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Design and Control of an Ultraprecision Stage Used in Grating Tiling

Abstract: Theory and experiment have demonstrated that the coherent addition of multiple small gratings to form a larger grating is viable, an approach referred to as grating tiling, and the key technology of which is to control the relative position and orientation of each grating with high precision. According to the main factors that affect the performance of the tiled grating, we develop a five-DOF ultraprecision stage for the tiled grating experiment. The design and control of the mechanism is discussed and part of experiment results is presented.

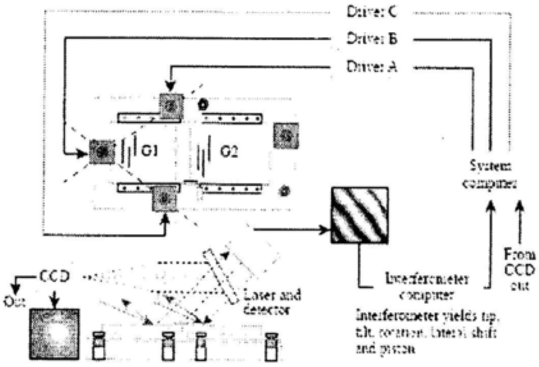
Key words: grating compressor; tiled grating; flexure mechanism; piezoelectric actuator

0 INTRODUCTION

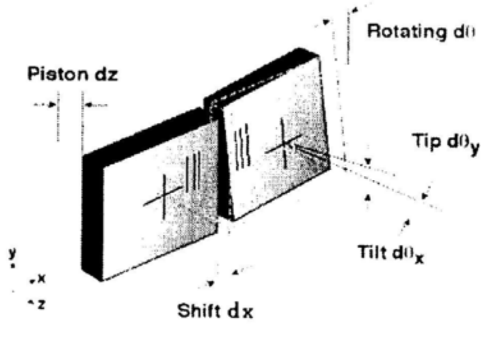
In the ICF project, to acquire high laser power output with several fs or ps short-pulse, diffraction grating with large aperture is necessary to compress the short laser pulse. The grating aperture of the pulse compressor is not less than 600mm×800mm. To get higher diffraction efficiency and higher damage threshold, it's recommended that the multilayer dielectric diffraction (MLD) is used. At the present time, the largest aperture of this kind of grating made by LLNL is 807mm×417mm [1], which is too expensive for the reason of difficult fabrication process. The MLD developed by ourselves is about 400mm×300mm, which can't satisfy the requirement of grating aperture 800mm×600mm at least for the petawatt laser system. So it's critical to resolve the problem of diffraction grating with large size aperture. As an alternative to this is the coherent addition of multiple gratings to form a larger grating with meter-sized aperture. We refer to this alternative as grating tiling. Namely, by the means of adjusting the relative position of several subaperture gratings with same optical parameters which are mounted adjacently to form a larger tiled grating, the phase error of them is small enough and will act as a monolithic optical element.

1 DESSCRIPTION OF TILED GRATING AND ALIGNMENT ERRORS

As shown in Fig.1, an example of coherent addition of two gratings to form a tiled grating system, there are six degrees of freedom between each adjacent grating, tip, tilt, rotation, along y-axis shift dy, in-plane shift dx, out-plane shift dz. The dz error between two gratings only has a little affect on the optical energy loss which can be ignored. Theory analysis and mechanism design calculate on the angular errors, the gap error dx, and piston error dz, which affect both temporal performance and spatial performance of laser beam. T Zhang et al [2] analyzed the influence of angular errors on temporal performance, the theoretical analysis and experiment of LLE [3,4] indicated that the relative piston error of the gratings caused the far-field focal spot to split into two spots. Zhao bo [5,6] studied the influence of the gap error dx and piston error dz on the tiled grating. Our theoretical simulation and primary experiment results indicated that the angular error had particular influence on the temporal performance while the gap and piston error affected the spatial performance distinctly. The above-mentioned theories demonstrate that the coherent summation of multiple gratings to form a larger grating is feasible, so far as we can control the position of each subaperture grating precisely. It is a significant challenge and a mechanism with submicrometer or even nanometer precision is necessary to control the angular errors and linear errors within permission range.



(a) Process of tiled grating



(b) Main assembled errors during the process of tiled grating

Fig.1 Schematic of the process of tiled gratings

2 DESIGN OF THE STAGE

2.1 Precision requirement and mechanical structure

For an example of coherent addition of segment gratings with the parameter of 1480l/mm for our experiment, the tiled grating influence on the laser beam in the temporal field should be less than 25%, and in the spatial field the influence on the wave front should be less than 1/10 wavelength. According to the requirement of which we can calculate that the angular errors must be within 20μrad so as to ensure the precision of coplanarity

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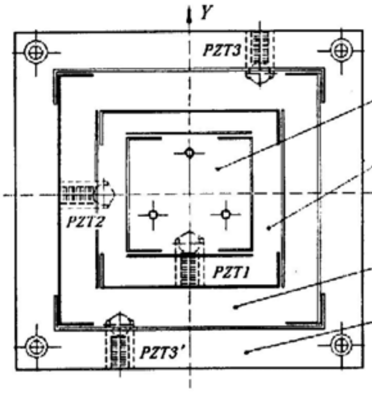
* [illegible]

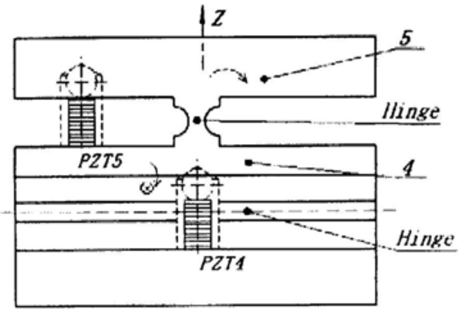
about several tens of nanometers: the piston error must be aligned to the

range of 3~5 times of wavelength of incidence: and the gap error should be less than 1/10 of groove width of the gratings. So it's necessary that the mechanism used in grating tilting would provide with nanometer resolution precision and nanometer positioning stability. The conventional mechanism such as using gear. lever. screw and others can't reach submicrometer-level precision for the existence of backlash and friction. To obtain a resolution of nanometer scale. a stage with five degrees of freedom which can be used in the coherent addition of gratings is developed here.

As shown in Fig.2. the movements of the stage are guided by flexure hinges and driven by piezoelectric actuators. This kind of structure is called as compliant mechanism and is widely used in optical modulation such as phase shift. wafer alignment and fiber alignment. The mechanism has five DOF realized by series combined manner. which has the advantages such as easy-to mount. adjust and control. The mechanism can be divided into two parts. the upper stage as shown in Fig2 (b) and the nether stage shown in Fig2 (a). The movement of nether part includes two-dimension translation along axis x-y and one rotation about axis z. The upper stage that has two rotation motion around axis x-y is mount on the under part. The "PZT" in Fig.2 represents piezoelectric actuator, among which the PZT1 and the PZT2 drive the movable part 1 and part 2 which are guided through parallel flexure hinge respectively, and by this means to adjust the gap error and piston error of adjacent grating. The movable part 3 is driven by PZT3 and PZT3' and it's apparent that a rotation motion of this part around z axis is accomplished. The movable part 4 and part 5 are linked to the mechanism body by notched flexure hinge 4 and 5 and driven by the actuators PZT4 and PZT5 to achieve rotation motion respectively. These rotation motions are used to adjust the grating to be coplanar and keep the groove line parallel. The above part1 to part5 are linked each one by another and which is referred as series combined mechanism, the subaperture grating is fixed on the part5 so as to be adjusted by afore mentioned motions.



(a) upper stage of the mechanism which has three DOF



(b) nether stage of the mechanism which has two DOF

Fig.2 Schematic of the five DOF mechanism

2.2 The parameter design of the mechanism

The motions of the mechanism include translation and rotation. The movement of translation is guided by a pair of parallel leaf flexures and the structure of which is shown in Fig.3. The rotation is realized by way of revolute pair formed by circular hinge whose structure is shown in Fig.4. In the design of compliant mechanism. if the piezoelectric actuators and drive power have been specified. the performance of the mechanism such as movement range. the resolution. the natural frequency. and the step response time are nearly related with the mechanism stiffness. The mechanism stiffness is determined by the stiffness of the flexure hinge which is the most crucial item in the design. The design principles of the flexure hinge stiffness are that the blocked force caused by the distortion of the hinge should be less than the maximum force that can be generated by the piezoelectric actuator. and the bending of the hinge stress should be less than the electric limit of the material. To increase the natural frequency of the mechanism so as to improve the ability of resisting environment disturbance and reduce the effect of ripple voltage of the power, the stiffness should be as large as possible. Many studies have been conducted to model and analyze the stiffness of the flexure hinge [7~10]. FEA method is reliable, whereas the math expression of the stiffness is presented in this paper instead. As shown in Fig.4, the mechanism is guided by a pair of parallel leaf spring. Where the thickness of the leaf spring is t, the length is a, and the width is b, then the stiffness of the mechanism is expressed by

$$k_s = \frac{4Eb(1-\mu^2)t^3}{a^3} \tag{1}$$

where E is the elastic modulus, and μ is Poisson's ratio. The notch hinge flexure shown in Fig.5, the notch radius is R, the thickness is t and the width is b, then the angular stiffness can be approximated from equation

$$k_R \approx \frac{2Ebt^{5/2}}{9\pi R^{1/2}} \tag{2}$$

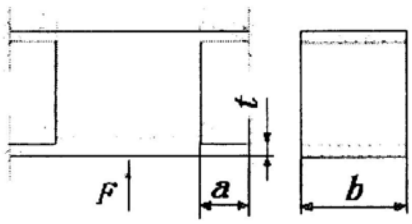


Fig.3 Translation mechanism guided by parallel leaf flexures

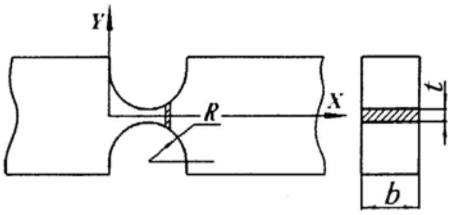


Fig.4 Model of circular notch flexure hinge

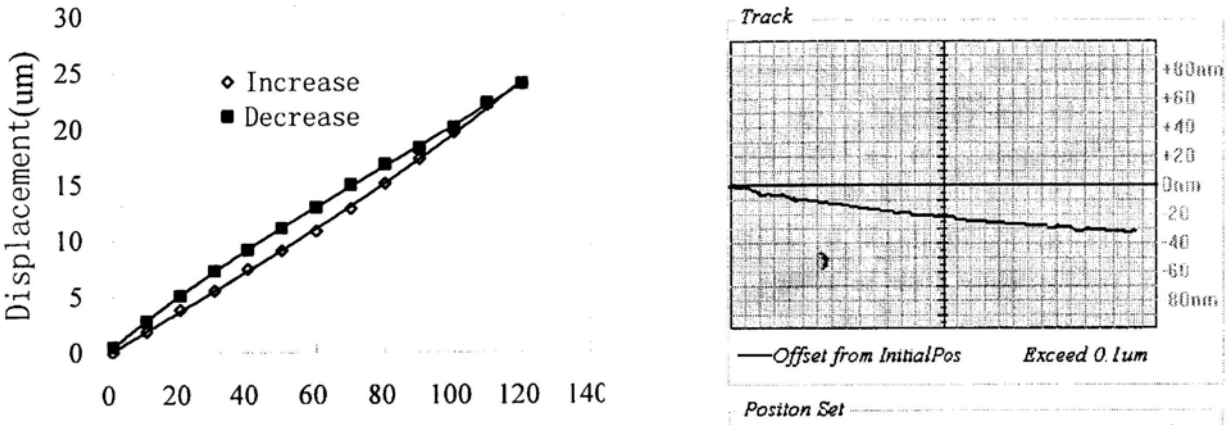
According to the stiffness of the flexure element we can calculate the stiffness of the structure. and then the nature frequency and output ability of the mechanism can be calculated. As an example of Fig.3 (a). the thickness of the stage is b=20mm. μ=0.3. t=$0.8mm$. a=$10mm$. E=210GPa. then the stiffness of the mechanism system k_s=$7.8N/\mu m$. The stiffness of the piezoelectric actuator is $28N/\mu m$. and the maximum normal displacement output is $35\mu m$. then the actual output can be calculated by

$$L_O = L_N\left(\frac{K_T}{K_T + K_s}\right) \tag{3}$$

where L_O is the actual output displacement. K_T is the stiffness of the actuator. K_S is the stiffness of the mechanism. then the maximum output of the mechanism is $d_{out} = 28\mu m$. The natural frequency can be computed by FEA and which is about 1084Hz.

2.3 The performance of the mechanism and control method

According to the requirement of the precision for grating addition. the mechanism used to adjust the grating should have high stability except for high resolution. Namely. the grating must be fixed when it is adjust to the ideal position. which requires that the mechanism has higher stiffness so as to reduce the disturbance caused by environment. Moreover. due to the characteristic of the piezoelectric actuator. to realize keeping stable position. the output of the actuator must be controlled effectively. Generally. the output of the actuator is affected by the characteristics such as hysteresis. nonlinear and drift. The characteristic of hysteresis and nonlinear means that the displacement output and voltage input is not proportional. and when the actuator is applied a voltage the displacement output will change slowly as time elapsed which is called drift. As an example of part1. Fig.5 (a) is the hysteresis curve of the displacement output and Fig.5 (b) is the drift curve when a certain voltage is applied.



(a) Hysteresis curve of the displacement output

(b) Creep curve of the displacement output

Fig.5 Performance of the output of part1 on open-loop condition

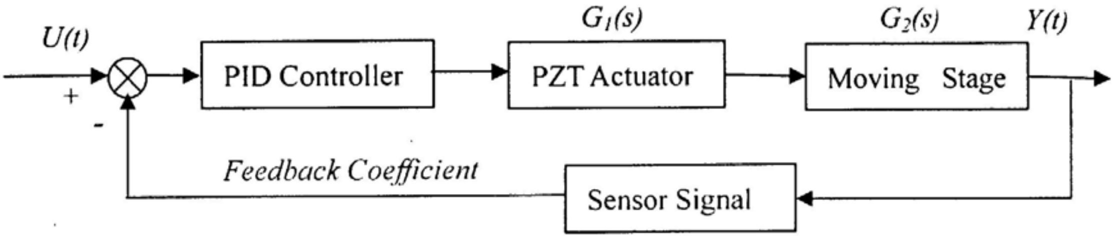


Fig.6 PID control process of part1

From Fig.5 we can conclude that it's difficult to keep stable position on open-loop condition. To eliminate the characteristics mentioned previously and acquire high stability. a capacitive sensor with nanometer level measurement precision is mounted on the stage of part1. the sensor measurement signal is used as feedback for the control system which adopts PID controller and uses voltage-control method. the PID control process of which is shown in Fig.6.

Among which $G_1(s)$ is transfer function of voltage input to displacement output. The actuator can be described by an equivalent model as Fig.7. by the equation

$$RC\frac{dU_o(t)}{dt} + U_o(t) = U_i(t) \tag{4}$$

and the relationship of displacement output to the voltage input can be approximately described by $x(t)=k_m U_o(t)$. where k_m is transfer modulus of voltage to displacement. then $G_1(s)$ can be described by

$$G_1(s) = \frac{k_m}{T_m s + 1} \tag{5}$$

Where T_m=RC is time constant of the equivalent circuit. And part1 of the stage can be simplified as a second-order system as shown in Fig.8. and according to the dynamic equation

$$m\ddot{y}(t) + \mu\dot{y}(t) + (k_A + k_B)y(t) = k_A x(t) \tag{6}$$

define

$$\varpi_n = \sqrt{\frac{k_A + k_B}{m}}.$$

$$\xi = \frac{\mu}{2m\varpi_n}.$$

$$k = \frac{k_A}{k_A + k_B}.$$

and according to Laplace transform, therefore $G_2(s)$ can be expressed by

$$G_2(s)=\frac{k\omega_n^2}{s^2+2\xi\omega_n s+\varpi_n^2} \qquad (7)$$

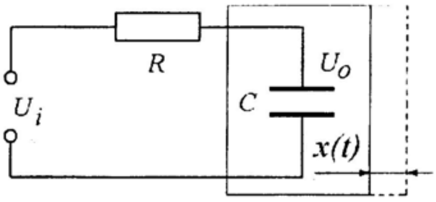


Fig.7 Equivalent model of piezoelectric actuator

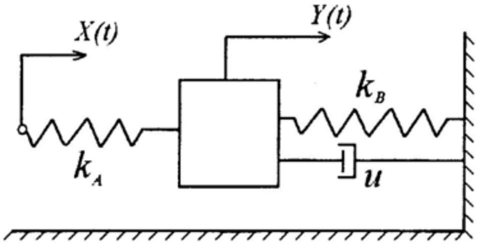


Fig.8 part1 of the stage can be simplified as a second-order dynamic system

2.4 Definition of the control coefficient

Position PID algorithm is used in our experiment to control the displacement output and the control result of which mostly depends upon the definition of control parameters K_P, K_I and K_D, due to the mathematical model of the part1 is comparatively precise, Matlab simulation can be used to determine these parameters primarily and then adjust these values slightly in actual experiments, which can reduce the amounts of experiments effectively. In the aforementioned example, the known parameters are $k_m=0.114\mu m/V$, $T_m=2.0\times10^{-3}s$, $k_A=25N/\mu m$, $k_B=7.8N/\mu m$, $m=0.1Kg$, $\xi\approx0.5$, and the system transfer function $G(s)=G_1(s)\cdot G_2(s)$, then according to the analysis of matlab simulation, the influence of the coefficients K_P, K_I and K_D is described by fig.9. To reduce the overshot, in the actual experiment we choose $K_P=0.5$, and the actual effect of the step response correspond to different input is shown as Fig.10.

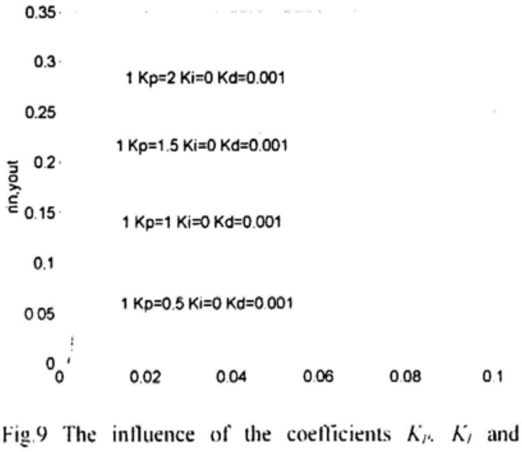


Fig.9 The influence of the coefficients K_P, K_I and K_D, simulated by matlab 6.5

It can be seen from the graph that the stable positioning precision of the stage can reach several nanometers level by means of PID close-loop control and it can satisfy the precision requirement for the tilting grating. As for the angular rotation output of the mechanism, we can replace the linear displacement parameter such as x in above equations with angular parameter and the control process is similar to part1 which is not necessary to describe in here. It's through the capacitive sensor to realize feedback control in above control process, whereas in the process of coherent addition of gratings, the feedback signal of the cap-sensor can be replaced by the diffraction fringes and far-field focus, and according with the change of which to control the movement of the mechanism so as to adjust the position of the gratings. As shown in Fig.11, two gratings are mounted adjacently and adjusted by the mechanism and the diffraction fringes are recorded by CCD camera. From the graph we can see that the orientation and density of the two gratings can be adjusted coherently which can satisfy our requirement of tile grating for farther experiments.

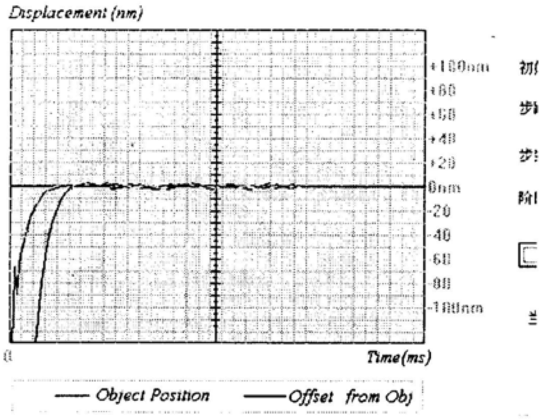


Fig.10 The actual effect of the step response correspond to different input

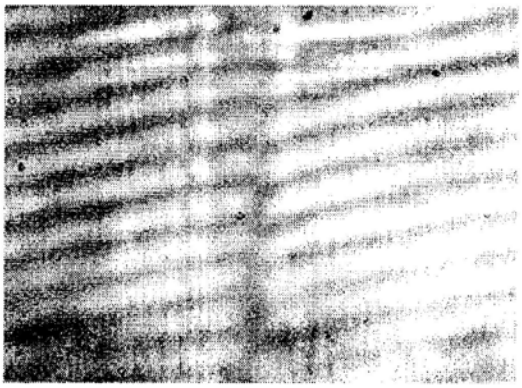


Fig.11 Two gratings are tiled adjacently and adjusted by the mechanism and diffraction fringes show the result of coherent addition

3 CONCLUSIONS

The coherent addition of multiple small gratings to form a larger grating is a complex project which relies on grating fabrication, mechanism design, optical detection, motion control and many other elements. The 5-dof mechanism discussed here can meet the requirement of adjustment precision for tile grating. The mechanism is compact and easy to control. According to different loads we can select appropriate actuators, but due to the output of the piezoelectric actuators that are limited within several hundreds of nanometers, the above mechanism is only used to as fine adjustment. Whereas, if the required range of adjustment exceeds the output ability of piezoelectric actuators, a stage with coarse precision but with large range output capacity should be used to work together with aforementioned mechanism which is not discussed here.

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