One Real-time Micro-thrust Measurement System Based on Barkhausen Effect

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Abstract. The thrust of the electric thruster for micro-nano satellites is very small, so it is very difficult to accurately measure the real-time variation of micro-thrust. In order to solve this problem, a real-time micro-thrust measurement system based on Barkhausen effect is proposed. Buckhausen effect is that under the action of external stress, the change of internal stress or strain of ferromagnetic material will cause the change of permeability, reluctance and flux of ferromagnetic material, which will result in Barkhausen noise under the external alternating magnetic field. Therefore, the change of stress or strain in ferromagnetic materials can be obtained by measuring Barkhausen noise. The micro-thrust measurement system based on Barkhausen effect proposed exactly in this paper transforms the change of thrust into the change of internal stress of the magnetoelastic element [1], which can realize real-time and high-precision measurement of instantaneous micro-thrust with the advantages of simple structure, easy operation and high reliability.

1. Introduction

As a product of the development of high and new technology and space exploration missions in the fields of microelectronics, micro-machinery, new materials and computers, micro-nano satellites have the advantages of light weight, small volume, short development period, high power density, flexible launch, low cost, fast networking and strong survivability, which play an important role in civilian and military aspects. Whether it is a single flight or a formation flight, it is necessary to control the orbit and attitude of the satellite accurately, which requires that the thrust generated by the propulsion device of the satellite is small, wide and controllable, usually within the order of μN~mN [2].

The thrust produced by the electric thruster is generally small, and its order of magnitude is between nN and N, making electric thrusters the proper propulsion devices of micro-nano satellites. For example, the thrust produced by pulsed plasma thruster is generally of μN order, while that of laser plasma micro-thruster based on laser ablation of solid working fluid is of nN magnitude. Although the micro-thrust of mN or N is easy to measure, it becomes very difficult to measure the micro-thrust of the order of μN~nN as the thrust decreases further. Moreover, in order to control the satellite more accurately, it is necessary to monitor the real-time change of the thrust.

At present, the micro-thrust measurement systems of electric thrusters mainly involve the measurement system based on the single pendulum, the electromagnetic balance based on the inverted pendulum, the measurement system based on the torsion pendulum and the measurement system based on the piezoelectric sensor. The measuring precision of the first two kinds of force measuring systems is low. Although the measuring system based on torsion pendulum has high precision and sensitivity,
and the lower limit of thrust measurement is low, twisting wires are easy to be affected by vibration and noise, and can only measure the average thrust. The measurement system based on the piezoelectric sensor has high sensitivity and is able to measure the change of instantaneous thrusts accurately. However, it is vulnerable to electromagnetic interference, which results in inaccurate measurement results or the measurement process not being carried out normally.

In summary, the existing measuring methods can not measure the tiny transient thrust generated in the working process of the electric thruster accurately and real-timely. To solve this problem, a transient micro-thrust measurement system based on Barkhausen stress detection method is proposed.

2. Measurement principal
Magnetoelasticity is a phenomenon in which the magnetic properties of ferromagnetic materials change with the action of mechanical stress or strain. Ferromagnetic materials are magnetoelastic elements.

Barkhausen effect was first discovered by German physicist Bardhausen in 1919. When he observed the hysteresis loop of the ferromagnetic material, he found that the curve was not smooth. After amplification, he saw the variation of step jitter [3] as shown in Figure 1. When placing the receiving coil on the surface of the sample, the voltage pulse and noise are generated. This phenomenon is called Barkhausen effect, and the corresponding magnetic noise is called Barkhausen noise, or MBN.

![Figure 1. Barkhausen noise generation diagram](image)

Barkhausen stress detection method is a nondestructive testing method based on magnetoelastic principle and Barkhausen effect, which is usually used to detect the stress state of ferromagnetic materials widely used in engineering. When ferromagnetic materials are subjected to external stress, the change of internal stress or strain will cause the change of permeability, reluctance and flux of ferromagnetic materials. Barkhausen noise induced by the external alternating magnetic field will reflect this change. Therefore, the change of stress or strain in ferromagnetic materials can be obtained by measuring Barkhausen noise. In this paper, the method is applied to micro-thrust measurement of electric thruster, which transforms the change of thrust into the change of internal stress of the magnetoelastic element. This method not only has the advantages of simple structure, convenient operation and high reliability, but also has high detection sensitivity and accuracy. It can measure the change of stress in real time, which means that it can accurately measure the tiny transient thrust of electric thrusters.

3. System composition
As shown in figure 2, the system consists of two parts: the stress detection system and the thruster system.

3.1. The stress detection system
The Barkhausen stress detection system based on digital signal processing (DSP) [4,5] includes an ARM human-computer interaction module, a DSP system, a power amplifier circuit, a signal
generation circuit, a signal conditioning circuit, a signal acquisition circuit, a magnetoelastic element, a sensor and two shields. Among them, the ARM human-computer interaction module is the key of human-computer interaction control, which realizes the display of stress and MBN signal eigenvalues. DSP is responsible for digital signal processing, controlling the generation of excitation and signal acquisition, and realizing the interactive communication with ARM. The power amplifier circuit can amplify the excitation signal and improve the load capacity. The signal generation circuit is responsible for generating the excitation signal and providing the external alternating magnetic field needed to generate the Barkhausen signal. The signal conditioning circuit filters and amplifies the received signal. The analog signal is sampled by the signal acquisition circuit, and then it is converted into a digital signal that can be processed by DSP. The sensor detects the MBN signal. When the exciting coil passes the alternating excitation signal, the alternating magnetic field is produced in the yoke, and the magnetoelastic element is magnetized locally. The receiving coil can sense the MBN signal generated by the magnetoelastic element due to domain reversal or domain wall movement. Shields shield the electromagnetic interference making the measurement results more accurate.

![Diagram](image)

1-the first shield box, 2-excitation coil, 3-yoke, 4-receiver, 5-magnetoelastic element, 6-rigid plate, 7-thruster, 8-the second shield box

Figure 2. The micro-thrust transient measurement system

3.1.1. The ARM man-machine interaction module. The ARM embedded hardware consists of the ARM microprocessor, the liquid crystal display (LCD), the flash memory, the synchronous dynamic random access memory (SDRAM), the universal asynchronous receiving / transmitting device (UART) interface, the universal serial bus (USB) peripheral interface, the SD card interface, the real-time clock (RTC), the external clock and the power supply battery. ARM embedded system is the key to realize man-machine interaction. The user can operate and control the whole system through LCD. At the same time, the ARM embedded system can store the detected stress data, display the stress curve, export data stored in U disk and drive some related peripherals. Flash memory is used to store programs and testing data. SDRAM provides guarantee for system operation. UART interface realizes communication with DSP system. USB peripheral interface can insert U disk and export testing data. SD card interface can be connected with SD card, realizing expansion of the system storage capacity. RTC provides clock signal for the whole system. The power supply battery provides the guarantee for the stable operation of the whole system.

3.1.2. The DSP digital signal processing system. The DSP mainly realizes the generation of the excitation signal and the processing of the acquisition signal. DSP has powerful data processing ability and can process a large number of data quickly. Thus, the design goal of real-time thrust detection can be realized.

3.1.3. The signal producing circuit. The essence of ferromagnetic materials generating MBN signal is domain reversal and domain wall movement. Therefore, the premise of MBN signal generation is the
external alternating magnetic field and alternating force. While the signal generation circuit can provide the excitation signal to produce alternating magnetic field. EMIFA expand the signal generation circuit, that is, digital-to-analog converter (DAC). In order to complete the conversion and control quickly, the conversion speed of DAC must meet the index requirements. In order to ensure the correct data processing, DAC must have enough conversion accuracy to reduce the error, so the conversion speed and accuracy are important parameters to measure DAC. In general, the more DAC bits, the higher its resolution and conversion accuracy. Most DACs used in industrial automatic control systems are of 10 or 12 bits, and the conversion accuracy can reach 0.5% to 0.1%.

3.1.4. The signal acquisition circuit. The signal acquisition circuit is a circuit that converts the analog signal which has been filtered and amplified by the signal conditioning circuit to the digital signal. EMIFA expand signal acquisition circuit, that is, analog-to-digital converter (ADC). In order to ensure the accuracy of the system processing results and realize the real-time control and detection of the rapidly changing signals, ADC must have sufficient conversion accuracy and high conversion speed, and it should satisfy the requirements of the input voltage range, the output digital coding, the working temperature range and the voltage stability, etc.

3.1.5. The power amplifier circuit. The function of the power amplifier circuit is to amplify the excitation signal generated by the DSP, and then to send the amplified excitation signal to the excitation coil, which magnetizes the magnetoelastic element to produce Barkhausen signal. In general, the load capacity of the signal generation circuit is poor and the impedance of the excitation coil is large, so it is necessary to pass the excitation signal generated by the signal generation circuit to the power amplifier circuit firstly and then pass the amplified signal to the excitation coil. The power amplifier circuit is essentially to provide enough power signals for the power equipment. The requirements for the power amplifier circuit are as follows: output power maximization, high conversion efficiency $\eta$ and low nonlinear distortion.

3.1.6. The signal conditioning circuit. MBN is a weak signal of mV level, and its bandwidth is 1 kHz ~2 MHz. The frequency bands of MBN signals produced by general materials are usually 1~500 kHz, so it is necessary to use appropriate signal conditioning circuit to amplify and filter MBN signals.

3.1.7. The magnetoelastic element. The ferromagnetic material of Q235 ordinary carbon steel is chosen as the magnetoelastic element. Q235 has moderate carbon content, and its strength, plasticity and welding property are relatively good, so Q235 has been widely used in engineering, especially in automobile, shipbuilding, building and aerospace, etc. The yield limit of Q235 is 235MPa, and the tensile limit is 400MPa. The composition and content of Q235 are as follows: carbon 0.14%~0.19%, silicon 0.12%~0.33%, manganese 0.3%~0.65%, chromium 0.3%, nickel 0.3%, beryllium < 0.045%, sulfur < 0.05% and the rest is iron. Q235 can adapt to the change of external environment and obtain good mechanical properties. The size of the magnetoelastic element, that is, length, width and thickness, should be reasonably selected according to the measuring thrust value and the sensitivity of the sensor.

3.1.8. The sensor. As the core component of the whole Barkhausen stress detection system, the sensor's ability to excite and receive the MBN signal directly affects the energy and signal-to-noise ratio of the original MBN signal. The necessary condition for the generation of the MBN signal is the jump of the magnetic domain. In practice, the method of electromagnetic induction is often used to excite, that is, the alternating current in the coil generates the dynamic alternating magnetic field. The coil is wound on the soft magnetic material with high permeability, the magnetoelastic element with which form a closed excitation loop to magnetize the magnetoelastic element. As shown in figure 3, the sensor consists of an excitation section and a receiver. The excitation part is composed of the excitation coil winding the U-shaped yoke and the receiver consists of the
receiving coil winding the cylindrical iron core. In detection, the receiver is placed in the middle of the U-shaped yoke and one end of it is in contact with the surface of the magnetoelastic element, and a sinusoidal alternating current of a certain frequency is passed through the excitation coil to produce an alternating magnetic field, and the magnetoelastic element is magnetized by the U-shaped yoke, generating the MBN signal, then the signal is received by the receiver. The frequency range of the Barkhausen signal of most ferromagnetic materials is 1~250 kHz. The resonance frequency of the excitation part needs to be much higher than the highest frequency of the MBN signal, which is generally above 10 times, so the material chosen for the yoke is Mn-Zn ferrite.

![Diagram](image)

1-the first shield box, 2-excitation coil, 3-yoke, 4-receiver, 5-magnetoelastic element, 9-low carbon steel shell, 10-silicon steel sheet, 11-double side shielded copper tape, 12-twisted pair wire

**Figure 3.** The sensor

The function of the receiver is to convert the inductive magnetic signal into the voltage signal, which plays a decisive role in the detected MBN voltage signal. When the frequency of magnetic core is close to the central frequency of Barkhausen signal, the inductive signal is relatively good, so Mn-Zn ferrite is chosen to be the core still. Mn-Zn ferrite is an ideal magnetic core with high permeability, low loss and low cost.

In order to make the detection equipment more dexterous and portable, the size of the sensor should be as small as possible. It is necessary to determine the diameter and the number of turns of the excitation coil and the receiving coil by certain tests to match the size and sensitivity of the thrust to be measured. The excitation frequency of the sensor is 5~500 Hz, and the excitation intensity is 0.1~2.0 T.

3.1.9. The first shield box. All kinds of electromagnetic devices in the measuring environment will cause electromagnetic interference to the sensor of the stress detection system, and the plasma produced by the electric thruster itself in the working process will also bring electromagnetic interference to the sensor. It is necessary to reduce the influence of stray electromagnetic field on the sensor by magnetic shielding technology. The first shield box adopts the annealed low carbon steel shell as the first shield box. Silicon steel sheet, which is the soft magnetic material of high magnetic conductivity, is pasted inside, and double-sided shielded copper tapes are wound on the external surface. The sensor is placed in the shield box.

In order to shield the external interference during the signal transmission, twisted-pair wires are used as the sensor signal wires to reduce the capacitive and inductive coupling, and to improve the common mode suppression ability.

3.2. The thruster system

The main function of thruster system is to generate thrust and transfer the thrust to the magnetoelastic element to keep it in a stress state. At the same time, it is necessary to ensure that the thruster will not
cause electromagnetic interference to the magnetoelastic element. As shown in figure 2, the thruster system includes a thruster body, a rigid plate and a second shield box.

The second shield box is the same as the first shield box, and the annealed low carbon steel shell is also used as the box, and the silicon steel sheet of high magnetic conductivity is attached inside, and the external windings are made of double-sided shielded copper tapes. However, the size of the second shield box should be large enough, otherwise, the plasma ejection of the thruster will be blocked and the size of the thrust will be affected, so the normal thrust value of the thruster can’t be obtained.

The role of the rigid plate is to connect the thruster with the magnetoelastic element and transfer the thrust produced by the thruster to the magnetoelastic element. In order to ensure the accuracy of measurement, the rigid plate should not be deformed or nearly deformed under thrust impact. Changing the shape (width and thickness) of the rigid plate and the cross-section moment, and properly arranging the position of the thruster and the magnetoelastic element on the rigid plate can change the thrust magnification, therefore, this method can measure the micro-thrust in the field of electric propulsion.

4. Summary
In this paper, Barkhausen effect is applied to the micro transient thrust measurement of the electric thruster. The change of thrust is transformed into the change of internal stress of the magnetoelastic element, then the Barkhausen stress detection device is used to detect the stress and obtain the thrust. This method has the advantages of simple structure, easy operation and high reliability. Most importantly, it solves the problem that the traditional thrust measurement method is difficult to measure the transient micro-thrust. It can realize real-time and high precision measurement of instantaneous micro-thrust.

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