30.3: Thin Film Strain Gauge Sensors for Ion Thrust Measurement

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Abstract:
In order to measure the thrust produced by a Stationary Plasma Thruster, a measurement system has been developed using a thrust balance with thin film strain gauge sensors. For this purpose, strain gauges were designed and deposited on the columns of the thrust balance fabricated and necessary signal conditioning circuit has been used. Performance of the system developed was studied, in a vacuum chamber under space simulated conditions, by activating the thruster. Insitu calibration was done using Lami's principle. For discharge powers varying from 210-275 Watts, the measured values of thrust werefound to be in the range of 11-16 mN with an accuracy of ± 1mN and resolution of 0.12 mN. Specific impulse and efficiency were also estimated.

1. Introduction

In space applications, a kind of propulsion is used to re-orient satellites placed in orbits. In recent years, Hall type of electric propulsion devices such as Stationary Plasma Thrusters (SPT) placed on board the satellites are activated for the purpose of station keeping and on-orbit maneuvering [1-71. In such situations, measurement of thrust is an important requirement. Techniques have been developed for the measurement of thrust produced by electric propulsion devices based on spring force, pendulum and a gas–bearing turntable [8-14]. Recently, we have reported the measurement of thrust produced by an SPT, using a thrust balance with conventional foil type of strain gauges [15]. In comparison with conventional foil type strain gauges, thin film strain gauges offer several advantages. Some of the advantages are absence of adhesive material, flexibility to tailor the properties of the sensor material in thin film form, good linearity and improved strain sensitivity etc. [16-17]

In the present paper, we report the attempt made to measure the thrust produced by an SPT by developing a measurement system using a thrust balance with thin film strain gauges made of platinum–tungsten (Pt-W) material. This material has been chosen because of its high sensitivity, good repeatability and excellent linearity. The details of the experiments carried out to study the performance of the thrust measuring system on the ground under space-simulated conditions and the results obtained are reported.

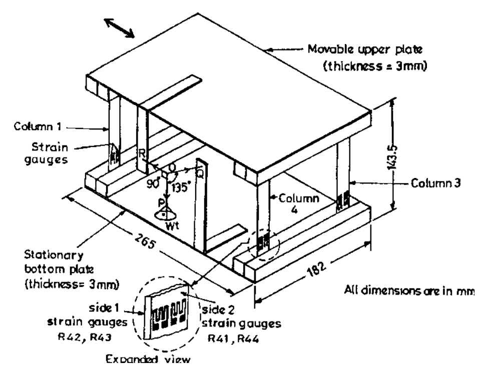

Figure 1. Schematic of the thrust balance assembly.

2. Thrust Balance assembly

The schematic of the thrust balance assembly developed is shown in figure 1. It consists of a stainless steel (SS) plate at the bottom with four columns of beryllium-copper alloy, mounted one on each of the four comers, simply supporting another SS plate at the top. Its bottom plate is stationary and its upper plate moves in response to a force while remaining parallel to the bottom plate. When the thrust balance is critically loaded, the columns buckle and even a small force in the transverse direction produces a large deflection of the columns, the deflection being proportional to the magnitude of force acting on them. An SPT was placed on the upper plate along with additional weights, so as to critically load the thrust balance in such a way that the four columns share the total load equally. To provide damping during the operation of the thruster, a viscous damper was provided. More details of the thrust balance are provided in our earlier paper [15].

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3. Preparation of thin film strain gauges

The strain gauge development carried out includes the design of strain gauge, surface preparation of the columns, deposition of thin film gauges, wiring and necessary signal conditioning. Thin film strain gauges had to be deposited on the lower region of the four columns of the thrust balance, where the strain is maximum. The suitable pattern required for the thin film strain gauge was first designed using AutoCAD. A photo-plot of the designed gauge pattern was obtained and with the help of it mechanical masks also of beryllium-copper material and of thickness 150 microns were made. In order to electrically isolate the thin film strain gauges from the metallic surface, a thin layer of polymer (M-Bond 610 of Measurements Group Inc, **USA)** was applied on either side of the columns. This polymer is suitable for temperatures up to +230°C. Prior to the application of polymer layer, the surface of the columns was prepared using standard polishing and cleaning procedures. The polymer layer was applied uniformly on the required region and heat treatment of the columns was done immediately in a temperature-controlled oven.

Figure 2. Photographs showing a portion ***of*** the thrust balance column on to which thin film strain gauges are deposited and wired.

Using the mechanical masks, thin film strain gauges were deposited on either side of the four columns using a DC magnetron sputtering technique. This technique has been chosen because of its high ionization efficiency and good adhesion of the deposited films. Good adhesion of film and hence better molecular bond ensures faithful transfer of strain experienced by the columns to the gauges. The sputtering system used consists of an arrangement in which, a plasma discharge is maintained between the anode or substrate (beryllium-copper columns) and the cathode or Target (92% platinum-8% tungsten).
The chamber was initially evacuated to a pressure of 10^{-6} torr using a combination of rotary and diffusion pump and back filled to sputtering pressure with the inert gas argon. The deposition parameters were optimized to achieve the required properties for the film. Following the deposition process, the columns were cured in an oven. Later, the gauges were connected in Wheatstone bridge configuration such that the pair of gauges on either side of the column forms the opposite arms of the bridge.

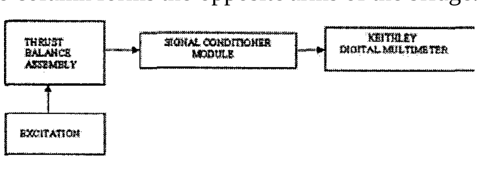

Figure 3. Block diagram of the measurement system

The block diagram of the measurement system is shown in figure 3. The necessary signal conditioning circuitry utilized includes an instrumentation amplifier. The detailed aspects of electronic circuitry utilized are provided in our earlier paper [15].

3.1 Gauge Factor Determination:

In order to determine the gauge factor of the thin film strain gauges deposited, a mechanical setup was designed and developed. The setup consists of a rectangular base plate made of stainless steel material with a cylindrical rod fixed vertically at the left wherein a fixture has been provided for holding

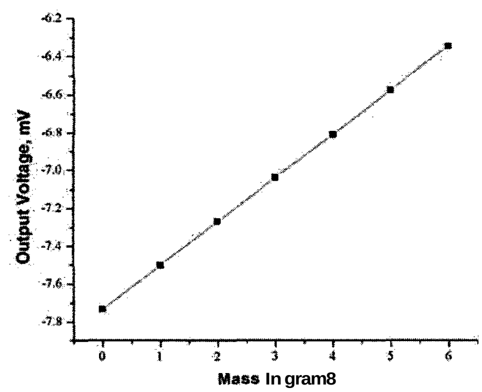

Figure **4.** Variation of the mass versus output voltage

the strain gauge columns in the form of a cantilever. The free end of the cantilever can be deflected by means of screw gauge (micrometer) fixed to a holder on the dovetail arrangement, which can be made to move to & fro along the length of the base plate.
The free end of the cantilever was deflected in steps and the corresponding bridge output voltages were recorded. The variation of the deflection versus output was found to be linear. Also, small masses were added in steps to the free end of the cantilever and the corresponding bridge output voltages were noted. Variation of the mass versus output voltage is as shown in figure 4. From the data obtained, the gauge factor of the thin film strain gauges was determined. The measured gauge factor was found to be ~ 3.5 for the Pt-W thin film strain gauges.

4. System Calibration and Performance Study

In order to have a calibration of the output voltage from the thrust measurement system, an arrangement was made in the thrust balance using a fine silk thread with a pan as shown in figure 1. The thread was tied such that the plane PQR was parallel to the vertical plane of the thrust balance. **An MS** nut of mass **1.03 gm** was attached **to** point P of the thread, whereas points Q and R were tied to the thrust balance. The thread OR was parallel to the horizontal plane and the thread OP was hanging vertically downward due to the weight attached to its lower end. Thus LPOR =90°. Point Q of the thread was tied to the thrust balance such that LPOQ = LROQ = 135". If **P** is the force acting along OP and **Q** the force acting along OQ and **R** the force acting along OR, then as per Lami's theorem,

$$\frac{P}{\text{Sin LROQ}} = \frac{R}{\text{Sin LPOQ}} = \frac{Q}{\text{Sin LPOR}}$$

$$\frac{P}{\text{Sin}135''} = \frac{R}{\text{Sin}135^\circ} = \frac{Q}{\text{Sin }90''}$$

$\therefore$ **P=R**

The downward force **P** due to a mass of 1.03 gm acting along OP is equal to the product of mass and the acceleration due to gravity, which is 10.1 mN. Hence the force **R** acting along OR is also equal to 10.1 mN.
The vacuum chamber used for the purpose of measurement is a cylindrical chamber of 1.2 m diameter and 1.4 m length made of stainless steel material. **A** combination of rotary, turbo molecular and cryo pumps was used to obtain pressures as low as 10^{-6} torr. The rotary and the turbo molecular pumps have been mounted on rubber pads to minimize vibration and have been connected to the vacuum chamber through metallic bellows so as to reduce the transmission of vibrations to the chamber.

While performing the actual *in-situ* calibration, the thrust balance was placed on a horizontal platform inside the cylindrical vacuum chamber. The SPT was placed atop the thrust balance and the thrust balance was critically loaded. Care was taken to see that the connections to the thruster were made in such a way that cable torque forces were negligible. **An** MS mass of 1.03gm was attached to point P of the thread arrangement shown in figure 1. A solenoid was used around the mass attached to point P, in order to lift it whenever required. In order to protect the strain gauges from direct ion impingement on them during the operation of the thruster, a stainless steel enclosure was placed surrounding the columns of the thrust balance. The chamber was evacuated to a pressure of 10^{-6} torr and *in-situ* calibration was done with the propellant flow ON at a pressure of 10^{-4}mbar.When the solenoid is in the normal state the mass hangs vertically downwards due to the force of gravity. At this condition the output voltage from the measurement system was noted. The solenoid was then energized and when the mass was thus lifted, the output voltage was once again noted. The difference between these two voltages correspond to a force of $1.03\times9.8 = 10.1$ mN. This was repeated a few times to check the consistency of the change in the output voltage corresponding to the force of 10.1 mN and the values were found to be consistent. This change in output voltage was utilized, as follows, in estimating the thrust produced when the thruster was activated. The SPT was operated and the actual change in the output voltage before and after the firing of the thruster was noted. Thus, the output thrust produced by the SPT is given by

$$\text{Thrust} = \frac{\text{(Change in output voltage)}}{\text{(Voltage change during } \textit{insitu} \text{ calibration)}} \times 10.1\,\text{mN}$$

Figure 5 shows the photograph of the thrust balance along with the thruster placed inside the vacuum chamber. In order to operate the thruster, the flow rate of xenon gas was set to 0.821 mg/sec. The thruster was operated as per standard procedure for electric propulsion thrusters. By varying the anode voltage and current, the thrust produced by the propellant for various discharge powers was measured from each of the four columns.

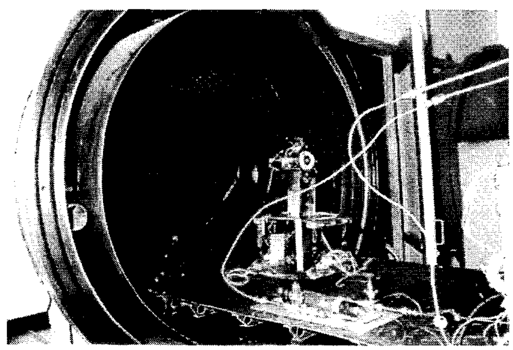

Figure 5. Photograph of the thrust balance along with the thruster placed inside the vacuum chamber

The experiment was also repeated for xenon flow rates of 0.889 mglsec and 0.957 mglsec. *In-situ* calibration check was also performed immediately after switching off the thruster. It has been found that the calibration remained unaltered. Care was taken to eliminate the possible noise in the output signal by providing proper shielding and grounding in the following manner. The cables, connecting the strain gauges deposited on the columns of the thrust balance placed in the vacuum chamber to the signal conditioner module and the power supplies kept outside the chamber, were shielded using flexible copper conducting tape. Apart from this, proper grounding of the thrust balance, the SS enclosure and the shroud of the vacuum chamber were also done for the above purpose. In addition to these, graphite blocks were placed inside the chamber at the closed end of the shroud - 1 m downstream of the thruster exit plane so as to form a background ion dump, which was held at ground potential. The experiment was repeated several times and it was found that the values of thrust estimated from the measured data from each column were almost same and the variation was less than a milli-Newton. The variation of the thrust produced versus thruster discharge power is shown in figure 6. It can be seen that the thrust produced

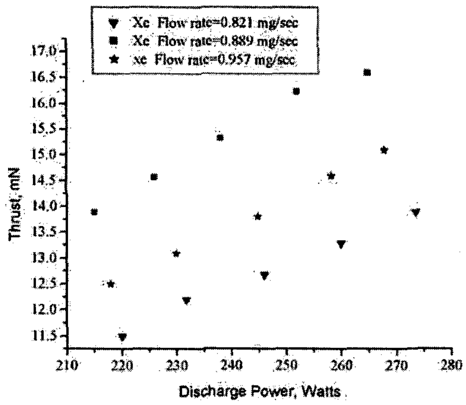

Figure 6. Variation of the thrust with discharge power

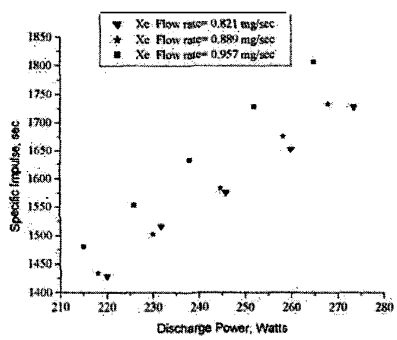

Figure 7. Variation of the specific impulse with discharge power

increases almost linearly with the discharge power. The measured values of thrusts were found to be approximately in the range of 11-16 mN, for discharge powers of 210-275 Watts. **Also** the specific impulse and the thrust efficiency were determined from the measured values of thrust using the following relations.

$$I_{sp} = T / m\, g \qquad \text{.........} \qquad (2)$$

$$\eta_T = 0.5\ m\, [I_{sp}.g]^2 / V_d \qquad \text{.........} \qquad (3)$$

Where T is the thrust, I_{sp} is the specific impulse, m is the mass flow rate of xenon, η_T is the thruster efficiency, V_d is the discharge voltage and I_d is the discharge current. The product $V_d I_d$ is the discharge power. For the mentioned range of discharge power, the specific impulse was found to vary from 1430 to 1800 sec and the thrust efficiency was found to vary from 36% to 57%. The variation of the specific impulse and the thruster efficiency with the thruster discharge power are shown in figure 6 and figure 7 respectively. In general, the thrust, specific impulse and efficiency were found to decrease as the mass flow rate was reduced. This behavior may be attributed to the reduction in ionization probability at low mass flow rates resulting in a reduced propellant utilization [18].

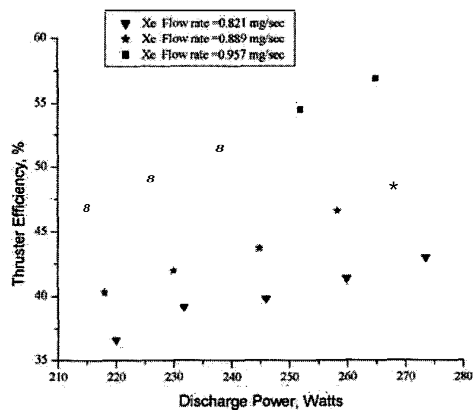

Figure 8. Variation of thruster efficiency with discharge power

5. Conclusion

A thrust measurement system, for measuring the thrust produced by a stationary plasma thruster,
has been developed using a thrust balance with thin film strain gauge sensors and associated signal conditioning circuitry. The output performance of the thrust measurement system has been studied in a vacuum chamber under space-simulated conditions by activating the thruster for various discharge powers using xenon as the propellant. In comparision with the thrust measurement system using conventional foil type strain gauges [15], the presently reported system with thin film strain gauges is found to have higher sensitivity, better stability & linearity and very good repeatability. However, thermal drift was found to exist in the present system, which can be overcome by using suitable temperature compensation technique. Specific impulse and the thrust efficiency have also been determined.

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