

Design of Magnetically Levitated Mechanism for Micro-Scale Materials Multifunction Testing Device

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Abstract

This paper presents the structural design and working principle of a magnetically levitated mechanism developed for a multifunctional micro-scale materials testing device. To enable testing in special environments, the micro-scale specimen and essential levitated components should be physically separated from the main device, ensuring mechanical contact. The levitation mechanism of the device is designed using three U-shaped hybrid electromagnets and a plate float. With three HEMs, the system can achieve actively controls in three degrees of freedom, including linear motion along the Z axis and tilting motion around the X and Y axes. This guarantees that the levitation plate float can be remain horizontally levitated and held in a constant position in vertical direction. In addition, the working principles of the loading modes are also introduced. At last, to verify the levitation capacity of the system, a finite element analysis using JMAG is conducted to describe the relationship among levitation force, current, and air gap length.

Keywords : Magnetic Levitation Systems, Structure Design, Mechanical Testing Device, Micro-scale Specimens, Noncontact test

1. Introduction

The noncontact nature of magnetic levitation technology makes it a promising compact-actuator method in many industrial applications. The characteristic is also particularly attractive for materials mechanical testing, as there is no mechanical contact between the stator and specimen gripper^[1-3], which is expected to facilitate materials testing in special environment. Material testing machines (MTM) is used to test the mechanical behaviors of materials. Generally, such tests to be characterized is on macro-scale form. However, some materials, e.g., micro-electromechanical system (MEMS) only be obtained as micro-scale specimens^[4]. The fundamental feature of the micro-scale specimens is the micrometers-level in size, leading to very limited size space for support and actuation, which makes it difficult to develop multiple testing functions. As a result, traditional micro-scale materials testing machine (micro-MTM) usually offer only to a single testing function^[5-6]. In reality, many micro-scale materials are often subjected to multiple forms of mechanical loading. Therefore, in order to comprehensively evaluate the behavior of materials, a micro-scale materials multifunction testing machine is required.

An ideal stage for micro-MTM would be one that integrates multiple testing functions into a single system. Taking the advantages without any mechanical contact, maglev technology can produce much purer forces, as levitation strictly depends on the balance of forces. This characteristic is particularly beneficial for improving testing accuracy in micro-scale materials testing. Since maglev systems can provide both support and actuation using magnetic forces without cross-axis interference, device can easily be miniaturized. Thus, integrating multiple functions micro-MTM is possible. Furthermore, magnetic levitation technology is especially suitable for micro-scale materials testing in a special environment, such as ultra-clean or inert atmospheres, where mechanical contact and electronics components of traditional micro-MTM can be problematic^[1-3]. By separating the micro-scale specimen from the micro-MTM, maglev systems reduce environmental constraints on the device, making it possible to test micro-scale materials in various environments.

This paper focuses on the structural design concept of a magnetically levitated mechanism developed for a multifunctional micro-scale materials testing device. The general principles of the loading methods used in the micro-MTD are described, including tension, bending and torsion testing. In addition, the structure and components of the levitation system are presented in detail.

2. Objective Function

Tension, bending, and torsion test are the most fundamental methods for evaluating the mechanical properties of materials, as they represent the primary deformation modes encountered in practical applications. The three methods are therefore widely adopted in micro-scale materials testing. Accordingly, the micro-scale materials multifunction testing device is designed to provide the three types of tests. The general principle of the loading method is illustrated in Fig. 1. Fig. 1(a) shows the initial state of the micro-scale specimen and levitation components. During the test, the upper part of the specimen should be held at a fixed height and angle by magnetic force, while the lower part should be pulled downward, tilted, or twisted through magnetic force actuation, thereby applying a tension force, bending moment, and torsion moment to the specimen, as illustrated in Fig. 1(b)-(d), respectively. In other words, tension can be applied along the central axis, bending moments can be applied perpendicular to the central axis, and a torsion moment can be applied around the central axis.

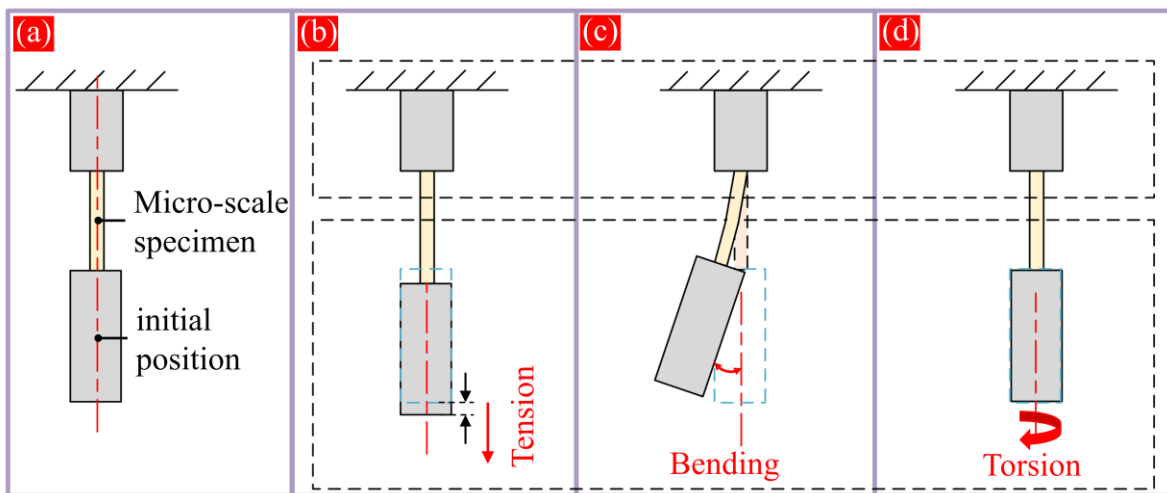


Fig. 1 Schematic of the loading method implementation of micro-scale materials multifunction testing device.

3. Design concept of the Levitation Mechanism

The concept of levitated system is developed for a three-degrees-of-freedom (DOFs) system using three U-shaped hybrid electromagnets (HEM: HEM1, HEM2, and HEM3), as illustrated in Fig. 2. As can be seen from the Fig. 2(b) and (c), the three HEMs are mounted on the upper plate and the corresponding magnetized target iron is mounted on the aluminum circular plate to form a levitation plate float. Each HEM is shown in Fig. 2(d), which consists of a permanent magnet, and two identical cores with coil and a coil frame. Structurally, the three HEMs are evenly distributed around the circular path with an angle of 120° between two adjacent HEMs, which can be controlled individually. Each levitation unit consists of one HEM and levitated plate float, as shown in Fig. 2(e).

In the device, the levitated float and the micro-scale specimen are magnetically suspended in a closed container, whereas the other assemblies are arranged out of the container. This container is thus able to separate out the micro-scale specimen from the main device, which create a special environment. Moreover, during testing, during the test, the levitated float need to remain horizontally levitated and held in a constant position.

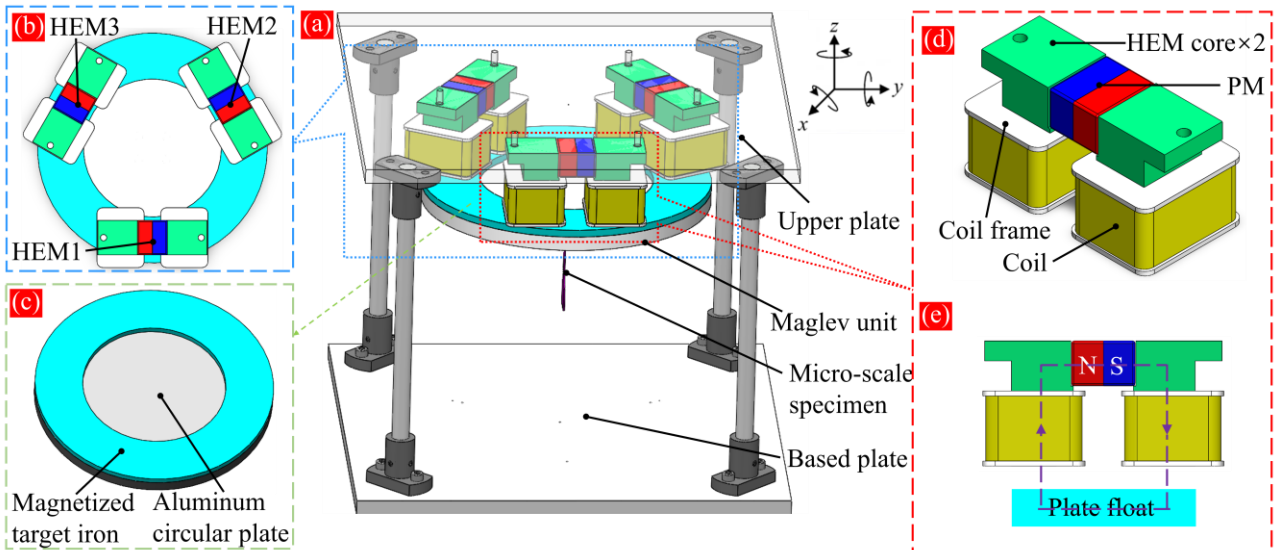


Fig. 2 Three-dimensional model of Levitation System. (a) Triaxial view of the system. (b) Bottom view of the three HEMs mounted on the upper plate (c) Isometric view of the levitated plate float. (d) Isometric view of each HEM. (e) Model of the maglev unit.

The levitation force analysis of the levitated plate float is shown in Fig. 3. With magnetized target iron, each HEM generates a magnetic force along the Z-axis, denoted as F_1 , F_2 , and F_3 for the three maglev units, respectively. The resultant force will be the levitation force. Furthermore, due to the symmetrical arrangement, the three HEMs can generate a tilt-controlling moment around the X and Y axes by individually adjusting the magnitude of each magnetic force. In other words, this configuration provides the system with the capability to resist tilting moment. Therefore, with three HEMs, the levitated plate float can be actively stabilized in three degrees of freedom, including linear motion along the Z axis and tilting motion around the X and Y axes. Note that the levitation plate of the levitation mechanism needs to remain horizontally levitated and held in a constant position, and thus the force balance and moment balance of the levitation plate must be satisfied.

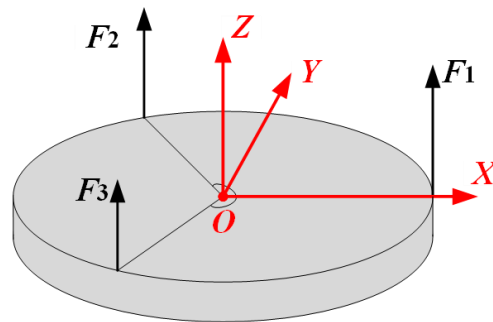


Fig. 3 Schematic diagram levitation force of the levitated plate float.

To verify the levitation capacity of the system, an example of levitation force analysis using JMAG software is shown in fig. 4. The result is used to describe relationships among the levitation force, current, and air gap length. The specific parameters of HEM are listed in Table 1. As shown in Fig. 4, when the air gap is 5 mm and the current is 4.085 A, the total levitation force generated by the three HEMs reaches approximately 200 N. This air gap length is selected based on the estimated container thickness of about 3 mm, making 5 mm the expected working distance. The current of 4.085 A also corresponds to the maximum allowable continuous current for the HEM coils.

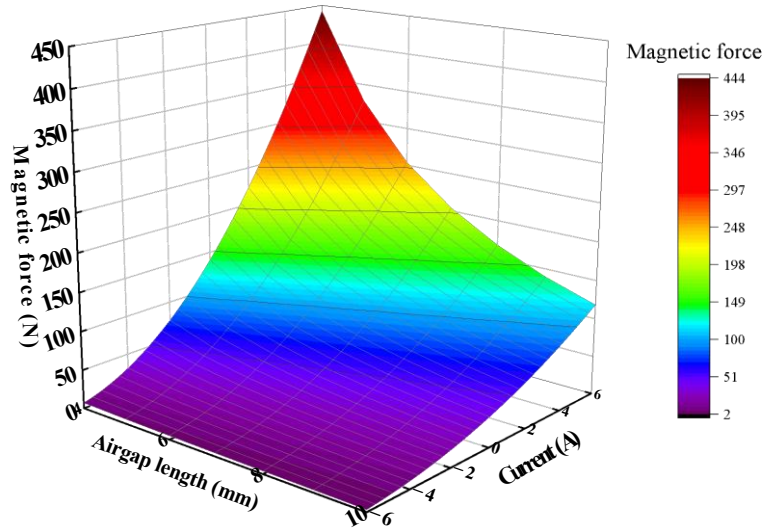


Fig. 4 FEM analysis results of magnetic force.

Table 1 Main specific parameters of HEM.

Parameters	Material/Value
Permanent magnet dimensions(mm)	30 × 25.4 × 18
Permanent magnet material	NdFeB N50
Number of turns per coil	250
HEM core material	SS400
HEM core sectional area(mm)	18 × 30
magnetized target material	SS400

4. Conclusion

This study focuses on the design and analysis of the levitation mechanism used in a micro-scale materials multifunctional testing device. A three-HEM configuration is proposed to realize active stabilization in three DOFs while providing sufficient levitation force to suspend test components. The design allows for future application in special environments, enabling noncontact test of micro-scale specimens. A finite element simulation example of the levitation force was carried out to verify that the system’s levitation capability under the expected air gap and current conditions. Future work will focus on design tension, bending, and torsion mechanism to complete the system, and then will make a prototype to perform the testing function.

References

Ren, M. and Oka, K., Design of a noncontact bending testing device using magnetic levitation mechanism, *IEEE Transactions on Industrial Electronics*, Vol.71, No.2 (2023), pp.1697–1707.

Ren, M. and Oka, K., Design and analysis of a non-contact tension testing device based on magnetic levitation, *IEEE Access*, Vol.10 (2022), pp.19312–19332.

Ren, M. and Oka, K., Design of a noncontact torsion testing device using magnetic levitation mechanism, *Actuators*, Vol.12, No.4 (2023), Article No. 89.

Xu, J., Nomura, M., Endo, M. and Toyoda, T., Specimen dimension and grain size effects on deformation behavior in micro tensile of SUS304 stainless steel foil, *Materials Transactions*, Vol.54, No.6 (2013), pp.984–989.

Wang, G., Wang, Q., Wang, Q., Luo, J. and Yang, R., Superplasticity and micro-arrayed deep-drawing behavior of Ni-Co/GO nanocomposite, *Journal of Materials Engineering and Performance*, Vol.26, No.12 (2017), pp.4760–4767.

Gorji, M. B., Furmanski, J. and Mohr, D., From macro-to micro-experiments: Specimen-size independent identification of plasticity and fracture properties, *International Journal of Mechanical Sciences*, Vol.199 (2021), 106389.