One Micro-thrust Measurement Method Based on the Dynamic Photoelastic Theory

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Abstract. A new method is adopted to measure the micro-thrust of the plasma thruster. In this method, the dynamic photoelastic theory is used to record the stress loaded on the special structure. This technique is called dynamic photoelasticity method. The photoelastic element is the core of the whole system as it can transform the thrust changes into the variation of fringe images. The variation of thrust can be recorded by a CCD camera and then the thrust changes in real-time could be obtained, which is helpful for developing a higher precision propulsion system. This method built in this paper is not only non-contact and non-destructive but also easy to operate with simple structure and high precision.

1. Introduction

Normal thrust measurement methods for the plasma thruster, such as the pendulum, twist and cantilever beam often fail to recognize such values of the thrust which are lower than the mN magnitude. Accurate measurements of the visatergo are not only prerequisite for orbit raising, drag makeup, attitude controlling and constellation station keeping but also thus useful for aerospace applications [1] [2].

Many studies have been conduct on the accurate measurement of the thrust. As reported in the pioneering work by Kurt A. Polzin [3], an electric propulsion thrust stand capable of supporting testing of thrusters has been developed on the basis of the pendulum while such method cann’t achieve a high precision. The most sensitive of these past devices appears to be the optical angular readout from Ref. [4] designed in Brian C D’s papers, which can measure thrust as low as 7 nN with loads up to 12kg. In a word, limited attempts having been made to measure the thrust cann’t show an absolute result, that is to say, there is no high accuracy measurement system at present. And so it’s urgent to raise the measurement accuracy of the measurement as exact as possible for promoting the development of micro-satellites.

One way to overcome these problems is to develop the sensor with better performance but this technique is rather limited. Therefore, the thrust is converted into other signal which could be recognized in a high precision. With the mechanical knowledge, we know the overall stress of the thruster varies with the thrust and such variation meets one certain physical rule. What’s more, it provides one good idea to measure the thrust converted from the stress. The thrust can’t be changed naturally while we can change certain parameters to get the large stress. As a stress monitoring item, the photoelasticity method has been widely used as a reliable tool to record the variation of the stress.

This paper builds one new measurement method basing on thephotoelastic theory for approving the situation that the traditional way of micro-thrust measurement cannot get the transient thrust value.
with high precision and the measuring process of piezoelectric sensors is sensitive to the electromagnetic interference. The photoelastic element is the core of the whole system as it can transform the thrust changes into the variation of fringe images. Thus adopting a CCD to record these images so that the thrust changes in real-time could be obtained, which is helpful for studying the mechanism of micro thrusters. This method built in this paper is not only non-contact and non-destructive but also easy to operate with simple structure and high precision.

2. Photoelastic theory
The dynamic photoelastic method that has gained wide application in industry was first described by Tuzi in his fundamental 1928 study. The author proposed a new method for measuring the stresses in an isotropic material. The phenomenon that the method is based on is in the difference of the refractivity to the direction of stresses in the materials under load, and it is called the anisotropy of the stressed medium. Traditionally, a Cranz-Schardin system with array cameras was used to capture a series of photoelastic fringe patterns as showed in Cranz and Schardin’s papers. This phenomenon has been termed the photoelastic effect and method for assessing the stress-strain state of structural elements is referred to as the photoelastic method. Nowadays, it is very easy to arrange a digital dynamic photoelastic system so that dynamic photoelastic fringe patterns can be taken using a digital video camera and analyzed later [5] [6].

Photoelasticity is a branch of mechanics that studies the interaction of structures, fluids, and lights. It involves ships, underwater weapons, aircraft, automobiles, buildings, chemicals, marine and water conservancy projects, and many other fields. It is an experimental technique for analyzing stress or strain fields in solids with birefringent properties. These normal photoelastic materials contain glass, epoxy and so on. In principle, when a photoelastic material is deformed, the electric vector of an incident polarized light beam can be decomposed into two components along the axes of the principal stresses in the material due to its temporary birefringence. Because of the difference in refractive indices along the axes of the principal stresses, the two components will be retarded differentially as they propagate through the material, leading to a relative phase shift. Consequently, an interference pattern will be formed as the two components are recombined outside the material by a downstream polarizer which is called the ‘‘analyzer’’ as well. Photoelasticity is, therefore, a classic common-path interferometric technique, with the surface of the photoelastic material acting as the beam splitter.

Based on the correlation between stress and the indices of refraction for temporary birefringent materials formulated by Maxwell, in the simplest case, the stress-optic law for a plate with only variable in-plane principal stresses can be written as [7]:

\[
\sigma_1 - \sigma_2 = \frac{N f_\sigma}{h}
\]

(1)

where \(\sigma_1, \sigma_2\) are the principal stresses in the temporary birefringent material, \(N\) is the relative retardation which is also known as the ‘‘fringe order’’, \(f_\sigma\) (\(=\lambda/C\), with \(\lambda\) being the wavelength and \(C\) the stress-optic coefficient) is the material fringe value (in units of N/m fringe) corresponding to the minimum difference in principal stresses to produce a unit change in the fringe order in a material of unit thickness, and \(h\) is the distance traversed by the light in the stressed plate [7].

Equation (1) applies to both static and dynamic loading conditions, except that the material-fringe value under dynamic loading \((f_\sigma \ast)\) is usually 10%–30% higher than that for the static case [5].

Dynamic photoelasticity has been widely used for transient stress analysis in fracture mechanics and geophysics. Dynamic photoelasticity was used by Jian Chang to visualize the fundamental behavior of polycarbonate gears and observe the stress under the impact loadings with different pulse width [8]. Image-processing techniques and stroboscopic photoelasticity were combined to observe the wave stress field generated by commercial ultrasonic probes in Nam and Lee’s papers. Xiaomao Li carried out the material surface strain measurement with photoelastic coatings for solving such problem that it is not easy to interpret distribution of the surface strain field [9]. However, seldom is such method applied to measuring the thrust, more application are in stress testing. And the goal of
this study is to obtaining the thrust data on the spatial and temporal dynamics of the variations when the micro-thrusters work.

Such method is not only a non-destructive method for measuring stress, but also one new means to analysis the non-transparent material’s stress as for its reliability, toughness, economical efficiency and easy-using. The fringe images change in accordance with the stress; therefore, we can get specific value of the stress by recording these images with one CCD device. What’s more, if the exposure time is arranged to be short enough, the fringe images recorded by the CCD at different times can be close to the real time variation of the stress of the photoelastic element. And then, the thrust can be calculated according to the equation of mechanics of materials as follows:

\[ \sigma = \frac{F}{S} \]

Where F is the internal force, S is the cross-section and \( \sigma \) is the principal stress which obtained from the fringe image.

Control the loading so that the thrust is equal to the internal force so that we can get the thrust by measuring the stress.

3. Experimental setup and theory

In this paper, the photoelastic element is regarded as the core of the system as it can reflect the variation of thrust through the change of fringe images. And such measurement method is built according to the characteristics of micro thruster and photoelastic theory. On the basis of the system, we can obtain the real-time change of the thrust when using high-speed signal collector to record the fringe images. This measurement is non-contact and non-destructive for a sensor or other measuring devices installed on the thrusters are not needful. Therefore, the system reduces the interference of mechanical vibration and power supply cables while solves problem like zero drift and unstable equilibrium position calibration, difficulty and low accuracy. General speaking, it has the advantages of simple structure, easy operation and high reliability while the most important thing is to provide a method to solve the problem of the traditional thrust measuring method which is difficult to measure the transient thrust.

Figure 1. System composition.

The instantaneous thrust measurement system basing on the principle of photoelasticity consists of four parts, which are optical environment system, thruster system, control system, fringe images collector and image processing system. The overall composition is shown in Figure 1.

The main function of the optical environment system is to create an optical environment for the photoelastic element so that the stress change of the acoustic elastic element can be reflected by the fringe images. The thruster system generates thrust and to amplify and transfer the thrust to the photoelastic element so that it is in a stress state. The duration of the pulsed laser is set to be 30-50 ns which correspond to the shutter time of the high-speed camera at a speed of million images per second in the control system. With this arrangement, we can think that the deformation of the photoelastic element is approximate zero within the time interval of light passing from such element to the camera. The key of such measurement method by photoelasticity is the fringe pattern of the elastic element. Therefore, the quality of fringe pattern directly determines the accuracy of thrust measurement. Matlab
is adopted in the image processing system. The control system and the fringe image collector ensure that the conversion thrust is approximate equal to the average thrust during the set time interval.

3.1. Optical environment system
As shown in Figure 2, the optical environment system includes a light source 1, a collimation lens 2, a polarizer 3, 1/4 wave plates 4 and 6, a photoelastic element 5, an analyzer 7 and a condenser 8. According to different ranges of the thrust, the photoelastic element 5 can be replaced to meet the requirement of measurement. Generally, the material of 5 can choose epoxy resin or polycarbonate with high optical sensitivity and temporary birefringence effect after loading. The light source 1 uses white light. In order to make the fringes clear in high speed photography imaging, the distance between the light source 1 and the Collimation lens is set to be a proper value. The function of the collimation lens 2 is to turn the conical beam from the light source into parallel light so that the light can be vertically entered into the photoelastic element. The polarizer 3 and the analyzer 7 are the same type of optical instrument but play different roles. Natural light is turned into plane polarized light by the polarizer 3 while the analyzer 7 is arranged to check the polarization state of the light wave. The 1/4 wave plate 4 acts to transform the plane polarized light into circularly polarized light. On the contrary, 6 is designed to transform the circularly polarized light into plane polarized light. The condenser 8 focuses parallel lights to the CCD camera 9.

The photoelastic element is in a very stable optical environment for producing photoelastic effect with the combination of these elements. More importantly, this optical path has high stability which can effectively reduce the error in late loading and data acquisition.

![Diagram of Optical Environment System]

**Figure 2. Optical Environment System**

3.2. Thruster system
The purpose of this paper is to realize the force measurement. Therefore, different types of thrusters can be replaced according to the requirements of the force measurement without considering the structure and function of the thruster. Pulsed plasma thruster is taken as an example. The thruster sprayed the plume which impacted on the photoelastic element and made such element under stress. According to the three laws of Newton, we can know that thrust is directly related to the plume. Meanwhile, the sound velocity variation of elastic element is directly related to the thrust’s change. The whole thruster is integrated into one hull as shown in Figure 2. The pressure value at the nozzle is one important parameter of the thruster working condition. Therefore the wireless pressure conveyer measures and sends the pressure value to the computer for displaying the pressure value. In order to
reduce the amount of calculation, the load can be equivalent to a concentrated load, so the plume ejection area is small.

The key of hull has a small outlet that causes the plume to be sprayed out from that outlet. The fringes variation of elastic element is directly related to the thrust’s change. The outlet can amplify the thrust in an appropriate ratio, and then provides a larger thrust for recording the velocity variation more precisely. Finally, real data is obtained by scaling the value according to the outlet parameters.

3.3. Control system
The system structure diagram is shown in Figure 3. For getting more fringe images with higher quality, it is necessary to make the light triggering time, thrust loading time and transient images acquisition time accurate synchronization control. The time for the thruster start working is equivalent to the origin of the coordinates in the coordinate system as shown in Figure 3. When the thuster works, the plume is ejected from the nozzle. And then the pressure on the exit will be recorded and a sensor 13 is triggered at the same time. The pressure trigger 13 produces a signal PC as the first trigger time of the light source 1, thus the first pulse light is generated at \( t_{Q1} \). When the photoelastic element 5 is subjected to impact, the electromagnetical trigger will produce another signal CT as the second trigger time of the light source due to the plasma electromagnetical shielding effect. The time \( t_{Q2} \) in which the light source produces second pulses of light is controlled by \( \Delta t \). \( \Delta t \) is up to the electronic control system of light source, and \( \Delta t \) is the time when the photoelastic element needs to be collected fringe images.

3.4. Images collector
The acquisition of image is mainly realized by CCD camera. It is important to note that the fringe image collected is not reflected the stress of the elastic element as the propagation of light between 5 and 9 also takes time. However, such time is small comparing to the light velocity, we can approximate the information of the 2 moment in the error range so as to simplify the calculation process.

3.5. Images processing system
The measurement results obtained by using the images collector are lots of stress fringe images. These pictures contain two important parameters: the stress direction and fringe order. The fringe order
represents the difference of the principal stress, but the principal stress can’t be calculated by the difference and the direction angle of stress. Therefore, the important work of obtaining the fringe image is the separation of the stress.

In this paper we use boundary element method to separating main stress. It can simplify the problem and provide a practical method for separating main stress. The element 5 is bored as shown in Figure 2 which introduces one free boundary, thus the main stress magnitude can be measured directly by the tripe series. Two symmetry axis of the isochromatic fringes depends on the direction of the principal stress. Because the stress value obtained after drilling is deviated from the value before drilling, it is necessary to calculate the stress value before opening by the corresponding formula from the stress value after opening. These steps can be realized by MATLAB.

The picture of each strain on the instantaneous thrust should always, and the control system and the transient image acquisition system ensures high-speed camera to get the instantaneous thrust roughly the size of the thrust as the set time interval, based on a series of stress image processing to obtain the thrust moment has successfully connected to can approximately reflect the real-time change of thruster thrust.

4. Discussion
In this paper, the photoelectric method, which has the advantages of simple structure, easy operation and high reliability, is first applied to the field of instantaneous thrust measurement field. Moreover, this method provides a basic idea for measuring the thrust of plasma thrusters, can realize high precision and accurate measurement of instantaneous thrust and impulse. Thrust measuring methods of the non-contact measurement, and non-destructive measurement methods, does not require a sensor or other measuring device is directly installed on the structure, can reduce the interference of mechanical vibration and power supply cables for thrust measurement, solve the present commonly used micro thruster and micro impulse measuring device of zero drift, balance position stable, low accuracy and calibration difficult problem.

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