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超精密机床宏/微双驱动微位移机构的设计与控制

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摘要：提出了一种宏/微双驱动微进给机构的设计与控制方法。介绍了宏/微双驱动微位移机构的结构设计，将宏动（大行程）和微动（高分辨率）两者串联以获得理想的运动性能。该机构用步进电机作为宏动的驱动装置以获得大行程和高响应速度，用压电陶瓷微位移器作为精密运动以提高运动分辨率和运动精度。设计了该机构的控制系统，用一个基于模型的开关控制器对微位移装置进行控制，并设计专门的运动分配模块对宏/微运动进行协调控制。最后，分别控制宏动和微动装置对该系统进行了实验，并用激光干涉仪检测。检测结果表明，宏动装置的行程为 90 mm，运动分辨率为 0.3 μm；压电陶瓷微动装置的行程为 40 μm，定位精度为 0.9 μm。理论分析和实验结果均表明了控制策略的有效性。

关 键 词：双驱动微位移器；开关控制器；控制策略
中图分类号：TH703.8 **文献标识码：**A

Design and control of dual-stage feed drive system in ultra-precision machine tools

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Abstract: The design and control of a Dual-stage Feed Drive (DSFD) system on a ultra-precision machine is presented. The DSFD system combining coarse (large stroke) and fine (fine resolution) drive stages in series is designed to provide the desired performance, in which a step motor is used for the coarse motion to obtain the large stroke and fast response speed, and a piezoelectric micro-actuator for the fine motion to achieve the high resolution and accuracy. A control system for the mechanism is developed based on a multiple model-based switching controller, and a movement distribution module is designed for the motion coordinations of coarse and fine movements. Finally, a experiment is undertaken by controlling both stages separately for the actual position on the DSFD system and a measurement is carried out by a laser interferometer. The experimental results show that the step motor has a working stroke of 90 mm with the displacement resolution of 0.3 μm and the piezoelectric micro-actuator has a working stroke of 40 μm with the positioning accuracy of 0.9 μm. The theoretical and exper-

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imental results show the validity of the control algorithm.

Key words: dual-stage drive micro-displacement system; switching controller; control algorithm

1 Introduction

Nowadays, high-bandwidth motion control systems are employed as a broad range of applications such as scanning microscopy, fast steering mirrors, servo tools and many adaptive structures[1-3]. Especially in ultra-precision machining field, a precision machine is required to provide versatility, fast speed and large work space as well as high-precision positioning. Furthermore, owing to the development of ultra-precision machining technology, high-precision positioning over a large work space has become one of the most important features[4-5]. The concept of the macro/micro dual-drive was first proposed by Andre Sharon[6] of Massachusetts Institute of Technology in 1984, which was used for solving the contradictions between the broad range and the high precision in robot motion control. Since then, it has been received wide attention and applications. For more than twenty years, the macro/micro dual-drive mechanism has presented unique advantages in many aspects, not only theory demonstrations but also actual applications. It has been proved that it′s an effective means to realize high-precision positioning in a broad range.

2 Common micro-displacement mechanisms in ultra-precision machine tools

Now, three types of mechanisms are widely employed for high-precision positioning in ultra-precision machines.

2.1 Leading screw pair

This is a traditional mechanism, which plays a leading role especially in early precise machine. However, there are a series of intermediate links existing in this structure from motor spindles to tool bits, such as coupling, screws, nuts, bearings and so on. In the motion process, these mechanical components bring the elastic deformation, friction, reverse gap, etc, which restrict the improvement of machine accuracy.

2.2 Piezoelectric micro actuator

Compared with leading screw pair, piezoelectric micro actuator has a much higher accuracy. Moreover, it has many excellent features such as fast response, large output force and low power consumption, etc, and thus receives extensive attention and applications. But owing to its structural constraints, this kind of actuator is limited in the workspace, which is usually on the magnitude from a few microns to several hundred microns.

2.3 Linear motor

Linear motor (LM) makes up the disadvantages of the above mechanisms, which has both a high accuracy and a large workspace. Nevertheless, the last effect and output volatility of linear motor limit its application range.

3 Macro/micro dual-stage feed drive mechanism

3.1 Structural design of mechanism

Fig. 1 presents the macro/micro dual-stage feed drive mechanism developed in this paper. The mechanism presented here combines the coarse drive stage with the fine drive stage to provide precise positioning in a broad range. It consists of a step motor for coarse motion and a piezoelectric micro actuator for fine motion. The macro motion component employs a step motor to drive a screw nut, so that it can provide a broad-long range positioning. The micro motion component employs a flexure base to improve the system positioning accuracy and response frequency, which is directly driven by a piezoelectric micro actuator (WTYD type).

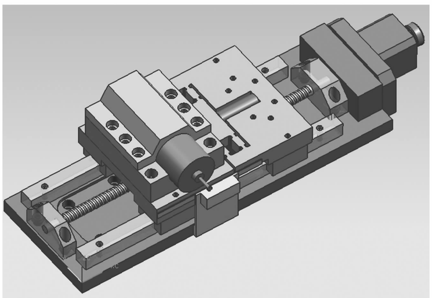


Fig. 1 Macro/micro dual-stage feed drive mechanism

In order to ensure the linearity in the direction of movement and avoid the cross coupling displacement in the vertical direction of movement, a double parallel flexure hinge base is designed (shown in Fig. 2). Owing to its structural symmetry, this mechanism can provide strict linear motion. It overcomes the shortcoming of single parallel flexure hinge base from the principle, which easily introduces cross-coupling displacement, and is preferred structure of precise micro-displacement mechanism.

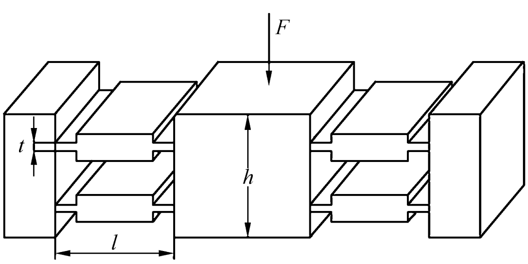


Fig. 2 Simplified model of double parallel flexure hinge base

3.2 Finite element analysis of mechanism

The stress and stiffness characteristics of the flexure hinge base are separately analyzed by static analysis and modal analysis. Fig. 3 and Fig. 4 show the nephograms of node displacement and average stress of nodes separately. We can get that the maximum stress appears in the root of the flexure hinge base. When loaded 200 N,

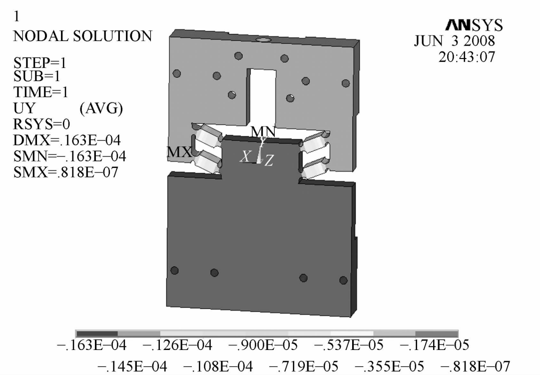


Fig. 3 Nephogram of node displacement

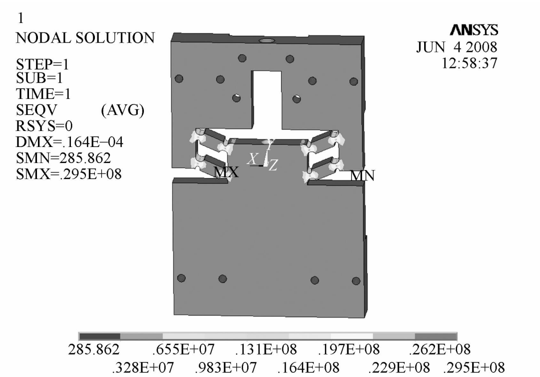
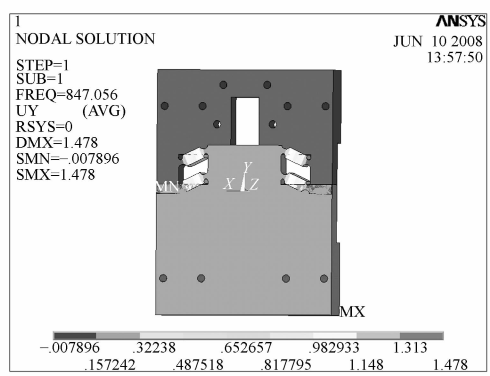
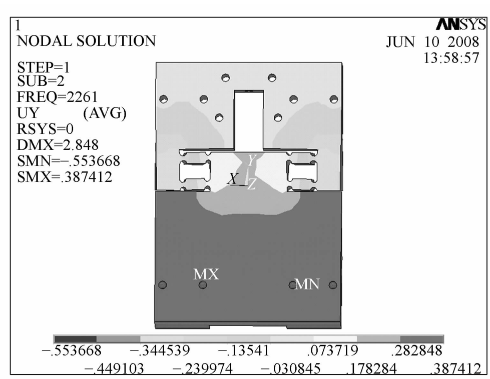


Fig. 4 Nephogram of average stress of nodes



(a) The first order modal shape



(b) The second order modal shape

Fig. 5 Modal shapes of flexure hinge base the maximum stress value is $\sigma_{max} = 29.5$ MPa, and the displacement value in the working direction is 16.3 μm. So we can get that the stiffness of the mechanism is 12.2 N/μm.

Fig. 5 shows the first two modal shapes of the flexure hinge base gained through modal analysis. From the figure, the first two natural frequencies are 847 Hz and 2 261 Hz separately.

4 Control strategy of macro/micro dual-stage feed drive mechanism

For the dual-drive mechanism, the output trajectory is the result of the two moving components working together in series. The improvement of control accuracy is the common results of high positioning accuracy of each moving component and the coupling of two moving parts[7]. So that the key of motion control system is the movement coordination of the two parts. Therefore, in this paper, on the basis of increasing the moving accuracy of individual component, the movement coordination of the two parts is controlled to improve the whole system accuracy.

In this paper, a multiple model-based switching controller (MMBSC) is designed for the coordination of the two parts. The step motor is controlled by using a feedforward controller which is connected with a feedback controller in series to ensure excellent disturbance rejection and a fast response in a board range, while the piezoelectric micro actuator is controlled with a

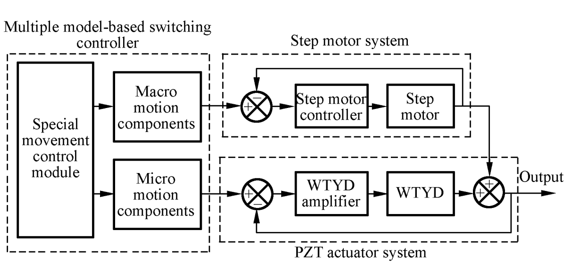


Fig. 6 Block diagram of the control system

preisach model to reduce its hysteresis. Besides, a special movement control module is designed for the movement distribution of the two parts. The control system block diagram is shown in Fig. 6.

5 Experimental results

In order to measure the availability of the dual-stage feed drive system, experiments are carried out, of which the objective is to measure the moving characteristics of the system. The testing results will help to evaluate the performance of the dual-stage feed drive system. From the actual measuring results gained by a laser interferometer, the working stroke of the step motor is 90 mm, with the displacement resolution of 0.3 μm. The working stroke of the piezoelectric micro actuator is 40 μm. The positioning accuracy of the piezoelectric micro actuator is 0.9 μm. Fig. 7 presents the tracking feature of the step motor system, and Fig. 8 shows the tracking feature of the piezoelectric micro actuator.

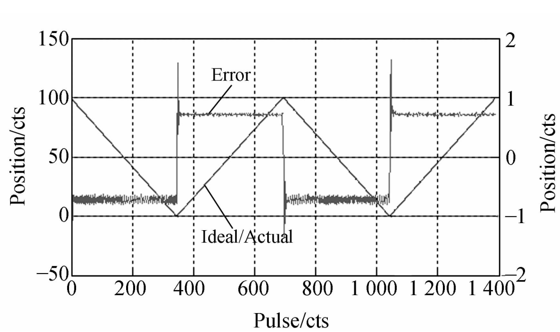


Fig. 7 Tracking feature of step motor system

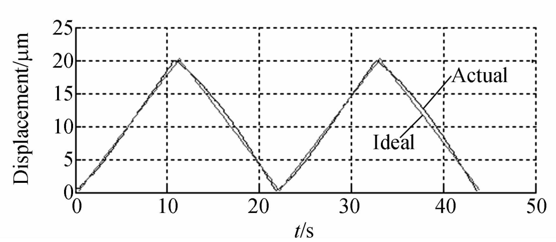


Fig. 8 Tracking feature of piezoelectric micro actuator

6 Conclusions

In this paper, we have presented the design and analysis of a dual-stage feed drive system in ultra-precision machine tools using newly developed MMBSC approach. The mechanism demonstrates good stress and stiffness characteristics in theory by finite element analysis. The stiffness of the fine drive stage is 12.2 N/μm, and the maximum stress value is $\sigma_{max} = 29.5$ MPa when loaded 200 N. Both the theoretical and experimental results show that the designed mechanism can be applied to ultra-precision machine tools.

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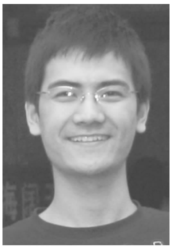

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