# THE REALIZATION OF MICRO TORQUE CALIBRATION AND MEASUREMENT DEVICE

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**Abstract:** The calibration and measurement of micro-torque have long been the research focus of inertial navigation system. In this paper, the micro-torque calibration and measurement device based on knife-edge support are proposed, which combine the electromagnetic force balance and indifferent equilibrium technology to realize selfish calibration and automatic measurement. This device can be used to measure $10^{-5}$Nm torque of components of inertial navigation system. This paper aims to describe the basic theory and critical techniques. Uncertainty is evaluated and experiments were done to evaluate the repeatability of the device. The work is standing out in the field of international torque calibration.

**Keywords:** Micro torque, calibration and measurement, electromagnetic force balance, knife-edge support.

## 1. INTRODUCTION

The calibration and measurement of micro-torque enjoy significance in fields of spaceflight, aviation and shipping. A mass of electromagnetic components, such as micro actuator and angle transducer, are used in inertial navigation system to obtain different signals. Researchers have recently been active in developing these electromagnetic components, which have small sizes. The torque developed by these devices is estimated to be lower than $10^{-6}$Nm [1, 2]. The development of these devices therefore requires a feasible method to evaluate very low levels of output torque. It is very difficult to calibrate and measure the micro torque of these electromagnetic components. Lots of research works were focusing on air bearing [3, 4], which can be used as the rotating and bearing part of the device. Instead of air bearing, a thin metal sheet is used to suspend the beam in [5]. In addition, some researchers used wind pressure to apply a load to turbine [1].

Although air bearing can reduce friction to some degree, but it has disadvantages such as instability, high cost and complicated manufacturing. Instability of the device will affect measurement precision of the system. Therefore, Shanghai Marine Equipment Research Institute (SMERI) designed and developed the micro-toque calibration and measurement device based on edge knife support. The innovations come from the integration of electromagnetic force balance theory , indifferent equilibrium theory, error-free closed-loop auto control and fast tracking measurement technology. Advantages of the design are lower cost, higher stability, self-calibration and automatic measurement. The

device can be used to measure 10-5Nm micro-torque of electromagnetic components of inertial navigation system.

## 2. OPERATING PRINCIPLE AND CRITICAL TECHNIQUES

1. The OPERATING principle and structure.

The device was fabricated according to the measurement principle shown in figure 1.
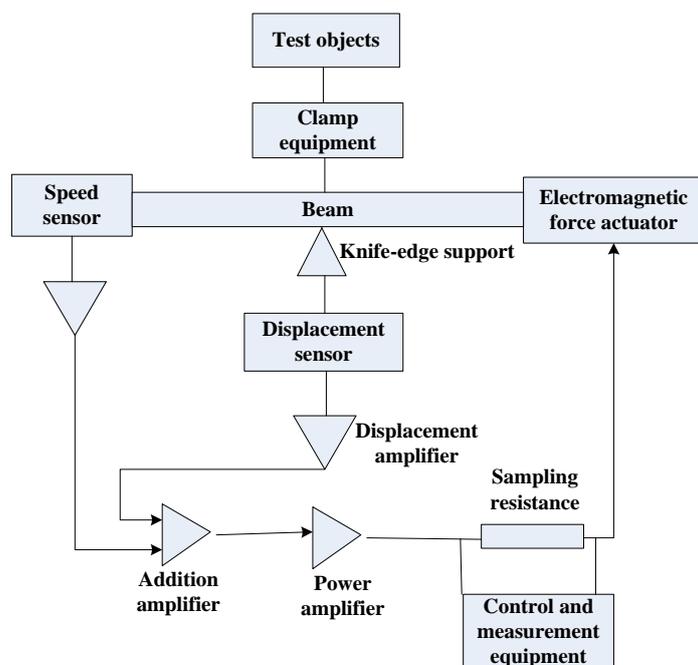


Figure 1 Operating principle of the device

It integrates electromagnetic force balance theory , indifferent equilibrium theory, error-free closed-loop auto control and fast tracking measurement technology. The device consists of a set of clamp equipment for clamping test objects, a beam for loading weights, a knife-edge support as rotating and supporting part of the device, a displacement sensor for measurement of the rotation displacement of the beam, an electromagnetic force actuator for applying magnetic force to balance the loading force, and a speed sensor for dampness. As shown in figure 1, the displacement sensor, the force actuator and the speed sensor are mounted on the beam. The displacement sensor and the speed sensor are connected with the

electromagnetic force actuator through the displacement amplifier, the speed amplifier and the power amplifier. When given a certain torque to the device, the system will automatically measure the output torque through magnetic force produced by the electromagnetic force actuator. Through sampling output signals of the sampling resistance R, we can obtain the output torque. To realize indifferent equilibrium, the center of the beam needs to be located on the blade and that makes it work in the case of indifferent equilibrium.

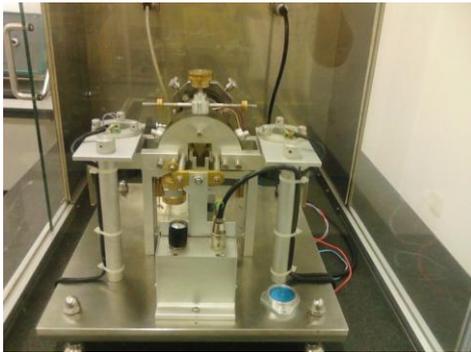The figures in fig. 2 to fig. 3 are the objects of the device.
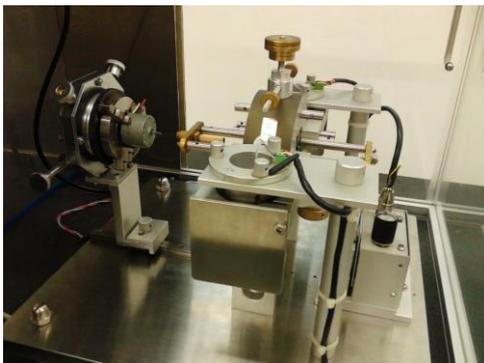


Figure 2 Frontal of the device



Figure 3 Side view of the device

## 2. CRITICAL TECHNIQUES.

The critical techniques of the device are as follows: Had the electromagnetic force balance principle and the indifferent equilibrium principle combined; Developed a new type of pendulum positioning support mechanism, solved the international problem of the relative position not being unique between blade and bearing, and improved the stability and accuracy; Developed the semicircular beam using the principle of the precise equal arm. The structure of the semi-circular beam is designed to reduce the measurement error compared with the device using the general long-structural beam; Realized the selfish calibration and error-free closed-loop fast tracking technology;

2.1 The application of electromagnetic power balance principle and indifferent equilibrium principle

The device is the innovation combining the electromagnetic power balance principle with the indifferent equilibrium principle of the mechanical balance.

The indifferent equilibrium is the basis for the realization of the error-free closed-loop automatic control. To realize the error-free closed-loop automatic calibration and tracking, the beam must be in the case of indifferent equilibrium. Only in this way, the error-free closed-loop automatic calibration and measurement system can be truly established. The key of realizing indifferent equilibrium and high sensitivity is designing the V-shaped knife-edge bearing, whose curvature radius is only 10-6m. By doing so, the center of the beam is fixed in the same position to achieve indifferent equilibrium.

2.2 The realization of the unique adjustment technology of the blade and knife-edge bearing

One of the key technologies to realize high precision lies in the uniqueness of the position between the blade and knife-edge bearing. If the position between the blade and knife-edge bearing is changed during the experiment, the whole circular beam will be dislocated, resulting in rubbing between the static and moving parts of the electromagnetic force actuator. All these will result in unstable and inaccurate calibration and measurement data.

Therefore, we developed a new type of positioning mechanism, which is the swing angle positioning support mechanism. This kind of swing angle positioning support mechanism is easy to use and easy to adjust, having high positioning accuracy, which ensures the position its uniqueness when the device is working, and also improves the stability and sensitivity of the device.

The swing angle positioning support mechanism has changed the positioning method of the traditional balance, and reduced the positioning reproducing error greatly. Meanwhile, it has solved the problem that the position is not unique between the blade and knife-edge bearing.

2.3 The application of the circular beam structure

Based on the principle of the uniform arm length, a circular beam structure is developed instead of a long-form beam. At the same time, a thin steel band is used in loading position. There is a small deflection angle when calibrating electromagnetic force actuator or measuring micro torque of micro motor. Due to using the circular beam, length of the beam will keep uniform at a random angle. The flexibility of the thin strip and the equal-arm beam characteristic can reduce measurement error and improve the measurement accuracy of the device compared to device with the long-form beam. The simple circular beam structure can increase the measurement precision of the system.

2.4 The realization of error-free closed-loop auto control and fast tracking technology

In order to make the electromagnetic torque of the electromagnetic force actuator express the standard torque uniquely, the error-free closed-loop auto control and fast tracking system needs to been formed. We adopted the technology of automatic control and precision measurement. The speed sensor, the displacement sensor and the electromagnetic force actuator are installed on the circular beam, which consist of automatic measurement system through connected test circuits. At the same time, the system is adjusted to meet the case of indifferent equilibrium through a variety of adjustments of the circular

beam. Therefore, the system's mechanical sensitivity is approximately infinite, and the control system becomes the error-free closed-loop auto control system. We can use electromagnetic torque to describe the standard torque value or measurement torque accurately.

## 3. UNCERTAINTY ANALYSIS

The device needs to be calibrated by weights before its actual employment. Namely, electromagnetic force generated by the electromagnetic force actuator has been calibrated by weights. Calibration method is adopted to make the standard torque generated by weight in order to balance the electromagnetic torque. The basic mathematical model can be expressed as:

$$M_A = M_m - \Delta M_\delta = mgL - \Delta M_\delta \qquad (1)$$

In the formula, $M_A$ denotes actual loaded torque value, $M_m$ denotes electromagnetic torque and $M_\delta$ denotes additional torque caused by uncoaxiality.

Therefore, the mass of the weight $m$, the length of the beam $L$, the coaxiality $\delta$ and electromagnetic force actuator need to been taken into account when evaluating uncertainty of the device. We use to $u(W)$ denote the relative uncertainty component caused by the mass of the weight, $u(L)$ to denote the relative uncertainty component caused by the length of the beam, $u(g)$ to denote the relative uncertainty component caused by the gravity acceleration in Shanghai, $u(\delta)$ to denote the relative uncertainty component caused by the coaxiality $\delta$, and $u(M_m)$ to denote the relative uncertainty component caused by the electromagnetic force actuator.

Synthetical measurement uncertainty

$$u_C = \sqrt{u^2(W) + u^2(L) + u^2(g) + u^2(\delta) + u^2(M_m)} \qquad (2)$$

Extended uncertainty

$$U_r = k.u_c \qquad (3)$$

## 4. TEST DATA ANALYSIS

The interference torque of some electromagnetic force actuator was measured with this device. The repeatability test was carried out three times. The original test data and repeatability results were shown in table 1.

After the uncertainty calculation and calibration by China Institute of Metrology, the technical indicators of the device are as follows: Measurement Range is $(0.2\text{-}10) \times 10^{-3}$ Nm and Measurement Uncertainty is $1 \times 10^{-3}$ ($k = 2$).

## 5. CONCLUSION

Uncertainty calculation and test data analysis shown that the device reaches the following indicators: measurement range is $(0.2\text{-}10) \times 10^{-3}$ Nm and measurement uncertainty is $1 \times 10^{-3}$ ($k = 2$). Simultaneously the device can measure $10^{-5}$ Nm torque, and the repeatability is close to 1%.

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Table 1 Test data and repeatability

| Current of electromagnetic force actuator (mA) | Test data for 1st (V) | Test data for 2st (V) | Test data for 3st (V) | mean(V) | Repeatability (%) | Corresponding torque value ($10^{-3}$Nm) |
|---|---|---|---|---|---|---|
| 1 | 0.00091 | 0.00091 | 0.0009 | 0.000907 | 1.10 | 0.01 |
| 2 | 0.00181 | 0.00182 | 0.00181 | 0.001813 | 0.55 | 0.02 |
| 5 | 0.00448 | 0.00449 | 0.00449 | 0.004487 | 0.22 | 0.05 |
| 10 | 0.00896 | 0.00896 | 0.00895 | 0.008957 | 0.11 | 0.09 |
| 20 | 0.01789 | 0.0179 | 0.01789 | 0.017893 | 0.06 | 0.18 |
| 50 | 0.04473 | 0.04474 | 0.04472 | 0.04473 | 0.04 | 0.44 |
| 100 | 0.08947 | 0.08948 | 0.08946 | 0.08947 | 0.02 | 0.90 |