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FULL LENGTH ARTICLE

Low-noise and fast-response variable cold gas micro-thruster developed for Taiji program



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Abstract The Taiji program is focused on achieving space-based gravitational wave detection in the frequency range of 0.1 mHz–1 Hz. To achieve drag-free control, Taiji satellites must be equipped with micro-thrusters that satisfy stringent requirements, including a continuously adjustable thrust, thrust resolution of 0.1 μN , thrust noise of 0.1 $\mu\text{N}\cdot\text{Hz}^{-0.5}$ and response time of less than 100 ms. This paper presents the progress of a variable cold gas micro-thruster being developed for the Taiji program. A series of technologies such as a bidirectional piezoelectric drive, spherical valve core, conical nozzle seal, miniature gas chamber, high thruster integration, combined digital and analogue communication and high-frequency closed-loop thrust control were employed to achieve engineering prototypes of a low-noise and fast-response micro-thruster. Ground performance tests indicate that the micro-thruster achieved a minimum thrust of close to 1.1 nN, a thrust resolution of 0.05 μN and a maximum specific impulse of 69.1 s using nitrogen gas as the working fluid. The thrust noise was less than 0.1 $\mu\text{N}\cdot\text{Hz}^{-0.5}$ in the frequency band of 10 mHz–1 Hz, and the thrust response time was 140 ms. The control parameters were further optimised to achieve a flow response time of 50 ms. The results indicate that the developed micro-thruster essentially met the performance requirements for drag-free control to facilitate space-based gravitational wave detection.

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1. Introduction

The discovery of gravitational waves by the Laser Interferometer Gravitational-Wave Observatory collaboration¹ has had a major influence on the basic sciences. Space-based technologies are the next focus for gravitational wave detection because they can reach a wider range of gravitational radiation sources than ground-based technologies.² Satellites for space-based gravitational wave detection rely on micro-thrusters to compensate for non-conservative forces such as solar radiation and cosmic radiation to achieve ultra-high micro-gravity for drag-free flight.^{3,4} In recent years, numerous space-based gravitational wave detection programs have been proposed, including the Laser Interferometer Space Antenna (LISA) program,^{5,6} Taiji program⁷ and TianQin program.⁸ Because of differences in their detection frequency bands, satellite sizes, inter-satellite distances, orbital parameters, propulsion system layouts and application scenarios, their requirements for micro-thrusters vary. Table 1 lists the key performance indicators for micro-thruster systems as stipulated by the Gravitational Wave Special Project of China's Ministry of Science and Technology Key Research and Development Program.⁹ Propulsion systems suitable for space-based gravitational wave detection include electric propulsion and cold gas propulsion. The LISA Pathfinder mission was equipped with eight Colloid Micro-Newton Thrusters (CMNTs) designed by Busek and the Jet Propulsion Laboratory.¹⁰ In-orbit experimental data indicated that CMNT #2 achieved a thrust of up to 60 μN near the end of the extended mission with a minimum thrust of 5 μN . Because of a malfunction, CMNT #1 had a thrust rise response time (5 $\mu\text{N} \rightarrow 30 \mu\text{N}$) of up to 170 s, whereas the other CMNTs had response times of less than 10 s. All CMNTs had slightly longer thrust fall response times (30 $\mu\text{N} \rightarrow 5 \mu\text{N}$) than the thrust rise response times, and the thrust fall response times were much longer for CMNTs #1, #6 and #7. The thrust noise was suppressed to below 0.1 $\mu\text{N}\cdot\text{Hz}^{-0.5}$ in the frequency band of 1–30 mHz. Meanwhile, the Taiji-1 satellite was equipped with four Radio Frequency (RF) ion micro-thrusters and four Hall micro-thrusters. The in-orbit experimental data showed that the RF Ion micro-Thrusters (RIT), which were developed by the Institute of Mechanics at the Chinese Academy of Sciences, achieved a continuously adjustable thrust output of 5–60 μN with a thrust resolution of less than 0.2 μN , thrust noise of less than 0.2 $\mu\text{N}\cdot\text{Hz}^{-0.5}$ and open-loop response time of less than 20 ms.¹¹ The Hall micro-thrusters, which were jointly developed by Nanyang Technological University and the University of Chinese Academy of Sciences, had a thrust output of 5–100 μN with a thrust resolution of 0.7 μN , thrust noise of less than 0.6 $\mu\text{N}\cdot\text{Hz}^{-0.5}$ (0.01–1 Hz)

and response time of 30 ms for nano-metre-level precision control.¹²

Cold gas propulsion is a highly reliable and non-polluting technology with low electromagnetic and thermal noise, which makes it an ideal solution to compensate for non-conservative forces. Fig. 1¹³ shows the internal structure of a cold gas micro-thruster developed in collaboration by Thales Alenia Space Italy and Leonardo S.P.A.^{14–17} The micro-thruster comprises a filter, a mass flow sensor, frontend electronics and the thruster head, all encased within a housing. The thruster head features a piezoelectric proportional valve that utilises a needle valve structure to achieve a seal between the piezoelectric valve core and nozzle. The mass flow sensor is a thermal flowmeter that adjusts the distance (i.e. opening) between the valve core and nozzle based on flow feedback to achieve closed-loop flow control to regulate the thrust. Ground performance tests indicated that this micro-thruster produced a thrust of 0.1–1 000 μN with a thrust resolution of 0.1 μN . When nitrogen gas was the working fluid, the average specific impulse had a range of 50–63 s and increased with the thrust. Fig. 2¹⁸ shows the results of a thrust noise test, which indicated that the thrust noise was less than 0.2 $\mu\text{N}\cdot\text{Hz}^{-0.5}$ at a thrust of 500 μN in the frequency band of 10 mHz–1 Hz. Because of its excellent ground performance, this micro-thruster has been used in various space missions. In 2013, the European Space Agency launched the Gaia satellite, which was equipped with 12 sets of cold gas micro-thrusters.¹⁴ Similarly, the LISA Pathfinder was launched in 2015 with 12 micro-thrusters. However, in-orbit measurements showed that the noise in the frequency band of 0.3–10 mHz was less than 0.17 $\mu\text{N}\cdot\text{Hz}^{-0.5}$, which was still 70% higher than the original mission requirement of 0.1 $\mu\text{N}\cdot\text{Hz}^{-0.5}$. The higher noise level was attributed to potential issues with the shared supply systems of the primary and backup micro-thrusters, but researchers concluded that this noise level was still within the acceptable range and did not affect the performance of LISA Pathfinder.¹⁹

In 2016, the Micro-SCOPE satellite, which was designed to test the weak equivalence principle in general relativity, was launched with 16 micro-thrusters with response times of 250 ms to achieve 63% of the commanded thrust.^{15,20} In July 2023, the Euclid space telescope was launched with 12 cold gas micro-thrusters to maintain a stable orbit for scientific observations.²¹ To meet the drag-free requirements of the TianQin-1 satellite,^{22,23} Beijing Institute of Control Engineering developed a variable cold gas thrust module, as shown in Fig. 3.²⁴ The module included a piezoelectric proportional valve based on the large-deflection elastic theory and fluid boundary slip theory to achieve thrust convergence control through the introduction of a mass flow sensor.²⁵ The first round of in-orbit measurements for TianQin-1²⁶ indicated that the thrust module had a thrust output range of 1–60 μN with a

Table 1 Performance specifications for micro-thrusters in space-based gravitational wave detection.

Parameter	Value
Thrust range (μN)	5–50
Thrust resolution (μN)	≤ 0.1
Thrust noise ($\mu\text{N}\cdot\text{Hz}^{-0.5}$)	< 0.1
Response time (ms)	< 50
Design lifetime (h)	$\geq 10^4$

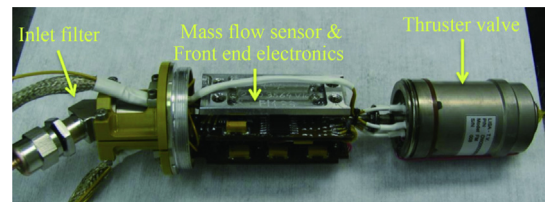


Fig. 1 Internal structure of Leonardo cold gas micro-thruster.¹³

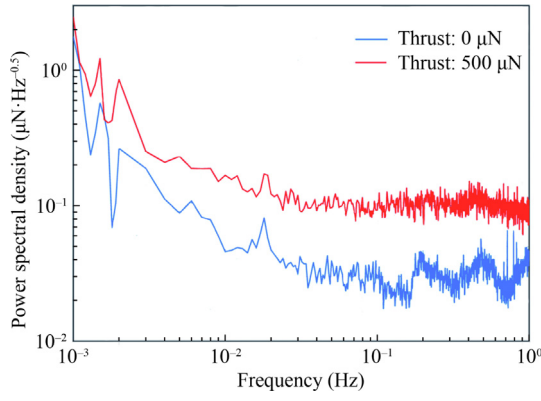


Fig. 2 Thrust noise of Leonardo cold gas micro-thruster.¹⁸



Fig. 3 Variable cold gas thrust module for TianQin-1 satellite.²⁴

thrust resolution of approximately $0.1 \mu\text{N}$. At a frequency of 0.1 Hz , the thrust noise was $0.3 \mu\text{N}\cdot\text{Hz}^{-0.5}$.

The above literature review shows that, while major advances have been made in the development of cold gas micro-thrusters for space-based gravitational wave detection, there is still room for improving the response time and noise control. The present study is focused on the development of cold gas micro-thrusters for the Taiji program. In July 2020, the key technology project for Taiji-2 was launched, and the Institute of Mechanics took on the task of developing a cold gas micro-thruster. To meet the mission requirements, a series of technologies were employed to develop engineering prototypes of a low-noise and fast-response variable Cold Gas Micro-Thruster (CGMT). Comprehensive ground performance tests were conducted to evaluate the prototypes, and the micro-thruster was integrated into the SY-01 satellite in July 2022 to evaluate its performance in a space environment. This paper presents the design of the new variable cold gas micro-thruster and the results of the ground performance tests.

2. Design

To achieve drag-free control, a micro-thruster needs to compensate for disturbances from solar radiation pressure, which is on the order of tens of micro-newtons. Because the scientific module separates from the propulsion module used for trans-

fer to orbit, a micro-thruster also needs to be capable of performing desaturation, attitude adjustment and orbit maintenance for the scientific module, which can require a thrust output of several hundred micro-newtons.¹⁶ The thrust resolution and thrust noise are directly related to the acceleration of a satellite, and multiple space-based gravitational wave detection missions^{7,19,26} have proposed that micro-thrusters should have a thrust resolution of $0.1 \mu\text{N}$ and thrust noise of $0.1 \mu\text{N}\cdot\text{Hz}^{-0.5}$, although they differ on the noise frequency band. The micro-thrusters used by LISA Pathfinder had widely varying response times. The Drag-Free Attitude Control System (DFACS) software operates at a frequency of 10 Hz to be well-separated from the bandwidth used for experimental measurements, so cold gas micro-thrusters must support a thrust update frequency of 10 Hz .¹⁶ The CMNT response time was 10 s .²⁷ The Taiji program requires a response time of 0.33 s ,⁷ although a time below 0.1 s is optimal.

Fig. 4 shows the design of the variable cold gas micro-thruster, which includes a filter, mass flow sensing chip, mass flow sensing electronics, piezoelectric drive, piezoelectric proportional valve, micro-nozzle and housing. The regulated gas passes through the filter to the mass flow sensing chip, where the mass flow sensing electronics detects the flow signal measured by the chip and the temperature of both the chip and proportional valve. Subsequently, the gas flows to the piezoelectric proportional valve, where the piezoelectric drive controls the valve's opening to adjust the flow rate. The gas is then accelerated through the micro-nozzle to generate thrust. Communication between the Micro-Propulsion Electronics (MPE) and the mass flow sensing electronics is facilitated via RS485, which receives feedback on the flow rate from the mass flow sensing electronics and controls the output of the piezoelectric drive to achieve closed-loop control of the flow and, thus, the thrust. MPE also determines whether to activate the heater based on the received temperature signal to achieve closed-loop temperature control.

2.1. Micro-nozzle

The primary function of the de Laval micro-nozzle is to increase the gas exit velocity and specific impulse, which makes it a core component of the variable cold gas micro-thruster. Its design parameters directly constrain the maximum thrust and specific impulse of the micro-thruster. The flow within the micro-nozzle is highly complex, but its analysis can be simplified by using reasonable assumptions. In this study, the micro-nozzle was designed by assuming the flow behaviour of the gas to be under one-dimensional steady-state isentropic conditions. The thrust F generated by the micro-nozzle can be expressed as

$$F = \dot{m}v_e + (p_e - p_b)A_e \quad (1)$$

where $\dot{m}$ is the mass flow rate, v_e is the gas velocity at the nozzle exit, p_e is the pressure at the exit, p_b is the background pressure and A_e is the cross-sectional area of the exit. For a supersonic gas flow, $\dot{m}$ can be expressed as

$$\dot{m} = \sqrt{\gamma} \left(\frac{2}{\gamma + 1} \right)^{\frac{\gamma+1}{2(\gamma-1)}} \frac{p_0 A_t}{\sqrt{RT_0}} \quad (2)$$

where γ is the specific heat ratio of the gas, p_0 is the inlet pressure of the micro-nozzle, A_t is the cross-sectional area at the

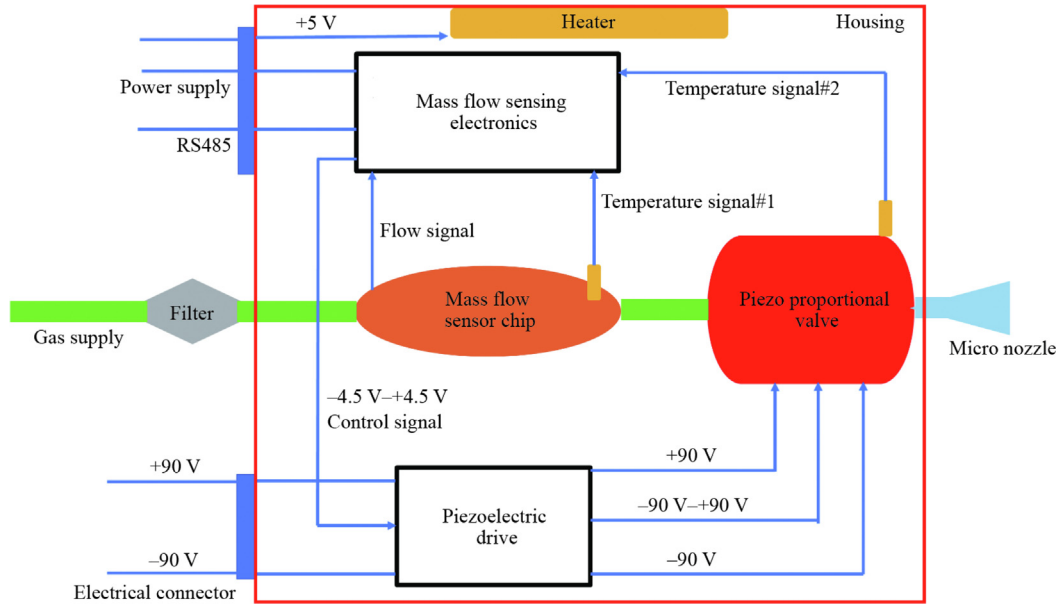


Fig. 4 Main components of variable cold gas micro-thruster.

throat of the micro-nozzle, R is the gas constant and T_0 is the gas temperature at the nozzle inlet. v_e is given by

$$v_e = \sqrt{\frac{2\gamma}{\gamma-1} RT_0 \left[1 - \left(\frac{p_e}{p_0} \right)^{\frac{\gamma-1}{\gamma}} \right]} \quad (3)$$

p_e is determined by the nozzle parameters. The Mach number Ma at any cross-section of the nozzle expansion section is related to the area ratio (i.e. the ratio of the cross-sectional area A to A_t), which can be expressed as

$$\left(\frac{A}{A_t} \right)^2 = \frac{1}{Ma^2} \left[\frac{2}{\gamma+1} \left(1 + \frac{\gamma-1}{2} Ma^2 \right) \right]^{\frac{\gamma+1}{\gamma-1}} \quad (4)$$

The exit Mach number Ma_e can be expressed as

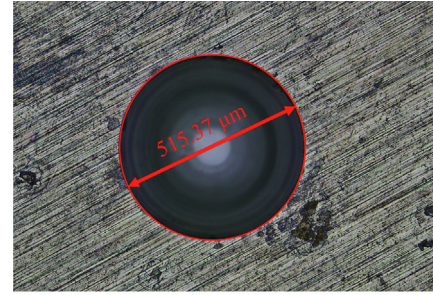
$$Ma_e = \sqrt{\frac{2}{\gamma-1} \left[\left(\frac{p_0}{p_e} \right)^{\frac{\gamma-1}{\gamma}} - 1 \right]} \quad (5)$$

Based on Eqs. (4) and (5), the relationship between the expansion ratios A_e/A_t and p_0/p_e can be calculated as

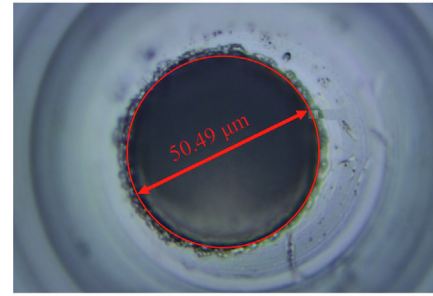
$$\left(\frac{A_e}{A_t} \right)^2 = \frac{\gamma-1}{2 \left[\left(\frac{p_0}{p_e} \right)^{\frac{\gamma-1}{\gamma}} - 1 \right]} \left[\frac{2 \left(\frac{p_0}{p_e} \right)^{\frac{\gamma-1}{\gamma}}}{\gamma+1} \right]^{\frac{\gamma+1}{\gamma-1}} \quad (6)$$

If p_0 and A_e/A_t are determined, then p_e can be calculated by using Eq. (6). Substituting p_e into Eq. (3) determines v_e while p_b is derived from the actual working environment. At this point, all parameters in Eq. (1) for calculating F can be determined. Thus, the micro-nozzle can be designed by using Eqs. (1)–(3) and (6).

Micro-nozzles were fabricated by electrical discharge machining with various throat sizes. Fig. 5 shows a micro-nozzle with a throat size of 50 μm , an expansion ratio of 100:1 and an expansion angle of 45° made from tungsten steel.



(a)



(b)

Fig. 5 Micro-nozzle with a throat size of 50 μm : (a) Exit; (b) Throat.

2.2. Driving method for valve core

There are multiple driving methods available for proportional valve cores, including electromagnetism, piezoelectricity, thermal gas, electrostatics and shape memory alloys. Piezoelectric drives utilise the inverse piezoelectric effect of piezoelectric ceramics. When a voltage is applied to a piezoelectric ceramic, it deforms, resulting in displacement. When the voltage is

removed, the ceramic returns to its original state. Compared to other driving methods, piezoelectric drives have a lower power consumption, faster response time and higher displacement resolution. In this study, the selected piezoelectric ceramic sheet can move bidirectionally from the initial position either upwards or downwards. Upwards displacement drove the valve core to open the valve while downwards displacement drove the valve core to close the valve without the need for an additional preloading mechanism.

The minimum thrust is influenced not only by whether the piezoelectric ceramic can return to its zero position but also by the seal between the valve core and valve seat. Achieving a minimum thrust below $1 \mu\text{N}$ is a basic requirement for drag-free control. Ensuring that the seal has a leakage rate of zero is essential to avoid wasting valuable working fluid.

2.3. Valve core and nozzle sealing

The micro-nozzle acts as the direct sealing interface between the valve seat and valve core to minimise the volume of the gas flowing from the valve to the nozzle exit, which increases the gas exit velocity and reduces the response time of the micro-thruster. The sealing mechanism restricts the flow, and the design parameters determine the maximum thrust. Gas leakage due to inadequate sealing not only wastes the working fluid but also affects the minimum thrust output and the effectiveness of drag-free control. The sealing mechanism also affects the gas flow characteristics, which influences the specific impulse of the micro-thruster. Fig. 6 shows the sealing mechanism employed in this study, which comprised a spherical valve core with a conical nozzle seat.

The effectiveness of the seal between the valve core and valve seat is influenced by several factors including the hardness of their materials, the mechanical design, the surface roughness and manufacturing defects. In soft seals, materials with lower hardness can achieve sealing even with certain defects when subjected to large forces that cause plastic deformation. However, piezoelectric ceramics are relatively brittle, and an excessive sealing force can cause damage. In addition, because the displacement of piezoelectric ceramics is only a few tens of micro-metres, any plastic deformation in the sealing

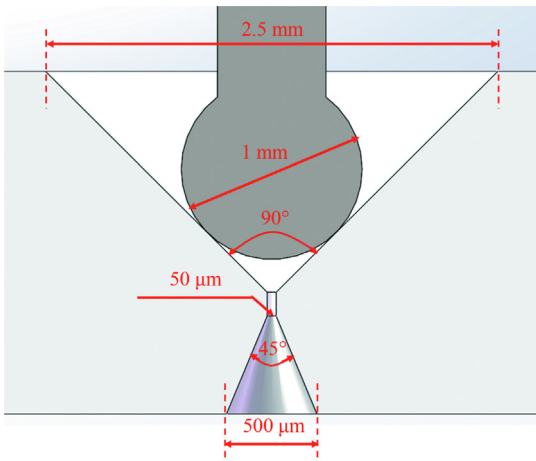


Fig. 6 Seal comprising a spherical valve core and conical nozzle seat.

material may exceed the nominal displacement of the piezoelectric ceramics. In this study, a hard seal was used with a ruby ball at the bottom of the valve core. The micro-nozzle was made of high-hardness metals such as tungsten steel and high-hardness and wear-resistant materials like ceramic gemstones.

2.4. Flow sensor

The design of the micro-thruster also needed to consider the hysteresis and creep characteristics of the piezoelectric drive. When the driving voltage of the piezoelectric ceramic is constant, the displacement of the ceramic slowly changes, which causes the flow rate to vary. Therefore, a flow sensor is required to provide feedback for closed-loop flow control. The flow sensor directly determines the effectiveness of flow control in terms of the flow resolution, noise and response time. In this study, a thermal flowmeter with a fast response time and high sensitivity was selected as the flow sensor. Fig. 7 shows the layout of the flow sensor chip, which comprised a gas channel and four temperature-sensing resistors: one to sense the upstream temperature (R_u), another to heat the mid-channel (R_h), a third to sense the downstream temperature (R_d) and a fourth to sense the ambient temperature (R_a). R_u and R_d were symmetrically distributed on either side of R_h .

The R_a sensor is used to detect the ambient temperature. By heating the R_h sensor, a constant temperature difference (ΔT) is created between its temperature and R_a . When gas flowed from upstream to downstream, it carried heat from R_h raising the temperature at R_d . The quantity of heat transported away can be expressed as

$$Q = hA\Delta T \quad (7)$$

where h is the convective heat transfer coefficient, A is the heat exchange area between the gas and R_h .

The relationship between the Nusselt number and the convective heat transfer coefficient can be expressed as

$$Nu = \frac{hL}{k} \quad (8)$$

where L is the characteristic length and k is the thermal conductivity of the gas.

In the context of laminar convective heat transfer, the expression for Nu is given as

$$Nu = BRe^x Pr^y = B \left(\frac{\rho v d}{\mu} \right)^x Pr^y \quad (9)$$

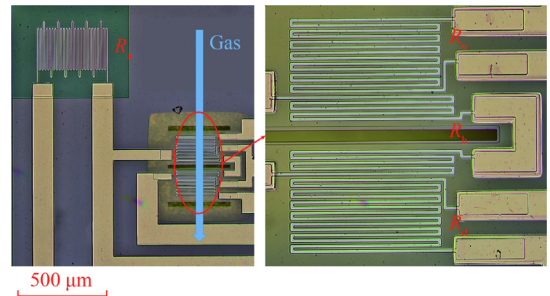


Fig. 7 Schematic diagram of flow sensor chip.

where v , ρ , d and μ are the gas flow velocity, density, diameter of the runner and viscosity coefficient of the gas, respectively. Pr is the Prandtl number. B , x , and y are constants related to geometry. Therefore, the expression for Q can be rewritten as²⁸

$$Q = B \frac{k}{L} \left(\frac{\rho d}{\mu} \right)^x Pr^y v^x A \Delta T \quad (10)$$

The resistor R_d absorbs a portion of the heat, resulting in an increase in its temperature and a corresponding alteration in its resistance value. This altered resistance difference can be expressed as

$$\Delta R = \frac{\alpha}{cm_{R_d}} \eta Q \quad (11)$$

where α is temperature coefficient of resistance, η is the absorption coefficient, c is the specific heat capacity of R_d , and m_{R_d} is the mass of R_d .

A constant current (I) source flowed through R_u and R_d , which exhibited identical resistance values. The difference in resistances between these two resistors was converted into a voltage signal (U), which was used to characterise the flow velocity of the gas. The expressions are as

$$U = I(R_d - R_u) = I \Delta R \\ = \left[I \frac{\alpha}{cm_{R_d}} \eta B \frac{k}{L} \left(\frac{\rho d}{\mu} \right)^x Pr^y A \Delta T \right] v^x \quad (12)$$

It can be posited that during the flow of gas, $I \frac{\alpha}{cm_{R_d}} \eta B \frac{k}{L} \left(\frac{\rho d}{\mu} \right)^x Pr^y A \Delta T$ will remain constant and is therefore noted as λ .

In conclusion, the volume flow rate of the gas ($\dot{V}$) can be expressed as

$$\dot{V} = \frac{\pi d^2}{4} \left(\frac{1}{\lambda} \right)^{\frac{1}{x}} U^{\frac{1}{x}} \quad (13)$$

The electronics of the flow sensor electronics also detected the temperature of the micro-thruster and sent an analogue signal to the piezoelectric drive. This signal was amplified twenty-fold by the piezoelectric drive before reaching the piezoelectric ceramic to control the opening of the proportional valve.

2.5. Thruster integration

Fig. 8 shows the integrated cold gas micro-thruster, which included (1) a piezoelectric proportional valve and micro-nozzle, (2) a piezoelectric drive, (3) a flow sensor, (4) a bracket for mounting the piezoelectric drive and flow sensor, (5) a filter and (6) an electrical connector. The flow sensor chip was positioned at the centre of the I-beam bracket. In this highly integrated configuration, the gas volume from the valve core and

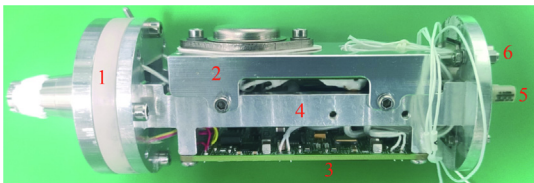


Fig. 8 Internal structure of variable cold gas micro-thruster.

nozzle seal to the flow sensor chip was approximately 0.27 mL, while the gas volume from the sealing point to the nozzle exit was only 0.03 μ L. Under these conditions, changes in flow at the sealing point can be quickly detected by the flow sensor, and the gas within the micro-nozzle could be rapidly expelled to generate thrust. A metal casing was added to the micro-thruster as physical protection and to provide electromagnetic shielding. The metal casing was wrapped with heating elements, which, in combination with the temperature-sensing resistors of the flow sensor, allowed for overall temperature control of the micro-thruster. To meet the requirements for drag-free and attitude control of space-based gravitational wave detection satellites, three prototypes of the variable cold gas micro-thruster. The components of the prototypes were identical except for the micro-nozzle, for which different throat diameters of 50, 100 and 150 μ m. With nitrogen gas as the working fluid at an inlet pressure of 100 kPa, the prototype with a 50- μ m throat diameter for the micro-nozzle (CGMT-50) was expected to achieve a maximum thrust of 200 μ N for drag-free control. The micro-thrusters with throat diameters of 100 μ m and 150 μ m for the micro-nozzle (CGMT-100 and CGMT-150, respectively) were designed to achieve maximum thrusts of several hundred micro-newtons and over 1 mN, respectively, which should facilitate not only drag-free control but also attitude control.

3. Experimental setup

3.1. Flow calibration and control

To calibrate the flow sensor, the micro-thruster was connected in series with the Fluke molbox1 + Flowmeter Calibrator, which has a resolution of 0.001 5% and an accuracy of $\pm 0.07\%$, as well as a response time of 1 s. The gas from a high-pressure cylinder was reduced in two stages before reaching the thruster inlet to a supply pressure of 240 kPa. The micro-thruster and electronics were connected via cables, and Fig. 9 shows the experimental setup used to handle the input of electronic commands and storage of various telemetry signals.

3.2. Leak rate detection

Fig. 10 shows the PHOENIX Magno Helium Leak Detector (Leybold) used to detect the leak rate. In vacuum mode, the minimum detectable leak rate is 5×10^{-13} Pa $\cdot$ m³/s. In sniffer mode, the minimum detectable leak rate is 1×10^{-10} Pa $\cdot$ m³/s.

The micro-thruster was supplied with helium at 200 kPa at the front end, and the leak detector was used in sniffer

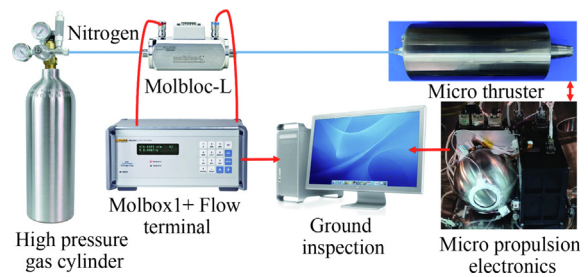


Fig. 9 Experimental setup for flow calibration.

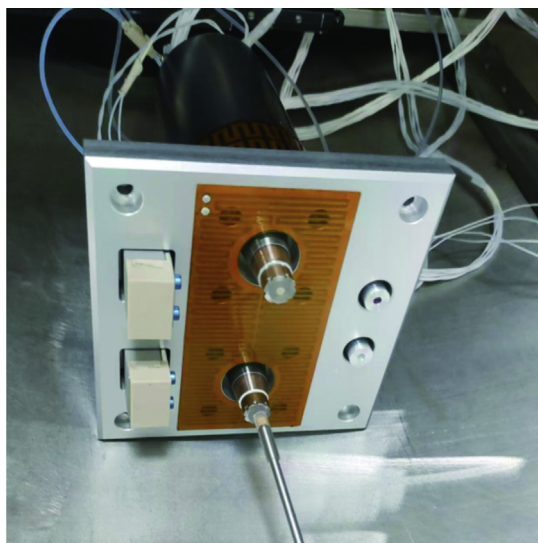


Fig. 10 Leak rate detection.

mode to detect the leak rate at the thruster outlet in the closed state.

3.3. Thrust measurement

Fig. 11 shows the experimental setup for thrust measurements. The resolution of the thrust measuring system is $0.025 \mu\text{N}$, with a measuring range of $0.025\text{--}2\,000 \mu\text{N}$. The background noise power spectral density is less than $0.1 \mu\text{N}\cdot\text{Hz}^{-0.5}$ in the frequency band between 7 mHz and 1 Hz. The system is capable of accurately measuring thrust response times in excess of 100 ms.²⁹ This system has been successfully used to calibrate the thrust magnitude, thrust noise and response time for RF ion micro-thrusters, cold gas micro-thrusters and ionic liquid micro-thrusters.³⁰ The vacuum system includes four molecular pumps, two cryogenic pumps, two xenon pumps and one screw pump for an effective pumping speed of up to $2.6 \times 10^4 \text{ L/s}$ for nitrogen gas. The vacuum chamber has a diameter of 1.8 m and a length of 3 m, and it can achieve a vacuum level of less than $2 \times 10^{-3} \text{ Pa}$ during micro-thruster operation with negligible backpressure effects on the thrust. The gas flow was depressurised from a high-pressure cylinder through a pressure regulator to reach the high-precision Alicat pressure controller with a control range of 0–400 kPa and control accuracy of $\pm 0.125\%$ full scal. The pressure control stability reached 0.01 kPa, which is sufficient for the pressure at the thruster inlet. Each micro-thruster was mounted on the thrust test stand with its electronics placed inside the vacuum chamber. The electronic cables were connected to the ground performance test equipment through vacuum flanges. The gas flow was controlled by the pressure controller before reaching the molbox1 + flowmeter. The gas line was connected to the micro-thruster through vacuum flanges.

4. Results and discussion

4.1. Flow calibration

The sampling and control frequencies for the gas flow of the micro-thruster were set to 50 Hz, and the Proportional–Inte

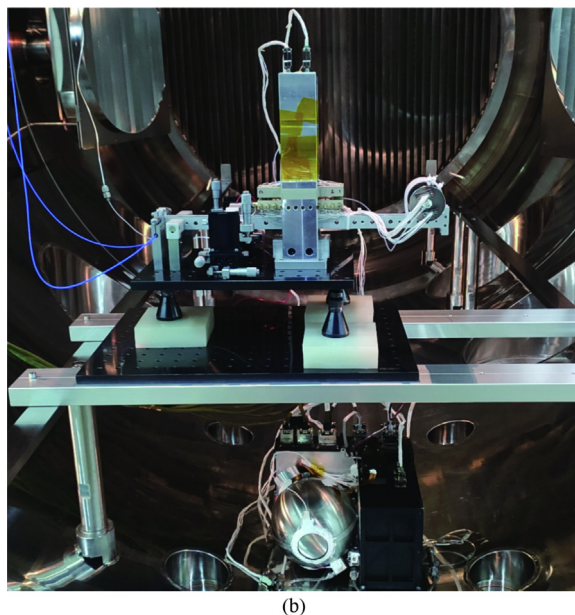
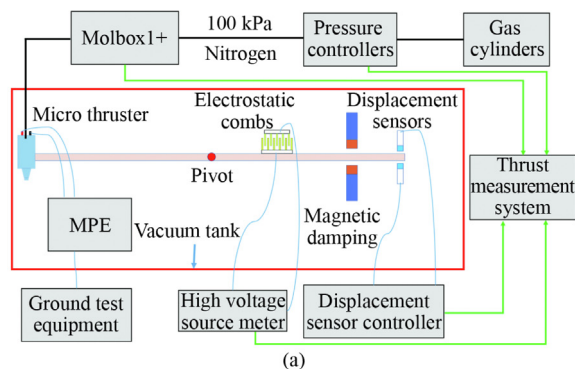


Fig. 11 Experimental setup for thrust measurements: (a) Schematic; (b) Photograph.

gral–Derivative (PID) control algorithm was used. The closed-loop flow control was used to regulate the voltage of the flow sensor, which in turn was used to obtain the corresponding flow rate measured in standard cubic centimetres per minute (scm). **Table 2** presents the obtained calibration data.

Fig. 12 illustrates the fitting curve of the flow from Fluke molbox1 + Flowmeter Calibrator and the voltage from flow sensor in **Section 2.4**. The flow sensor electronics had an actual voltage detection range of -10 mV to $+10 \text{ mV}$. Therefore, the flow sensor had a maximum detection range of up to 170 scm for nitrogen gas.

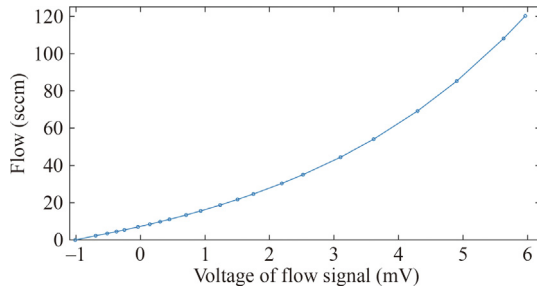
4.2. Flow control

Fig. 13 presents the experimental results for the flow control range, resolution, noise and response time of CGMT-100.

Fig. 13(a) compares the flow control noise and baseline noise of the flow sensor. The control noise was slightly higher than the baseline noise. To improve the closed-loop response speed, the P-value in the PID control parameters was increased. This caused substantial fluctuations at 11.2 Hz,

Table 2 Measured voltages and the corresponding flow rates.

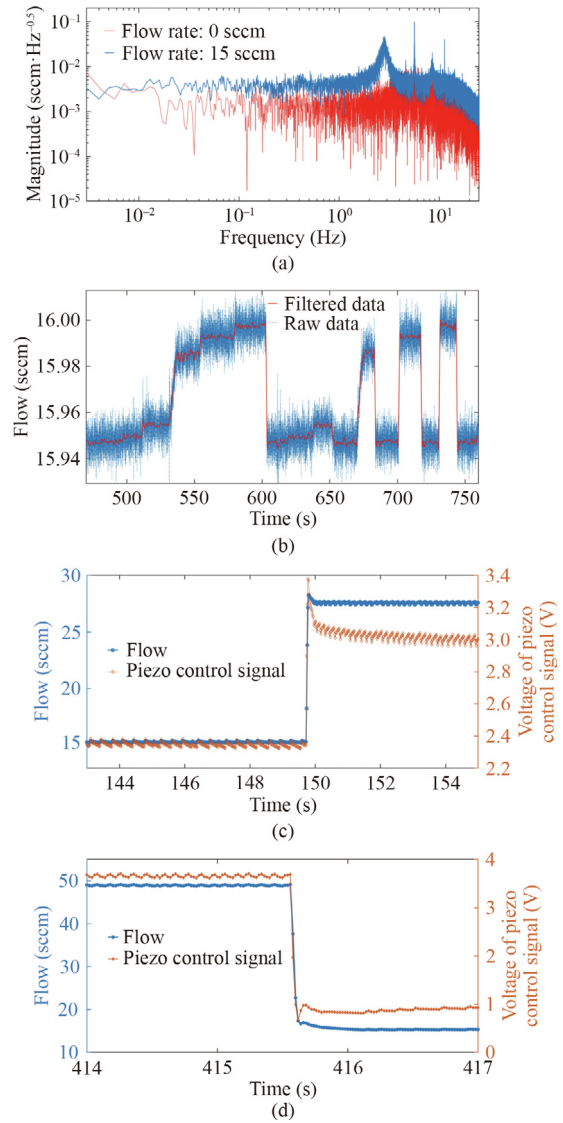
Voltage (mV)	Flow (sccm)	Voltage (mV)	Flow (sccm)
-1.012 0	0	1.234 7	18.76
-0.694 8	2.34	1.504 5	21.77
-0.515 7	3.53	1.750 5	24.69
-0.372 0	4.54	2.191 1	30.40
-0.249 8	5.41	2.519 6	35.09
-0.039 0	7.00	3.101 1	44.46
0.144 4	8.47	3.613 6	54.04
0.303 9	9.80	4.296 5	69.24
0.449 0	11.07	4.902 0	85.24
0.706 7	13.41	5.629 2	108.15
0.932 9	15.63	5.965 4	120.25

**Fig. 12** Fitting of voltage and flow rate.

resulting in greater noise at 2.8, 5.6 and 11.2 Hz. However, in the frequency band below 1 Hz, which is critical for gravitational wave detection, the flow control noise was less than $0.007 \text{ sccm} \cdot \text{Hz}^{-0.5}$. Fig. 13(b) presents the results for the flow control resolution. Because of the sampling frequency of 50 Hz, there was substantial high-frequency noise that could obscure small resolution steps. After a low-pass filter to the raw data, the filtered flow resolution steps become clearly visible, with the resolution reaching 0.005 sccm. Fig. 13(c) displays the rising edge for the closed-loop control as the flow rate was increased from 15 sccm to 27.5 sccm. A slight overshoot occurred, but 90% of the target flow was achieved within 50 ms. Fig. 13(d) shows the falling edge as the flow rate was decreased from 49 sccm to 15 sccm. No overshoot occurred, and the target flow step was reached within 50 ms, followed by a gradual adjustment to the target flow. The same PID parameters produced different curves for the rising and falling edges, and the piezoelectric drive voltage decreased from 2.4 V to 1 V at the same flow rate (15 sccm). These observations can be attributed to the non-linear relationships between the piezoelectric drive voltage and ceramic displacement (i.e. hysteresis) and between the changes in displacement and flow rate. Single PID control parameters may work well for one flow range but could result in longer adjustment times and poor stability for other flow ranges.

4.3. Leak rate and minimum thrust

The sealing performances of two nozzle materials were compared: Polyether Ether Ketone (PEEK) and tungsten steel. With

**Fig. 13** Experimental results for flow control of CGMT-100: (a) Comparison between flow control noise and baseline noise; (b) Flow control resolution; (c) Rising edge for closed-loop flow control; (d) Falling edge for closed-loop flow control.

PEEK, the leak rate at the outlet was $1.01 \times 10^{-6} \text{ Pa} \cdot \text{m}^3/\text{s}$. With tungsten steel, the leak rate was slightly higher at $1.51 \times 10^{-6} \text{ Pa} \cdot \text{m}^3/\text{s}$. This is because PEEK is a softer material and thus provides a better seal. When helium was used as the leaking gas at an inlet pressure of 200 kPa, the leak rate was $1.01 \times 10^{-6} \text{ Pa} \cdot \text{m}^3/\text{s}$. Then, Eq. (2) can be used to calculate the corresponding area of the leak. When nitrogen was used as the leaking gas at an inlet pressure of 100 kPa, the corresponding mass flow rate was approximately $2.2 \times 10^{-12} \text{ kg/s}$. If a specific impulse of 50 s is assumed, then the minimum thrust can be estimated as 1.1 nN.

4.4. Thrust measurements

The thrust ranges of all three prototypes were tested, and the specific impulses of CGMT-100 and CGMT-50 were evalu-

ated. In addition, the thrust resolution, noise and response time of CGMT-50 were tested.

4.4.1. Thrust range

CGMT-100 had a throat diameter of 100 μm , expansion angle of 12° and exit diameter of 200 μm . The thrust steps at various flow commands were measured, and the corresponding flow rate, piezoelectric drive signal and thrust data were recorded. Fig. 14 shows the measured thrust range. When the piezoelectric drive signal was -1.5 V , CGMT-100 was in a closed state. When a flow command was sent, the piezoelectric drive opened the valve, and a thrust was output. Because of the hysteresis of the piezoelectric ceramic, the initial response time to open the valve was relatively long, but it subsequently stabilised. When the flow command exceeded the maximum thrust output (i.e. last two thrust steps), the output became saturated when the piezoelectric drive signal reached $+4.5\text{ V}$, and the maximum thrust was about 600 μN . Because of the creep characteristics of the piezoelectric ceramic, the valve opening changed continuously, which caused slow variations in the flow and thrust. Under the same conditions (i.e. inlet pressure of 100 kPa, nitrogen gas as the working fluid), the maximum thrusts of CGMT-50 and CGMT-150 were 220 μN and 1.6 mN, respectively.

4.4.2. Specific impulse

Fig. 15 shows the thrust and flow steps for CGMT-50. Then, the formula for calculating the specific impulse was used to derive the specific impulse of CGMT-50 at different thrust levels, as shown in Fig. 16. Based on the data in Fig. 14, the specific impulses of CGMT-100 at different thrust levels are shown in Fig. 17. Because of the heating effect from the power consumption of the piezoelectric drive during measurements, the temperature of the micro-thrusters reached 46°C . Both CGMT-50 and CGMT-100 showed increases in the specific impulse with increasing thrust, which aligns with the specific impulse test results for the cold gas micro-thrusters of the Gaia satellite. Additionally, as the thrust increased, the rate of growth in the specific impulse gradually slowed and tended to stabilise. This is because an increase in thrust indicates a larger valve opening (i.e. characteristic dimension). As the characteristic dimension increases, the Reynolds number at the flow restriction increases, which reduces the frictional losses and increases the specific impulse. However, the gas exit velocity does not increase indefinitely. According to Eq. (3), the maximum gas exit velocity v_{max} can be expressed as

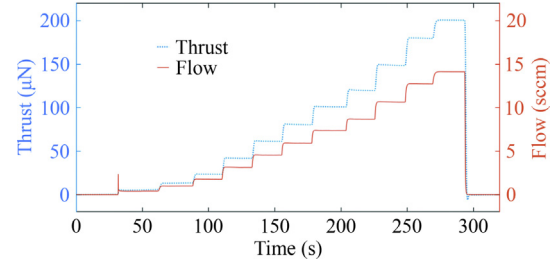


Fig. 15 Thrust and flow steps for CGMT-50.

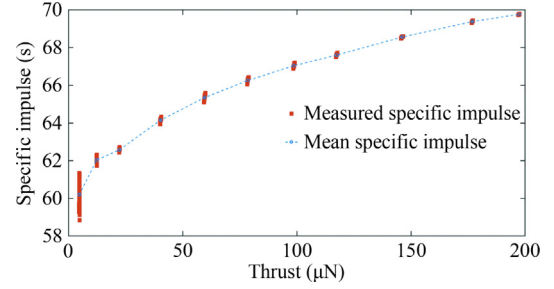


Fig. 16 Specific impulse I_{sp} of CGMT-50 at different thrust levels.

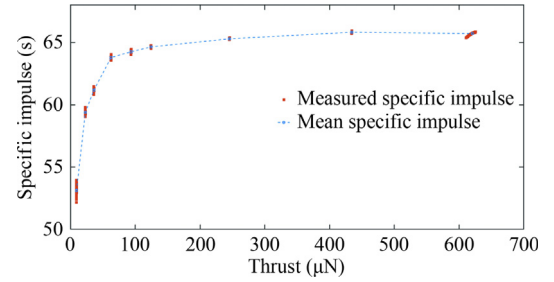


Fig. 17 Specific impulse of CGMT-100 at different thrust levels.

$$v_{\text{max}} = \sqrt{\frac{2\gamma}{\gamma-1} RT_0} \quad (14)$$

Eq. (14) is derived from the theory of one-dimensional steady isentropic gas flow. When a gas continuously accelerates and expands to its limit state, the pressure, temperature and enthalpy reach zero. In the isentropic adiabatic state, this implies that the gas converts all of its internal and pressure energy into kinetic energy to reach the maximum velocity. In reality, however, a state with zero pressure, temperature and enthalpy does not physically exist. From an energy conversion perspective, kinetic energy is lower in quality than internal and pressure energy, which makes it impossible to convert all enthalpy into kinetic energy. In addition, experimental considerations such as variations in the gas exit velocity and internal viscous forces for the micro-nozzle must be considered, which results in the actual specific impulse being lower than the theoretical specific impulse. Between CGMT-50 and CGMT-100, the former had a higher specific impulse at similar thrust levels. This is because the micro-nozzles had different throat diameters. At the same thrust, the distance between the valve core

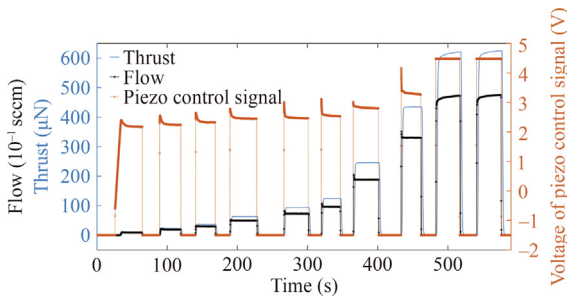


Fig. 14 Thrust range of CGMT-100.

and micro-nozzle (i.e. characteristic dimension) was greater for CGMT-50 than for CGMT-100, so CGMT-50 had a higher Reynolds number at similar flow rates. When the micro-thrusters were fully open, CGMT-50 had a lower specific impulse because CGMT-100 had a lower expansion ratio.

4.4.3. Thrust resolution and noise

The thrust resolution of CGMT-50 was measured at a thrust output of 11 μN . Fig. 18 shows the results after the torsional pendulum drift was eliminated. A step at 0.05 μN is clearly visible, which corresponds to the previously discussed flow control resolution. For the thrust noise test, the thrust was measured at 10 μN and 100 μN each for durations exceeding 2 000 s. After the data drift was processed, the thrust noise was obtained and compared with the background noise when the micro-thruster was not operating. Fig. 19 shows the processed background noise. The measured thrust noise was less than $0.1 \mu\text{N}\cdot\text{Hz}^{-0.5}$ in the frequency band of 10 mHz–1 Hz. This result demonstrates that the requirement set out by the Taiji program has been met, as the stipulated requirement is that the thrust noise should be less than

$0.1 \times \sqrt{1 + (0.01/f)^4} \mu\text{N}\cdot\text{Hz}^{-0.5}$ in the frequency band of 0.1 mHz to 1 Hz. At 1 Hz, both the background noise and thrust noise exhibited peaks of up to $0.5 \mu\text{N}\cdot\text{Hz}^{-0.5}$ caused by disturbances from the cryogenic pump affecting the entire vacuum chamber and, subsequently, the thrust measurement stand. When the cryogenic pump was turned off, this peak disappeared.

4.4.4. Thrust response time

To measure the thrust response time, CGMT-50 was set to increase its thrust from 1 μN to 100 μN and then decrease back to 1 μN . The displacement data during this period were collected by a displacement sensor at a sampling frequency of 520.83 Hz. Simultaneously, the electrical signal of the flow control was collected. These data points were combined to estimate the thrust response time. Fig. 20 shows the thrust response time when the thrust was calculated from the flow control signal based on the specific impulse, and the acceleration curve was derived from the displacement data after filtering and double differentiation. Fig. 21 shows magnified views of the thrust rise and fall. The time for the displacement acceleration to rise (or fall) from 0 to its maximum (or minimum) value roughly coincided with the time for the thrust to rise (0% $\rightarrow$ 90%) or decrease (100% $\rightarrow$ 10%). According to the thrust curve derived from the flow control signal, the thrust response time from 1 μN to 100 μN was 140 ms for both the

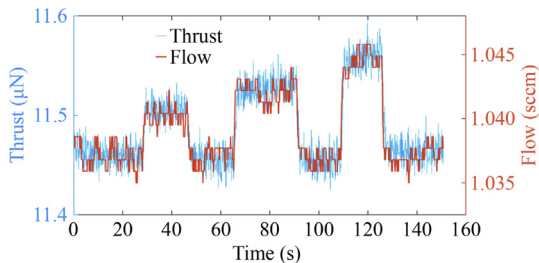


Fig. 18 Thrust output resolution of CGMT-50.

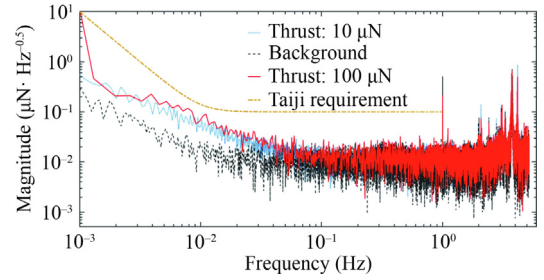


Fig. 19 Thrust noise of CGMT-50.

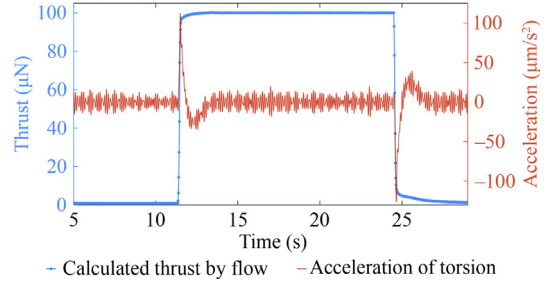


Fig. 20 Thrust response time.

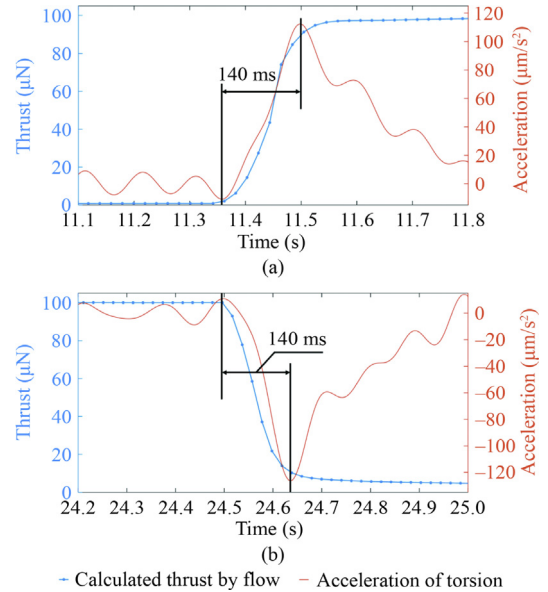


Fig. 21 Thrust rise and fall times: (a) Rising edge; (b) Falling edge.

rise and fall times. The acceleration curve also indicated rise and fall times of 140 ms, which supports the thrust response time obtained by the flow control curve. The flow control curve also shows that the response time of CGMT-100 reached 50 ms (Fig. 13(c) and (d)), which is much faster than that of CGMT-50. This is because CGMT-100 had a larger P-value in the PID control, which caused an overshoot during adjustment and a noise frequency of 11.2 Hz. To avoid these issues, a smaller P-value was used for CGMT-50, which resulted in a slower response time.

5. Conclusions and outlook

To meet the requirements for drag-free control and help the Taiji program achieve space-based gravitational wave detection, a series of technologies was employed to develop engineering prototypes of variable cold gas micro-thrusters with low noise and fast response. The main conclusions are as follows.

- (1) Ground performance tests demonstrated that the minimum thrust was effectively zero. CGMT-50 achieved a maximum thrust control output of 220 μN . Simply by changing the micro-nozzle, thrust outputs of 600 μN were achieved for CGMT-100.
- (2) At a thrust of 5.2 μN , the corresponding specific impulse reached 60.2 s. As the thrust increased, the specific impulse continued to rise and reached 69.7 s at a thrust of 200 μN . This highlights the impact of the Reynolds number and expansion ratio on the specific impulse.
- (3) The prototypes demonstrated a thrust resolution of up to 0.05 μN and a thrust noise of less than 0.1 $\mu\text{N}\cdot\text{Hz}^{-0.5}$ in the frequency band of 10 mHz–1 Hz. According to the thrust curve feedback from the flow signal and the torsional pendulum acceleration curve, the thrust response time is 140 ms. Modifying the PID parameter enables the flow control response time to be reduced to a minimum of 50 ms.
- (4) Based on the ground performance tests, the developed micro-thruster essentially met the performance requirements for drag-free control. However, if a wider thrust range is required, the non-linear relationship between the drive voltage and flow makes it difficult for the PID control method and single PID control parameters to meet the response speed requirements for arbitrary thrust steps.

Future work will involve optimising the closed-loop control method and parameters of the micro-thruster to ensure high control stability and response speed across a broader thrust range. The longevity of the micro-thruster is also a crucial factor for future space applications, and 1:1 lifetime experiments are currently being conducted on the ground to assess its long-term reliability.

CRedit authorship contribution statement

Chao YANG: Writing – original draft, Resources, Methodology, Investigation, Formal analysis, Conceptualization. **Jianwu HE:** Writing – review & editing, Methodology, Data curation, Conceptualization. **Chu ZHANG:** Software. **Li DUAN:** Supervision. **Qi KANG:** Writing – review & editing, Methodology, Investigation, Conceptualization. **Shuang YANG:** Validation, Software.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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