



# Verification of a novel micro-torsion tester based on electromagnetism using an improved torsion pendulum technique



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## ABSTRACT

An optimized micro-torsion tester with high torque resolution, designed based on electromagnetism, is present. The torque capacity of this tester is  $1.3 \times 10^{-3}$  N m with resolution of  $4 \times 10^{-8}$  N m and the angle capacity is 115 deg with resolution of 0.016 deg. In order to verify the reliability of this tester, an improved torsion pendulum method is employed with the influences of damping, swing and axial force being carefully inspected. The same kind of copper wires with diameter of about 200  $\mu$ m are tested using both this micro-torsion tester and the improved torsion pendulum. The two kinds of results of shear moduli are very close, which verifies the reliability of the self-developed micro-torsion tester.

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## 1. Introduction

Torsion test, which can present pure shear stress conditions, is a smart and effective approach to study the shear deformation behaviors of materials because the results have definite physical meanings. For macro-scale specimens, the torsion test can be easily conducted by commercial torsion testing machines. The torque, greater than  $10^{-1}$  N m, can be strictly calibrated by standard machine [1]. However, for micro-scale specimens, the involved torque sharply drops to  $10^{-4}$  N m or even less. Commercial torsion testing machines are not suitable for these tests because their torque resolution is not good enough.

In order to fulfill this task, several kinds of torsion test techniques for micro-scale specimens have been developed [2–7]. In 1994, Fleck et al. [2] conducted the torsion experiments of copper wires to demonstrate the size effect in micro-scale, in which the glass fibers are employed as the torque sensor. Deadweight and pulley arrangement were used for the torque calibration. However, the friction of the pulley arrangement would affect the calibration results. In 2011, Lu and Song [3] replicated the torsion tests using glass fiber as torque sensor, which is calibrated using a commercial torque sensor. Surprisingly no size effect was found. However, it is a pity that the calibration data dispersion is up to 17% because the

capacity of the commercial sensor is about three orders greater than that of the glass fiber sensor. In 2011, Walter and Kraft [4] developed a torsion technique based on an atomic force microscope (AFM). The torque is calibrated by a tungsten fiber, whose shear modulus is assumed the same as bulk tungsten. However, one unresolved issue is whether or how well the shear modulus of tungsten fiber is equal to that of bulk material. Moreover, the accuracy of the tungsten fiber sensor is severely influenced by its size error, which is not described. In 2012, Liu et al. [5] developed a high-resolution torsion technique based on an automated torsion balance. The torque is measured by a tungsten fiber, whose torsion constant was calibrated by means of the torsion resonance method. In this study, size effect was found again on copper wires. In 2015, Song and Lu [6] adopted two MEMS force probes as the torque sensor to repeat the torsion experiments of copper wires, demonstrating no size effect again. Thus, different experiments give us inconsistent results, which arouse reasonable doubts about the reliability of the micro-torsion test techniques.

In contrast, the micro-torsion test technique developed by Huan [7] is based on electromagnetism, in which a coil is placed into a radial magnetic field for actuating and torque measuring. The torque is calibrated using electronic balance, which makes the torque measurement traceable. In the following work [7], metallic glass fibers were tested using this tester. However, the tested shear modulus is obviously lower than that of the bulk material, which introduces new doubt to this tester. Of course, it is not very reasonable to verify the test result of micro-specimen according to that of

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macro-specimen. Even so, it is necessary to present other evidences to verify the reliability of the novel micro-torsion tester.

Therefore, the torsion pendulum technique is introduced to fulfill this task. In 1947, Ke T S [8] firstly employed the torsion pendulum technique with the aid of damping oil to measure the internal friction and rigidity of wire specimen. For a long time, torsion pendulum test technique had nearly been the only method to obtain the shear modulus of wires. Most of them employed the simple harmonic oscillator where a mass (usually a flat disk) was suspended at the end of the wire [9–12]. However, there are a lot of factors influencing the results in practice, such as the damping, swing and axial force. Although a hood sometimes is used to decrease the air damping, the effect is not entirely clear [13]. In order to get the reliable results, the torsion pendulum technique should be improved firstly, with the influences of damping, swing and axial force are carefully considered.

Therefore in this paper, the same kind of copper wires with diameter of about 200  $\mu\text{m}$  are tested using both this micro-torsion tester and the improved torsion pendulum. The shear modulus is selected as the criterion to verify the reliability of the self-developed micro-torsion tester.

## 2. Micro-torsion tester

An optimized micro-torsion tester, designed based on electromagnetism, is presented, shown in Fig. 1(a). The actuating and torque measuring function is undertaken by a coil-magnet element, shown in Fig. 1(b). The coil can rotate when the current gets through it. The torque is proportional to the current if the magnetic flux density is constant. More details are presented in Ref. [7].

The structure of the optimized tester is shown in Fig. 1(c), in which the angle is measured by a non-contact inductive angular transducer in order to avoid the additional friction. The fork is actuated by the coil. One end of the specimen is fixed on upper grip and the other end is glued a cross bar, which is inserted into the fork. Compared with the original tester in Ref. [7], the optimization mainly embodies in the following aspects: (1) The uniformity of magnetic field is improved. That is to say, uniform magnetic field can be achieved in greater angle range. Thus the rotation angle range is increased from 90 deg to 115 deg. (2) The torque capacity is increased from  $1.1 \times 10^{-3}$  N m to  $1.3 \times 10^{-3}$  N m. (3) The specimen position adjustment is optimized. Four dimensions positioning stage (3D translation and 1D rotation) is used, which made it more convenient and accurate to adjust the position of the specimens with different lengths. (4) The tester became more artistic and portable after optimization. The optimized technical parameters are listed in Table 1.

Torsion tests were performed on copper wires (99.9% purity) with diameter of 200  $\mu\text{m}$  and gauge length of 5 mm using the

**Table 1**

Maintechnical parameters of the micro-torsion tester.

Technical parameters	Value
TorqueCapacity	$1.3 \times 10^{-3}$ N m
TorqueResolution	$4 \times 10^{-8}$ N m
Rotation angleCapacity	115 deg
Rotation angleResolution	0.016 deg

micro-torsion tester mentioned above. The exact diameter of each specimen is measured using optical microscope, as shown in Fig. 2. A hexagon paper-window was used to fix the specimen in order to avoid accidental damage. After the specimen had been fixed on the tester's grip, the paper-window was cut off and the test started with  $10^{-4}$ /s strain rate at the wire's surface.

For three specimens, the curves of shear stress–strain at surface present clear elastic–plastic behavior, shown in Fig. 2. The shear modulus of copper wire is  $27.72 \pm 1.67$  GPa, which is significantly less than that of bulk copper (nominal value 46 GPa [14]).

## 3. Torsion pendulum experiments

### 3.1. Experimental setup

An improved torsion pendulum is shown in Fig. 3. An oscillator is fixed on the middle of the wire specimen. Tensile stress was applied on the lower end of the wire in order to avoid swing of the oscillator. A non-contact laser displacement sensor (MTI Instrument, LTS-025-02) is used to measure the vibration of the oscillator. The measurement distance, range, accuracy, sensitivity and laser power of the sensor are 25 mm,  $\pm 1$  mm, 0.03% FSO, 0.25  $\mu\text{m}/\text{mv}$  and 1.2 mW respectively.

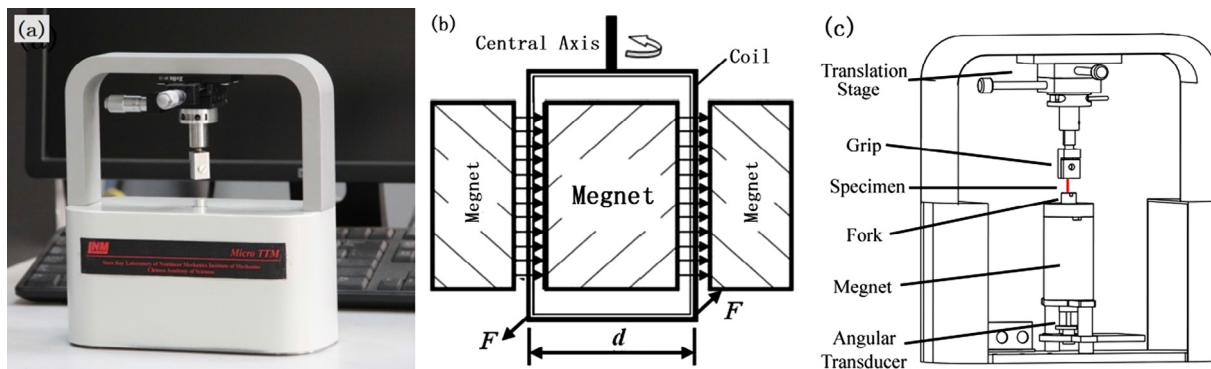
The frequency, coupled with damping, then is obtained, which meets the following formula [15]:

$$f_o = \frac{1}{2\pi} \sqrt{\frac{k}{I_c} - \frac{c^2}{4I_c^2}} \quad (1)$$

where  $f_o$  is the vibration frequency,  $I_c$  is the inertia moment of torsion oscillator,  $c$  is the damping coefficient of the oscillator system, and  $k$  is the torsion constant of the wire.

Here the torsion pendulum system can be regarded as two simple pendulums in parallel. Hence, the equivalent torsion constant is [15]:

$$k = \frac{G\pi D^4}{32} \left( \frac{1}{L_1} + \frac{1}{L_2} \right) \quad (2)$$



**Fig. 1.** Illustration of the micro-torsion tester: (a) the exterior view, (b) the detail of the coil-magnet actuator and (c) the schematic diagram of the structure.

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