



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



W. Liu <sup>a,b</sup>, Y. Huan <sup>a,b,\*</sup>, S.F. Wang <sup>a,b</sup>, B. Chen <sup>a,b</sup>, J. Dong <sup>a,b</sup>, Y.H. Feng <sup>a</sup>, D. Lan <sup>c</sup>, H.Y. Jia <sup>a,b</sup>

<sup>a</sup> State Key Laboratory of Nonlinear Mechanics (LNM), Institute of Mechanics, Chinese Academy of Sciences, Beijing 100190, China

<sup>b</sup> School of Engineering Science, University of Chinese Academy of Sciences, Beijing 100049, China

<sup>c</sup> Key Laboratory of Microgravity (National Microgravity Laboratory), Institute of Mechanics, Chinese Academy of Sciences, Beijing 100190, China

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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

\* Corresponding author at: State Key Laboratory of Nonlinear Mechanics (LNM), Institute of Mechanics, Chinese Academy of Sciences, Beijing 100190, China.

E-mail address: [huany@lnm.imech.ac.cn](mailto:huany@lnm.imech.ac.cn) (Y. Huan).

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.

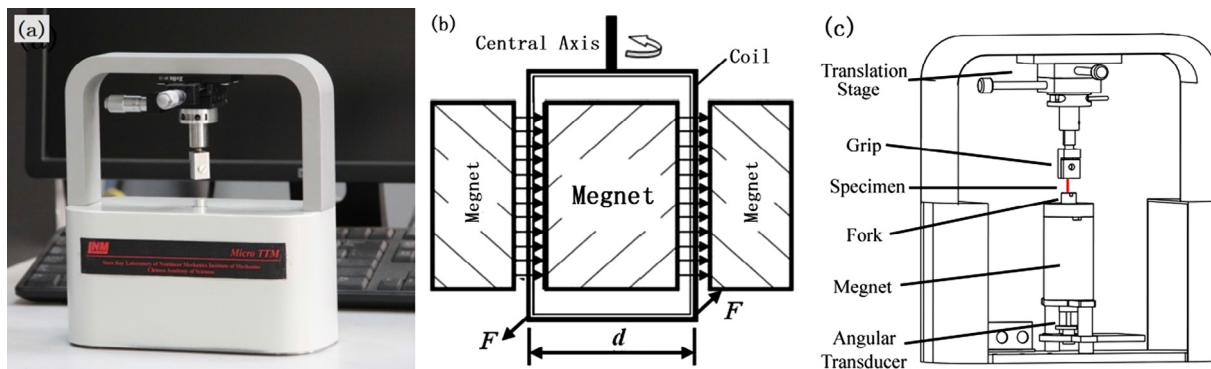
The frequency, coupled with damping, then is obtained, which meets the following formula [15]:

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

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.

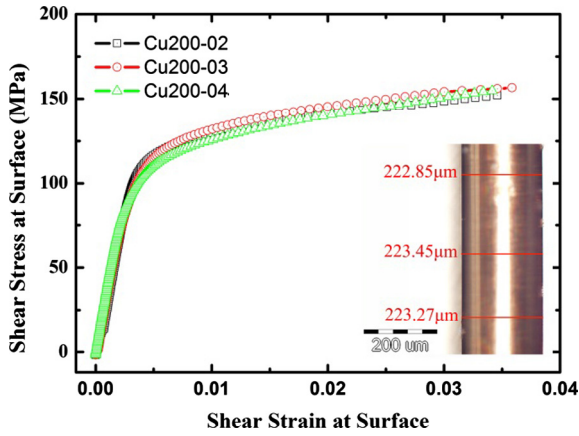


Fig. 2. Shear stress–strain curves at surface of three specimens.

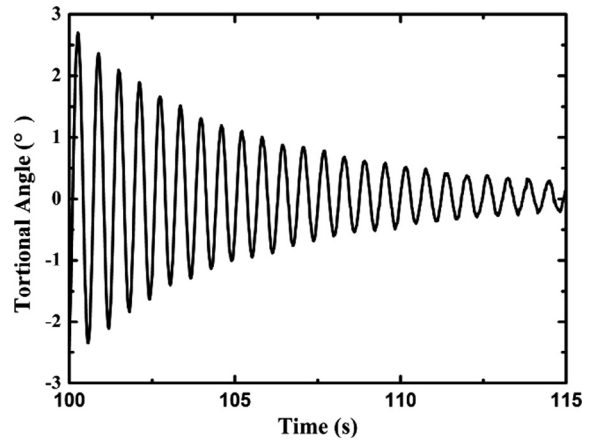


Fig. 5. Typical vibration curve of the torsion pendulum test.

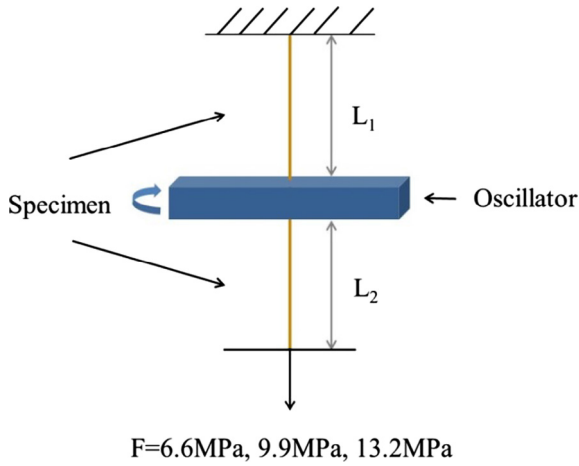


Fig. 3. The diagram of torsion pendulum apparatus.

where  $D$  is the diameter of specimen,  $L_1$  and  $L_2$  are the lengths of upper and lower segment of the wire respectively. The damping coefficient is calculated as [15]:

$$c = \frac{2I_c f_o \ln(\theta_m/\theta_n)}{n - m} \quad (3)$$

where  $\theta_m$  and  $\theta_n$  is the vibration amplitudes corresponding to times  $t_m = m/f_o$  and  $t_n = n/f_o$  respectively.

Substituting Eqs. (2) and (3) into Eq. (1), the shear modulus of the specimen can be obtained [15],

$$G = \frac{128\pi I_c f_o^2 L_1 L_2}{D^4 (L_1 + L_2)} \left\{ 1 + \left[ \frac{\ln(\theta_m/\theta_n)}{2\pi(n - m)} \right]^2 \right\} \quad (4)$$

Practically, this term  $\left[ \frac{\ln(\theta_m/\theta_n)}{2\pi(n - m)} \right]^2$  can be neglected since the effect of the air damping is usually less than 0.1%. Eq. (4) can be simplified as [15]:

$$G = \frac{128\pi I_c f_o^2 L_1 L_2}{D^4 (L_1 + L_2)} \quad (5)$$

### 3.2. Torsion pendulum tests of copper wires

The same copper wires (99.9% purity) as that used in micro-torsion tester, with diameter of 200  $\mu\text{m}$  and gauge length of 280 mm, were tested using this torsion pendulum. However, it should be noted that two extrinsic factors, tensile stress applied on the wire and the air damping to the oscillator, are not listed in Eq. (5). Therefore, in order to determine the influences of these two factors, each specimen was tested for 3 times with different tensile stress of 6.6 MPa, 9.9 MPa and 13.2 MPa. In addition, three kinds of oscillators with different shapes, shown in Fig. 4(a)–(c), were applied. For (a) and (b), the inertia moment is:

$$I_c = \frac{1}{12} m(l_0^2 + \delta^2) \quad (6)$$

and the effective area of air damping is:

$$A = l_0 d \quad (7)$$

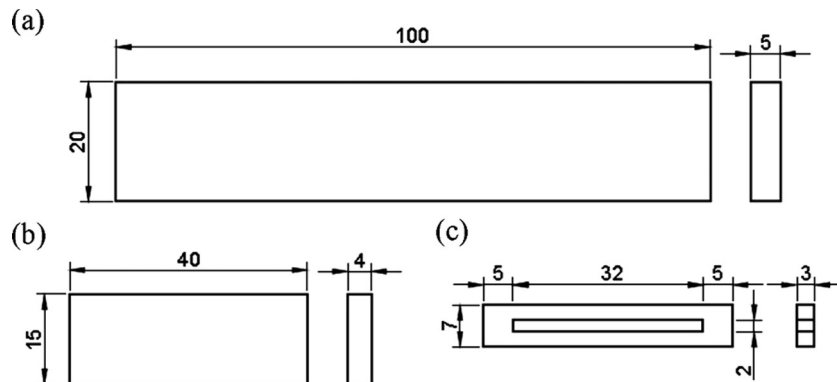
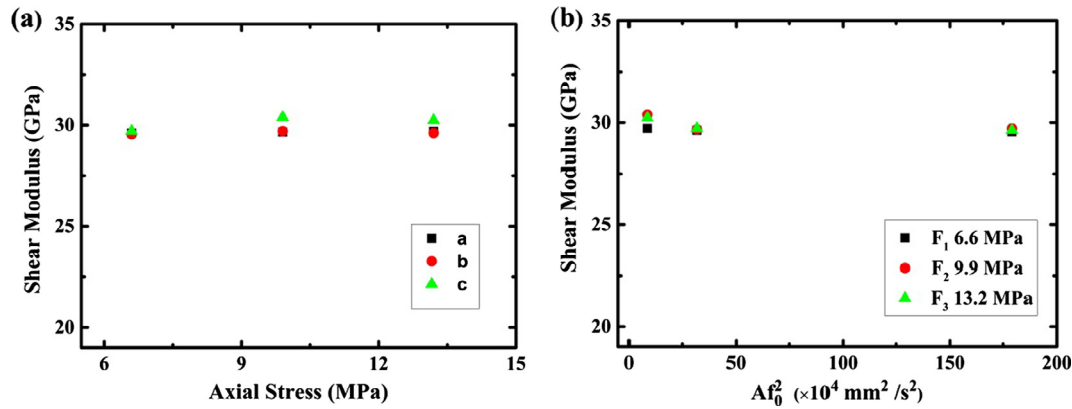


Fig. 4. Three oscillators with different shapes and different inertia moment.



**Fig. 6.** The results of the torsion pendulum test. (a) The shear modulus in different tensile stress: a, b and c represent three kinds of oscillators respectively. (b) The shear modulus for different shape oscillators:  $Af_0^2$  represents the change of the air resistance force.  $F_1$ ,  $F_2$  and  $F_3$  represent different axial tensile stresses.

For (c), these are,

$$I_C = \frac{1}{12} m \left( \frac{l_1^3 d_1 - l_2^3 d_2}{l_1 d_1 - l_2 d_2} + \delta^2 \right) \quad (8)$$

$$A = l_1 d_1 - l_2 d_2 \quad (9)$$

where  $I_C$  is the inertia moment of torsion oscillator,  $l_0$ ,  $\delta$ ,  $d$  and  $m$  is the length, thickness, breadth and mass of the oscillator respectively,  $A$  is the effective area of air damping.

Suppose the velocity of a certain point at the oscillator is  $v_p$ , at this moment, the air resistance force  $P$  of the oscillator is:

$$P = \frac{1}{2} C \rho \int v_p^2 dA \quad (10)$$

where  $C$  is the coefficient of the air resistance,  $\rho$  is the density of air. Additionally,  $v_p$  is directly proportional to the frequency  $f_o$ , namely  $v_p \propto f_o$ . Therefore, the air resistance force  $P$  is directly proportional to the product of  $f_o^2$  and  $A$ , namely  $P \propto Af_o^2$ . Hence, if  $Af_o^2$  is different from each other for different oscillator, the damping will be different.

A typical oscillation curve of the torsion pendulum is shown in Fig. 5 and the results are shown in Fig. 6. It can be observed that the tested shear modulus was nearly consistent under different tensile stress conditions, shown in Fig. 6(a). For different shape oscillators, the change of damping, corresponding to different value of  $Af_o^2$ , has little or no effect on shear modulus, shown in Fig. 6(b). Thus, it can be concluded that the air damping and axial force have little or no effect on shear modulus in this study. In addition, the swing has been avoided because the torsion pendulum is extended by axial force. The tested shear modulus of copper wire is  $29.80 \pm 0.28$  GPa, which is in good agreement with that ( $27.72 \pm 1.67$  GPa) measured by micro-torsion tester above.

#### 4. Conclusion

In this paper, an improved torsion pendulum technique was used to verify the reliability of the high-resolution micro-torsion tester developed by Huan [7] based on electromagnetism. The shear moduli of the same copper wires, with diameter of 200  $\mu$ m, were tested using the micro-torsion tester and the torsion pendulum respectively. Additionally, in torsion pendulum tests, the influ-

ences of damping, swing and axial force are carefully eliminated. The shear moduli obtained using two methods are  $27.72 \pm 1.67$  GPa and  $29.80 \pm 0.28$  GPa respectively, which are in good agreement with each other. In conclusion, the reliability of the novel micro-torsion tester is verified.

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#### References

- [1] A. Nishino, K. Ogushi, K. Ueda, Bilateral comparisons of measurement capabilities for the calibration of low nominal capacity torque measuring devices between NMIJ and PTB in the range from 0.1 N m to 10 N m using different procedures, *Measurement* 68 (2015) 32–41.
- [2] N.A. Fleck, G.M. Muller, M.F. Ashby, Strain gradient plasticity: theory and experiment, *Acta Metall. Mater.* 42 (1994) 475–487.
- [3] W.Y. Lu, B. Song, Quasi-static torsion characterization of micro-diameter copper wires, *J. Exp. Mech.* 51 (2011) 729–737.
- [4] M. Walter, O. Kraft, A new method to measure torsion moments on small-scaled specimens, *J. Rev. Sci. Instrum.* 82 (2011) 035109.
- [5] D.B. Liu, Y.M. He, X.T. Tang, H.M. Ding, P. Hu, Size effects in the torsion of microscale copper wires: experiment and analysis, *J. Scripta. Mater.* 66 (2012) 406–409.
- [6] B. Song, W.Y. Lu, An improved experimental technique to characterize micro-diameter copper wires in torsion, *J. Exp. Mech.* 55 (2015) 999–1004.
- [7] Y.J. Dai, Y. Huan, M. Gao, J. Dong, W. Liu, Development of a high-resolution micro-torsion tester for measuring the shear modulus of metallic glass fibers, *J. Meas. Sci. Technol.* 26 (2015) 025902.
- [8] T.S. Ke, Experimental evidence of the viscous behavior of grain boundaries in metals, *J. Phys. Rev.* 71 (1947) 533–546.
- [9] D.W. Hadley, P.R. Pinnock, I.M. Ward, Anisotropy in oriented fibres from synthetic polymers, *J. Mater. Sci.* 4 (1969) 152–165.
- [10] S.J. Deteresa, S.R. Allen, R.J. Farris, R.S. Porter, Compressive and torsional behaviour of Kevlar 49 fibre, *J. Mater. Sci.* 19 (1984) 57–72.
- [11] J.F. Villeneuve, R. Naslain, Shear moduli of carbon, Si-C-O, Si-C-Ti-O and alumina single ceramic fibers as assessed by torsion pendulum tests, *J. Compos. Sci. Technol.* 49 (1993) 191–203.
- [12] C.T. Fallen, J. Costello, G. Crawford, Measuring the elastic properties of fine wire, *J. Biomed. Mater. Res.* 58 (2001) 694–700.
- [13] C.L. Tsai, I.M. Daniel, Determination of shear modulus of single fibers, *J. Exp. Mech.* 39 (1999) 284–286.
- [14] www.matweb.com.
- [15] D.B. Liu, Y.M. He, X.T. Tang, P. Hu, A modified torsion pendulum for measuring the shear modulus of a single micro-sized filament, *Acta Mech. Solida Sin.* 27 (2014) 221–233.