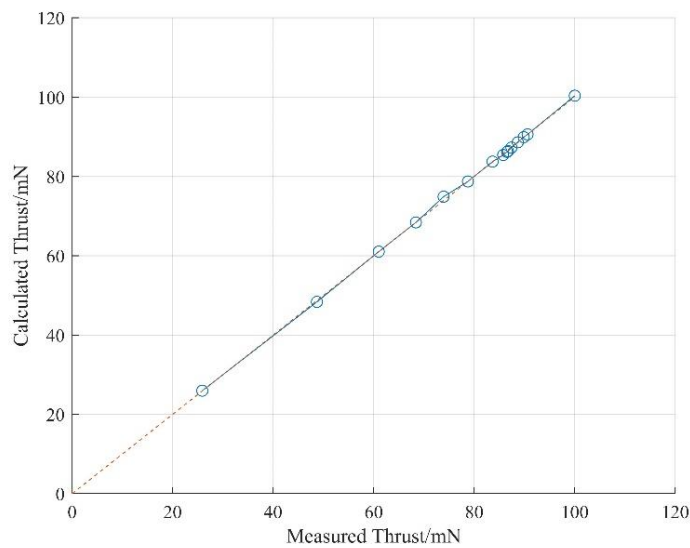


Fig. 4 Comparison of measured and measured thrust

3 Time Domain Thrust Noise Analysis

In order to study the thrust noise characteristic in long-term period, the thruster is ignited in the vacuum chamber for more than 10^4 second. The variation of anode voltage, anode current and xenon flow rate are measured by the power source (Fig. 5) and the xenon supply system. The measured result and calculated thrust by previous model are shown in Fig. 6.



Fig. 5 Power source for hall thruster testing

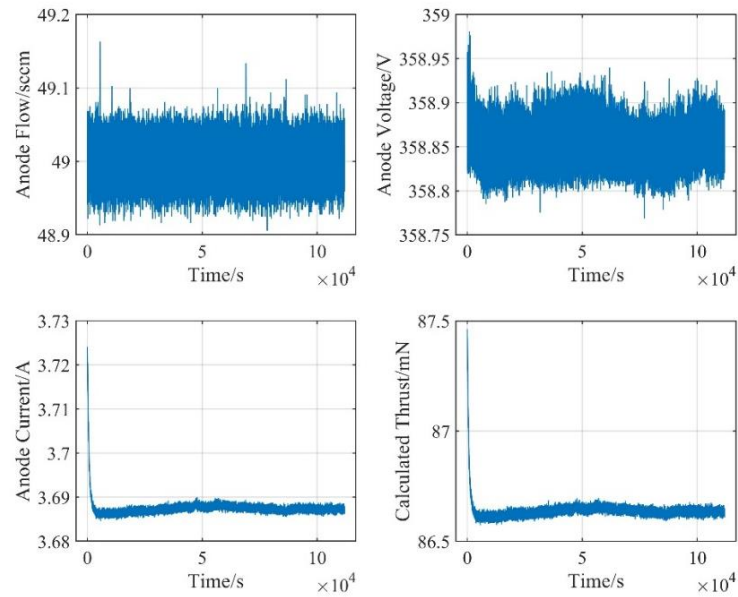


Fig. 6 The original measured data of thruster working

In the time domain, there are two types of noise: long-term drift and small fluctuation. In order to clearly view the change trend of each parameters value over time, the dates are denoised by the wavelet decomposition with db4 basis^{[19][20]}. This result of wavelet decomposition is shown in Fig. 7.

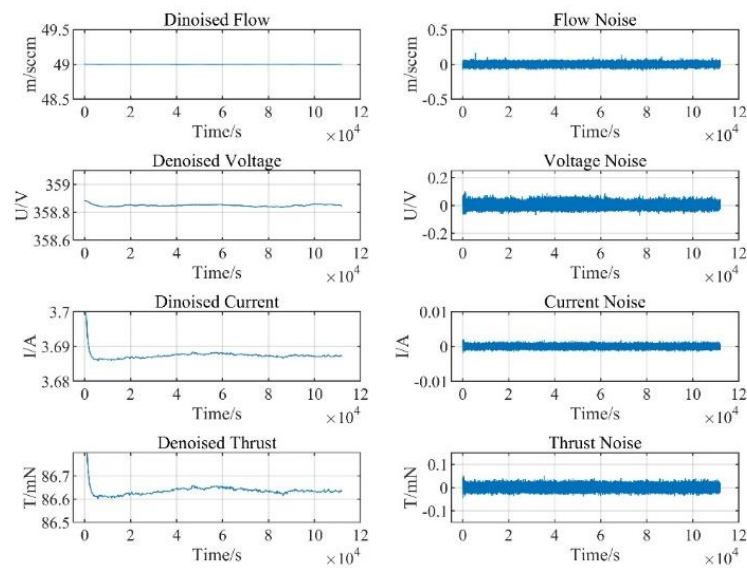


Fig. 7 Wavelet denoising of working parameters

For the long-time drift, it can be clearly seen that the denoised xenon flow and anode voltage fluctuates slightly around their mean value. The maximum peak to peak deviation is 0.0068 sccm (0.15% of mean value) in xenon flow rate, and is 0.0467 V (0.13% of mean value) in anode voltage.

The change of anode current and thrust is relatively more complicated. After ignition, the anode current decrease for 0.037A (9.86% of mean value) in the first hour, and fluctuate at a magnitude of 0.0025A (0.67% of mean value) in the remaining time. The calculated thrust decrease for 0.823mN (10.29% of mean value) in the first hour, and fluctuate at a magnitude of 0.0584mN (0.73% of mean value) in the remaining time.

According to the result, the anode current and thrust undergo an unstable stage in the first hour of ignition and its magnitude is higher than the thrust precision limitation (less than 2%). The variation trend has a time-scale of about an hour, which is close to the time required for the thruster to reach thermal equilibrium. This indicating that the thrust noise in this time range is caused by interference factors such as temperature drift in the working environment and residual gas release in the structural material of the thruster.

To evaluate the small thrust fluctuation during the steady running condition, the noise distribution of the measured and calculated data in the state which has reach thermal equilibrium (after 1 hour of ignition) was shown in Fig. 8. The mean value, absolute and relative standard deviation are list in TABLE II.

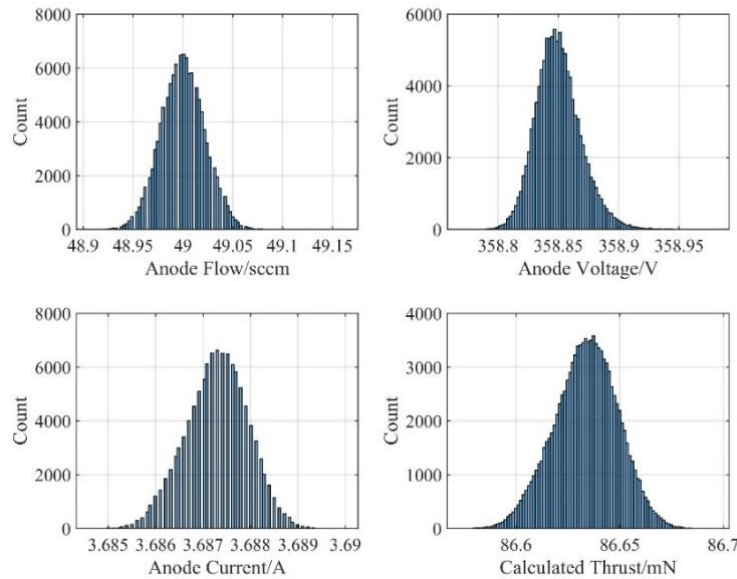


Fig. 8 Deviation distribution of measured parameter

TABLE 2 Comparison of parameter bias

Variable	Unit	Mean Value	Standard Deviation	%
Anode Flow	sccm	48.99	0.0220	0.449
Anode Voltage	V	358.85	0.0187	0.052
Anode Current	A	3.687	6.54×10^{-4}	0.174
Thrust	mN	86.83	0.0153	0.191

According to the result, the anode flow has the highest relative standard deviation, the anode current and the thrust have similar relative standard and the voltage has the lowest standard deviation. The measured anode flow data has a relative noise level higher than the anode current, this may be caused by the low measurement accuracy of the flow system.

To verify the influence factors of input noise on thrust noise of thruster, a simple variation of thruster thrust with respect to external inputs can be derived. According to the principle of the thrust generated by the thruster, it can be known that when other conditions remain unchanged, the thrust is roughly proportional to the propellant flow rate and proportional to the square root of the anode voltage. If k is a proportional coefficient, the formula of thrust can be expressed as

$$T = km\sqrt{U}$$

When the influence of other factors such as environmental factors and the transformation of thruster itself

is neglected, in order to study the influence of xenon flow rate and anode voltage input deviation on thruster thrust, the partial derivative of thrust with respect to propellant flow and anode voltage is obtained as the following formula

$$\begin{aligned} \Delta T &= \frac{\partial T}{\partial \dot{m}} \Delta \dot{m} + \frac{\partial T}{\partial U} \Delta U \\ &= k\sqrt{U_0} \Delta \dot{m} + k\dot{m}_0 \frac{1}{2} \frac{1}{\sqrt{U_0}} \Delta U \\ &= k\dot{m}_0 \sqrt{U_0} \frac{\Delta \dot{m}}{\dot{m}_0} + \frac{1}{2} k\dot{m}_0 \sqrt{U_0} \frac{\Delta U}{U_0} \\ &= T \left(\frac{\Delta \dot{m}}{\dot{m}_0} + \frac{1}{2} \frac{\Delta U}{U_0} \right) \end{aligned}$$

Where \dot{m}_0 and U_0 is the normalized value of xenon flow and anode voltage.

According to TABLE II. , the relative deviation of xenon flow $\Delta \dot{m}/\dot{m}_0$ is 8.5 times greater than anode voltage anode deviation $\Delta U/U_0$. As a result, from the formula we can conclude that the effect of anode flow deviation on thrust is about 17 times of the anode voltage deviation, and it could be inferred that the anode flow fluctuation is the main external factor of the thrust noise in steady working condition of the thruster. Improving thrust accuracy in the future should mainly focus on improving the accuracy of xenon flow control and measurement systems.

4 Frequency Domain thrust noise Analysis

To analysis the thrust noise characteristic in frequency domain, it is required to evaluated the power spectrum density of measured noise. The classical power spectrum estimation methods include period graph method (includes Bartlet method and Welch method) and correlation graph method (includes BT method)^[21].

According to the comprehensive comparison of various classical power spectrum estimation methods, Welch method has large amount of adjustable parameters, and different parameters can be set for estimation according to the estimation requirements of different frequency bands, and there are packaged MATLAB functions^{[22][23]}. Therefore, Welch method is an ideal estimation method for estimating thrust noise characteristics among classical power spectrum estimation methods^[21]. Welch method is used to perform the following noise power spectrum analysis of measured xenon flow, anode voltage and current in the thermal equilibrium state (Fig. 9).

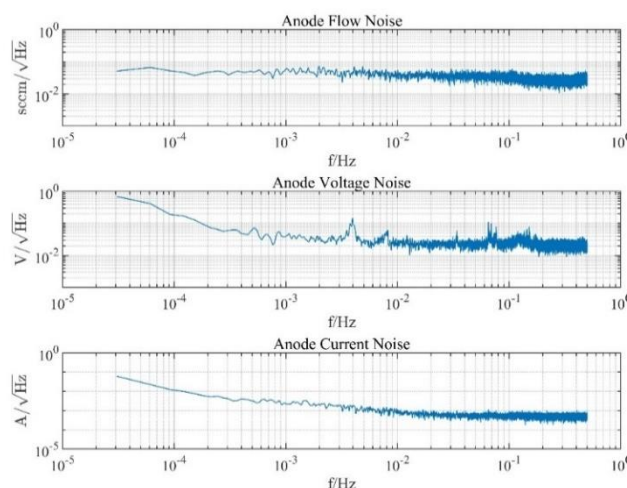


Fig. 9 PSD of xenon flow rata, anode voltage and current

According to the power spectrum density of the three measured parameter, the xenon flow rate has an almost identical level of noise magnitude at the computed frequency range, and the maximum value is around $0.1 \text{ sccm/Hz}^{1/2}$. For anode voltage noise, the noise level is less than $0.1 \text{ V/Hz}^{1/2}$ at the frequency higher than 10^{-3}Hz , and the noise level increases monotonously in lower frequency. And the anode current has a noise level lower $10^{-3}\text{A/Hz}^{1/2}$ at the frequency higher than 10^{-2}Hz , and increases monotonously in lower frequency.

Based on the thrust performance model of the thruster formed by previous equations, the influence of voltage and flow fluctuation on thrust noise can be analyzed by combining the measured data of input anode voltage and current. The following three example studies are carried out. Example 1 calculates the thrust noise by substituting all the measured fluctuation data of voltage and current into the thrust performance model of thruster. In example 2, the thrust is calculated only using the measured anode current data, and the voltage is set as the average value of the experimental data, which is kept constant during the calculation process to analyze the influence of the single fluctuation of anode current on the output thrust. In example 3, the anode current is set as a constant value, and the thrust fluctuation data is calculated only by using the measured voltage noise data to analyze the influence of voltage fluctuation on thrust noise. The thrust calculation results of the three examples are shown in Fig. 10.

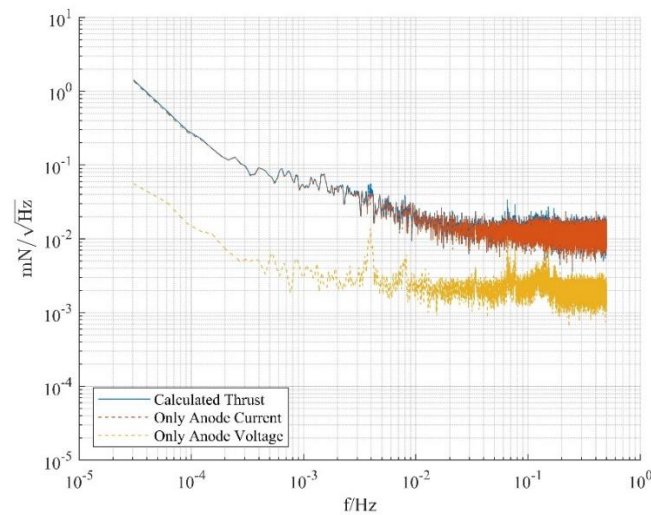


Fig. 10 The calculated thrust noise spectrum of each case

The results of examples 1,2,3 is analyzed. The measured anode current noise is considered in examples 1,2, and the difference lies in whether the measured fluctuation data of anode voltage is used. However, the thrust calculation results of the two examples are almost identical. Compared with the measured thrust noise, the calculated results of example 3 are about 1-2 orders of magnitude smaller. Both of these phenomena indicate that under current experimental conditions, the fluctuation of anode voltage has little effect on thrust noise, and anode current noise is the main factor forming thrust noise in this frequency band.

5 Conclusion

This research uses parameter fitting to construct the thrust characteristic of a 1.35kW hall thruster with anode voltage and current. The fact that the fitting error is less than 0.33 mN indicates that the result is tolerant to changes in the anode voltage, anode flow rate, and magnetic field.

Time domain study measures the anode voltage, current, and xenon flow over an extended period of time.

The previous thrust model was used to determine the thrust. The determination of the absolute and relative standard deviation provides evidence that the primary cause of thrust fluctuation is the variation in xenon flow, which exhibits the biggest deviation.

Power spectrum density of variable is assessed in the frequency domain. The xenon flow is nearly consistent over the whole frequency range, but the anode voltage and current exhibit increasing levels of noise at lower frequencies. Upon conducting a thorough analysis, it has been determined that the primary cause of thrust noise is the anode current, with the anode voltage having the least effect. Less than $0.1 \text{ mN/Hz}^{1/2}$ is the highest limit of thrust noise in the frequency range of 10^{-3} - 0.5 Hz , which is higher than the previous tested type thruster in TABLE I. When compared to other kinds of thrusters, the noise level is comparatively low at $0.0125 \text{ Hz}^{1/2}$ because hall thrust has a higher thrust magnitude.

Several external and internal strategies could be taken into consideration to increase the hall thruster's thrust accuracy even further.

The external means is mainly to improve the precision of prepollent supply system. Since the fluctuation of anode voltage is proof to has little influence on the thrust noise, thruster accuracy should be improved mainly by increasing the accuracy of the flow system. For a thrust accuracy requirement of 0.2%, the noise level of the flow control system should not exceed 0.09 scem.

For the thruster internal factors, there are several ways to make improvement. 1) As the velocity of xenon gas atoms, and the characteristic of the magnetic circuit material are all impacted by temperature variations, the temperature variation of the thruster should be controlled with suitable approach; 2) The thruster might have different thrust noise level in different working condition, it is useful to find the working condition with the least amount of thrust noise through testing and comparison; 3) Constructing the hall thruster's closed-loop control system using the power source and xenon feed system models can halt the thruster long-term performance drift.

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