論 文 内 容 の 要 旨

1. Research background

Magnetic levitation(Maglev) can avoid mechanical contact between two parts, due to this advantage, it has been used in various industrial applications, such as magnetic bearings, maglev trains and bearingless motors. In addition to these applications, in this dissertation, we first proposed applying magnetic levitation to noncontact mechanical testing devices, which allow specimens to be separated from testers, thus is expected to be used for mechanical tests in special environments. Special environments include vacuum, flammable gases and corrosive liquids, etc., as well as environments with abnormal air pressure or temperature, which may greatly influence the mechanical performance of parts or materials, and some parts or materials need to work in special environments, such as gas-lubricated bearings, silicon-based photonic chips and high-purity aluminum. Therefore, it is necessary to facilitate the mechanical tests in special environments. Previously, if we wanted to test some parts or materials' mechanical properties in special environments, a whole mechanical tester attached with a specimen had to be placed in special environments. However, the problem is, some parts of the tester are sensitive and cannot work under various special environments, such as some circuits in the force sensors and actuators of the tester. On the contrary, with magnetic levitation, the specimen can be separated from the tester, as a result, only the specimen and few magnetic fixtures need to be placed in special environments, which avoids exposing the sensitive parts of the tester to special environments, greatly reducing the difficulty of the mechanical tests in special environments.

Following the above concept, we have developed three types of noncontact mechanical testing devices using maglev mechanism, i.e., magnetic levitation bending testing device(MBTD), magnetic levitation tension testing device(MTTD) and magnetic levitation torsion testing device(MTOTD). In addition, another device has been designed and is being made, that is magnetic levitation multi-function testing device(MMTD), which integrates tension, shearing and torsion into one unit. In this abstract, to comprehensively introduce this research, first of all, we introduce the four devices one by one, then, based on research finding, we draw several core issues for this novel application of magnetic levitation.

2. The devices we developed in this dissertation

(1) Magnetic levitation bending testing device(MBTD)

In this work, a noncontact bending testing device(MBTD) using magnetic levitation was developed. With FEM analysis, a structure allowing four levitation degrees of freedom to be passively controlled was designed. Experiment demonstrated that the structure can guarantee the passive stability of the four degrees of freedom. In addition, a fixed stiffness-damping controller was designed to maintain the levitation under the bending force, and a force control system was designed to control the loading of the bending force. The experiment results with the high-stiffness specimen demonstrated that FSD controller allow the device to withstand a bending force up to 50N at the rate of 1N/s while maintaining the levitation stable. The experiment results with the low-stiffness specimen demonstrated that the force control system allows the device to load the bending force smoothly even under large deflection.

Furthermore, to explore different possibilities, an adaptive sliding model controller(ACSMC) was proposed to allow the device to bear different kinds of bending force. Control simulations were conducted to investigate the performances of the controller, simulation results demonstrated that ACSMC has the good performance in compensating for three kinds bending load(Ramp, sinusoidal and step). Finally, experiments were performed with ACSMC, experiment results demonstrated that ACSMC allows the device to withstand ramp bending load, sine bending load and step bending load up to 50N.

(2) Magnetic levitation tension testing device(MTTD)

In this work, a noncontact tension testing device(MTTD) using magnetic levitation was developed. First of all, to guarantee the alignment of the tension force, the magnetic characteristics of three shapes of floators were investigated via FEM analysis. It was found that a ring floator combine the advantages of strong magnetic force, low mass, and easy alignment of the tension force. Also, the structure of the device was minimized while ensuring sufficient magnetic force. In addition, a centralized feedback linearization control algorithm was proposed for the device. Furthermore, control simulations demonstrated that the proposed feedback linearization control algorithm has satisfactory dynamic performance and robustness even in the case of a mismatch between the controller and the plant. Moreover, an SVM-based model for estimating specimen elongation was established. After iterative optimization and correction, the final estimation model performed with the estimation error range of -0.1988mm to 0.2269mm, RMSE of 0.0843mm and

$R2$ of 98.76%. Finally, a levitation experiment and a tension experiment are given to prove the feasibility of MTTD. Levitation experiment results demonstrated that the proposed feedback linearization controller has better dynamic performance than PD controller. The tension experiment results indicated the prototype can withstand a tension force up to 37N. Combining the two kinds of experiment results, it is concluded the centralized feedback linearization controller is much better than traditional PID controller in both step response and tension experiments, but it performs well in tension experiments only when used in conjunction with internal force compensation methods.

(3) Magnetic levitation torsion testing device(MTOTD)

In this work, a noncontact torsion testing device(MTOTD) using magnetic levitation was developed. First of all, to ensure the stability of the six levitation degrees of freedom, four levitation Degrees of freedom are passively controlled by some permanent magnets, while two levitation Degrees of freedom are actively controlled by four electromagnets. Furthermore, a plant model was built for the control of the two levitation degrees of freedom. With the plant model, two PD controllers were designed, and the simulation result demonstrated that the designed PD controllers make the system have good dynamic performance. Finally, an experiment was performed to test the stability of the levitation and the torque load capacity. The experiment result indicated that the device can apply a 0.126 N·m noncontact torque to the specimen while maintaining levitation. Currently, the control mode of the torque is open-loop, which makes it impossible to accurately control the amount of torque. In the future, a torque feedback system will be constructed using torque sensors to apply the desired amount of torque.

(4) Magnetic levitation multi-function testing device(MMTD)

In this work, a noncontact multi-function mechanical testing device(MMTD) using magnetic levitation mechanism was designed. A preliminary structure and mechanism were designed. Furthermore, the reasonability of the structure and mechanism was verified by FEM analyses and control simulations. The simulation results demonstrated that the designed structure and mechanism are reasonable, and the levitation system has good stability and robustness under the maximum tension force, compression force, bending force and torque.

Moreover, we added two superconducting magnetic bearings using II-type superconductors in the design to introduce passive mechanisms for MMTD, FEM analysis was conducted to calculate the radial stiffness and axial stiffness the superconducting magnetic bearings can provide. With the calculated values of the radial stiffness and axial stiffness, it can be concluded that the superconducting magnetic bearing can provide enough support for the levitation, compression and shearing instead of the original parts.

3. The core issues of the development of magnetic levitation mechanical testing devices

(1) How to maintain levitation under large range of load forces

In this research, generally, the specimen has two sides, one is levitation side where the weight is hold and also where all the degrees of freedom are fixed, the other one is load side, where load forces are applied. For ordinary magnetic levitation, we only need to consider the levitation side, but in this research, we need to consider not only the levitation, but also how to maintain the levitation under load forces. For ordinary magnetic levitation, traditional PID controller derived based on a linearized and simplified magnetic force model, is widely used, and fixed PD gains are enough to hold the levitation. But in this research, to compensate for large range of load forces, the current of electromagnet used for levitation also need to work in wide range, which will cause the nonlinearity of the magnetic force to appear. Therefore, fixed PD gains are only effective when the range of load force is small. As a solution, we scheduled the PD gains of a PID controller according to the load force, so that the same dynamic characteristics of the levitation can be maintained even the load force change on a large scale. In addition, we also used some other nonlinear control methods, such as feedback linearization, sliding mode control, they can also solve this problem. And the principle of these nonlinear control methods are essentially the same, i.e., scheduling PD gains in real time. In a word, this problem was solved by gain scheduling. Finally, MBTD can bear 50N bending force, MTTD can bear 37N tension force and MTOTD can bear 120N· mm load torque while maintaining stable levitation.

(2) How to save control hardware used for levitation while stabilize all the degrees of freedom of levitated objects

The second issue is, in the levitation side, all the six degrees of freedom need to be fixed without contact, which means the six degrees of freedom need to be absolutely stabilized. The general method to stabilize levitation degrees of freedom is active stabilization, however, actively stabilizing six degrees of freedom costs six actuators and six displacement sensors, which is not cost-effectively. As a solution, during the design, we tried to take advantage of passive stability, i.e., inherent stability obtained through some special structural configurations, which doesn't require any actuators or displacement sensors. To get as much passive stability as possible, we take full advantage of all kinds of possibilities that can create passive stability, e.g., edge effect of magnetic circuit, repulsive force of permanent magnet and special topological structure. As a result, all the three devices(MBTD, MTTD and MTOTD) have only two degrees of freedom that need to be actively stabilized.

(3) How to control noncontact load forces(Magnetic forces) when airgaps at load sides decreases irregularly

The third issue is, when the specimen is deformed, the load sides' airgap will change, which will influence the control and loading stability of the load force. In addition, specimens of difference materials will cause different deformation characteristics, which lead to much irregularities. This problem was especially pronounced on MBTD. To solve this problem, first of all, we built a plant model for the deformation, the specimen was simplified to a spring and damper in the plant model. In addition, we collected some typical materials' stiffness and damping for analysis, with these material data, we did simulation and found PI controller and force feedback control are effective in maintaining force loading stability for most materials. Furthermore, we deduced the conditions that make the force feedback control system stable, that is, as long as the P gain of the PI controller is large enough, the force control system will be stable for most materials.

(4) How to add passive stabilization mechanisms to MMTD

Based on the success of the above three device experiments, we tried our best to integrate the functions of tension, compression, shearing and torsion into one unit. Finally, we designed the preliminary structure of MMTD, and the feasibility of the preliminary structure was verified by simulations. Although the preliminary structure could provide considerable load forces, it requires all the degrees of freedom to be actively controlled, in addition, to provide sufficient forces, some parts' coil turns are too much. Too many coils will aggravate power loss, therefore, we considered introducing some passive mechanisms to reduce coils and save control hardware. Generally, there are three ways to achieve passive stability, i.e., special configuration of magnetic circuit, using repulsive forces of permanent magnets and using superconductors. Getting passive stable configuration of magnetic circuit take luck, and due to the structural complexity of MMTD, we think it is difficult to design passive stable configuration of magnetic circuit. Using repulsive forces of permanent magnets can easily get passively stable degrees of freedom, however, it will inevitably cause the instability on the other directions of degrees of freedom, although the other directions of degrees of freedom can be stabilized by adding active mechanisms, it will inevitably influence the load amount in other directions, which is not acceptable for a multi-function testing device, because applying different directions of load forces independently is a basic function for a multi-function testing device. By utilizing the magnetic flux pinning characteristics of II-type superconductors in a magnetic field, some degrees of freedom can be passively stabilized without affecting the stability or forces in other directions, which is very suitable for this case. Ultimately, we decided to use II-type superconductors to add passive stabilization mechanisms for MMTD.