

Light-beam stabilizing control in long-distance transmission systems subject to mechanical vibrations

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Abstract—The performances of various optical systems are inevitably influenced by mechanical vibration. In order to compensate the pointing errors of the light-beam caused by the mechanical vibration in long-distance light-beam transmission systems, a new scheme of light-beam stabilizing control is presented, which uses two position sensitive detectors to detect the pointing errors, and a single fast steering mirror to stabilize the jitter of the light-beam. An experimental setup was established and a series of experiments were conducted. The experimental results show that the pointing errors can be effectively suppressed, thus the newly proposed stabilizing technique is feasible. Finally, several suggestions on improving of the experimental setup are discussed.

I. INTRODUCTION

IN long-distance light-beam transmission systems, the angular deviation of the emergent beam must be controlled under a very small value (e.g., less than a few seconds) in order to achieve high precision transmission due to the long travel distance. Compared to the angular deviation, the translational deviation of the emergent beam can be relatively larger because its influence on the transmission accuracy is independent of the travel distance. Many possible factors may cause the instability of the emergent light-beam in long-distance light-beam transmission systems, among which the mechanical vibration is the most difficult due to its unpredictability and complexity in frequency content^[1]. By taking a satellite laser communication system for example, the mechanical vibration aroused from adjusting the attitude of the satellites and the operation of the power equipments can result in communication failure or even communication interruption.

Skormin *et al.*^[2] presented an adaptive feed-forward compensation scheme for laser communication system, which uses an angular transducer to detect the vibration and a fast steering mirror to suppress the jitter of the emergent beam, and the simulation and analysis were given. McEver *et al.*^[3] combined passive control with active control to eliminate the vibration of light-beam. Ma *et al.*^[4] used a CCD to detect the vibration and a fast steering mirror to achieve the feed-forward compensator, which gives a good measure for compensating

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low-frequency large-amplitude vibrations. The NEWPORT Corp. developed a beam-stabilization module^[5] which incorporates two fast steering mirrors working with two quadrant detectors, as shown in Fig. 1.

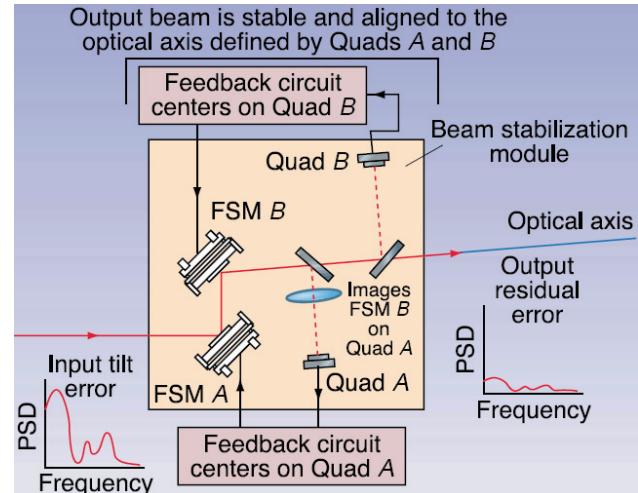


Fig. 1. Schematic diagram of a beam-stabilization module^[5] developed by the NEWPORT Corp.

To eliminate the angular deviation of the emergent beam in a long-distance transmission system working in environment with mechanical vibrations, a new scheme of light-beam stabilizing control is proposed, which utilizes a single fast steering mirror (FSM) working with two position sensitive detectors (PSD). The feasibility of the scheme is demonstrated by the experimental results.

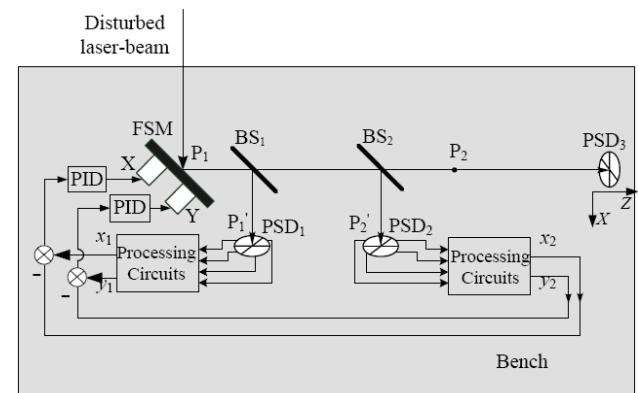


Fig. 2. Schematic diagram of the proposed light-beam stabilizing control system. PSD₁ and PSD₂ (working with two beam splitters, i.e., BS₁ and BS₂) are used to sense the direction changing of the emergent light beam, and the FSM is used to stabilize the light beam.

II. SCHEME OF THE LIGHT-BEAM STABILIZING CONTROL

Figure 2 shows the schematic diagram of the new approach of light-beam stabilizing control, which uses a Fast Steering Mirror (FSM), two position sensors (PSD₁ and PSD₂) and their processing circuits, two beam-splitters (BS₁ and BS₂) and two PID controllers for the *X*-axis and *Y*-axis, respectively. The desired emergent light-beam can be determined by two reference points P₁ and P₂ on the optical bench.

The working principle of this new scheme can be described as follows: BS₁ and BS₂ reflect small parts of the light-beam to PSD₁ and PSD₂, respectively. PSD₁ and PSD₂ receive the reflected light and determine the deviations of emergent light-beam on the reference planes at position P₁ and P₂. If the deviations at the two positions are equal, we know that the emergent light-beam is parallel to the desired one and no action should be taken. Elsewise,

if the deviations are different, the emergent light-beam is tilting and adjustment is required. In this case, the difference between the two deviations detected by PSD₁ and PSD₂ is sent to the PID controller as an error signal. Through a control algorithm, the error signal is converted into a driving voltage, which is used to control the FSM to compensate the tilt error of the emergent light-beam.

It should be noted that PSD₃ shown in Fig. 1 is independent of the control system. It is used to measure the deviations of the controlled emergent light-beam after point P₂.

III. EXPERIMENT SETUP

The experiment setup established to verify the feasibility of this new method is shown in Fig. 3. The key devices are described in the following.

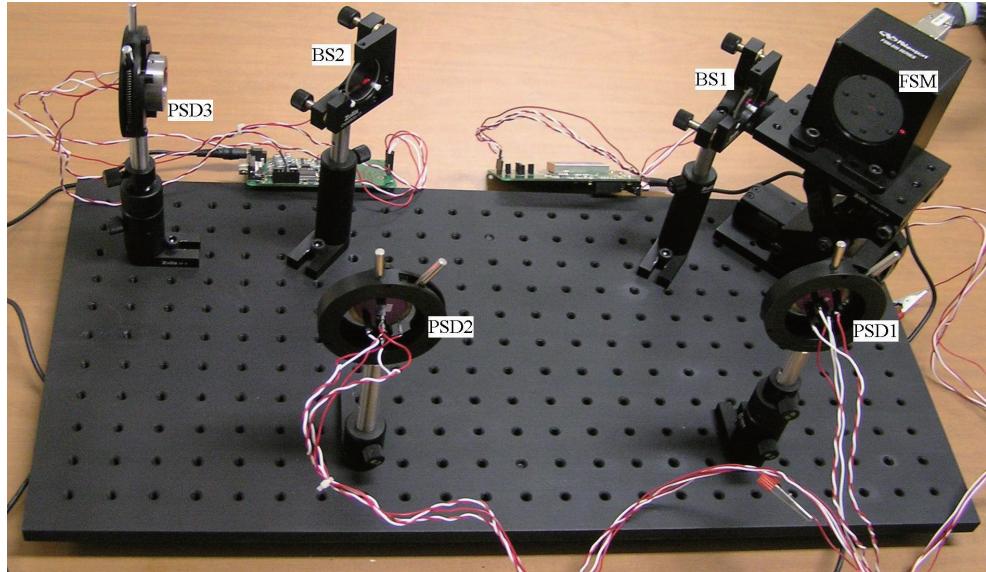


Fig. 3. Experimental setup. The devices are mounted on an optical bench.

A. Fast Steering Mirror (FSM)

FSM is the actuator of the system, whose performance is directly related to the performance of the system. In the experiment, we use a FSM-002-02^[6] offered by NEWPORT Corp. In the FSM, a flexure suspension is utilized to confine the motion of the mirror producing a single pivot point rotation, and four voice coil linear motors are incorporated in push-pull pairs to provide smooth and even torque to tip and tilt the mirror around the *X*-axis and *Y*-axis.

The typical specifications as follows:

- 1) Range of Driving Voltage: $\pm 10V$
- 2) Angular Range from $\pm 10V$: $\pm 1.5^\circ$
- 3) Resolution: $\leq 1\mu\text{rad rms}$
- 4) Peak angular velocity: 2.5rad/s
- 5) Peak angular acceleration: 900rad/s^2
- 6) Mirror Diameter: 45.7mm

- 7) Closed-loop amplitude bandwidth (-3dB) at small amplitude: 550Hz
- 8) Closed-loop Phase Bandwidth (60° lag) at small amplitude: 300Hz

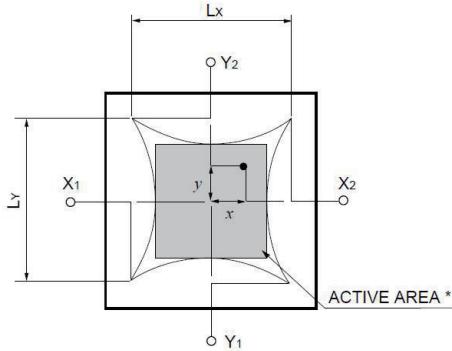
B. Position Sensitive Detector (PSD)

PSD is an optoelectronic position sensor utilizing photodiode surface resistance, which can provide high resolution and high-speed position sensing. It is perfect for our experiment because its detection accuracy doesn't depend on the intensity of the light spot (the gravity center of the light spot is calculated for output) and it is nontrivial to evenly reflect the light-beam to the two PSDs. We use S1880 PSD manufactured by HAMAMATSU (Japan) in the experiment. As shown in Fig. 3, the fringe of the sensitive area of S1880 is of circular arc form, which can greatly reduce the mutual interference between the output electrodes in the *X* and *Y* directions. The four output

electrodes are in the same plane and the output polar is connected to the diagonal of photodiode surface resistance. By testing the electric currents ($I_{x1}, I_{x2}, I_{y1}, I_{y2}$), the position (x, y) of the spot can be calculated by the Eq. (1) and (2).

$$x = \frac{L_x}{2} \cdot \frac{(I_{x2} + I_{y1}) - (I_{x1} + I_{y2})}{I_{x1} + I_{x2} + I_{y1} + I_{y2}} \quad (1)$$

$$y = \frac{L_y}{2} \cdot \frac{(I_{x2} + I_{y2}) - (I_{x1} + I_{y1})}{I_{x1} + I_{x2} + I_{y1} + I_{y2}} \quad (2)$$



* Active area is specified at the inscribed square.

Fig. 4. Sketch drawing of a PSD [7]. PSD is an optoelectronic position sensor utilizing photodiode surface resistance and it provides continuous position data and features high position resolution and high-speed response.

The main specifications of S1880 include:

- 1) Spectral response range: 320~1060nm
- 2) Position resolution: 1.5μm
- 3) Frequency response range: ≥1kHz

C. PID controller

DSP TMS320LF2407 offered by TI Corp. is used to implement a fundamental PID algorithm.

D. Other devices

In the experimental setup, a diode laser is used as the light source whose wavelength is 650nm. To enhance the measuring accuracy and reduce the influence by the ambient light in the scene, we attached a narrow band-pass filter whose center wavelength is 640nm and half power bandwidth is 15nm to each PSD. In addition, the diode laser is mounted on a compliant cantilever excited by a vibration exciter to simulate environment vibrations.

IV. EXPERIMENTAL RESULTS

A. Step response test

The step response is often used to evaluate the response speed and the steady-state error of a control system. In the step response test, we introduced a definite error on the X -

and Y -axes, respectively, by installing the diode laser with a small angular deviation. The errors are defined as:

$$\Delta x = x_2 - x_1 \quad (3)$$

$$\Delta y = y_2 - y_1 \quad (4)$$

where (x_1, y_1) is the light spot position on PSD_1 while (x_2, y_2) for PSD_2 . The step response of the system can be achieved by starting the control and watching the change of the error. Figure 4-5 plot the step responses along X -axis and Y -axis, respectively.

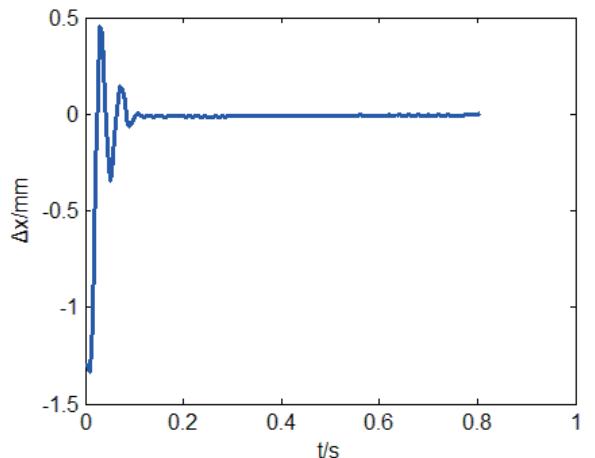


Fig. 5. Step response in the X -axis. It can be seen that the system works well with very short response time and small steady state error.

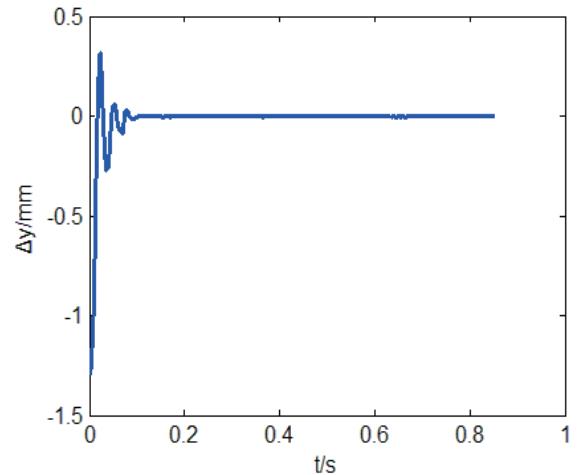


Fig. 6. Step response in the Y -axis. It can be seen that the system works well with very short response time and small steady state error.

From Fig. 5-6 we may see that this system shows a very good performance in the step response test both in the X -axis and the Y -axis. It takes a few oscillations for the emergent light-beam to be settled in parallel with the desired direction with the response time less than 100 ms and the steady state error about 7 μm.

B. Vibration test

To test if the proposed light-beam stabilizing control technique works in hostile vibration environment, we installed the diode laser on a slender cantilever beam whose fixed end was mounted on a vibration exciter. We started to record data gathered from PSD₁ and PSD₂. After about 3 seconds, we ran the vibration exciter to produce a sine vibration with a frequency of 20 Hz and amplitude of 0.5 mm. And 2 seconds later, we turned the control system on. The recorded results are plotted in Fig. 7, where ΔE can be expressed as

$$\Delta E = \sqrt{(x_2 - x_1)^2 + (y_2 - y_1)^2} \quad (5)$$

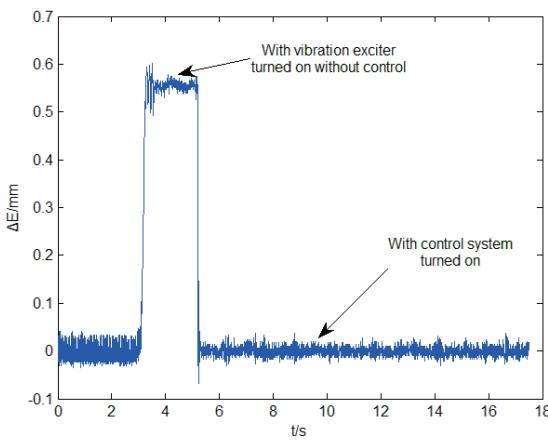


Fig. 7. Response in a continuous vibration test.

As shown in Fig. 7, before the vibration exciter was turned on, ΔE was fluctuating around 0, which was because of the small vibration in the experimental environment, the influence of the ambient light in the scene and the instability of the diode laser. Right after the vibration exciter was turned on, ΔE increased dramatically, which indicates that the emergent light-beam deviated from the desired direction. By turning on the control system, ΔE went down into a reasonable deviation range close to 0. The distance from P₁ to P₂ is 0.4 m and the maximum ΔE without control is about 0.6 mm. Using these two parameters we can figure out that the maximum angular deviation was about 1.5 mrad. After the control system turned on, the angular deviation was suppressed into a range of 87 μ rads. Moreover, we put PSD₃ 10 m away from the FSM to capture the emergent light-beam. Before the control system was turned on, we could not record results because the spot of the emergent light was jittering beyond the range of the photodiode surface of PSD₃. However, when the control system was turned on, the light spot swayed on PSD₃ in a range of 3.5 mm.

Then we increased the frequency of the vibration exciter while remaining the amplitude as a constant. As the frequency increased, ΔE increased but not much. When the

frequency reached 90Hz, the maximum value of ΔE was less than 0.05 mm. When the frequency increased to 93Hz, the slender cantilever beam resonated and we had to stop the experiment.

C. Suggestion on improving the experiment

First, we found that the light spots on PSD₁ and PSD₂ were different in shape and size, which might affect the performance of the system. Thus, more work should be done on the selecting light sources and beam splitters. Second, increasing the distance between BS₁ and BS₂ can improve the performance of the control system. Last, the system can be improved by choosing some newly developed control techniques such as robust control, auto-disturbance rejection control and so on.

V. CONCLUSION

The influence of mechanical vibrations on the performance of optical systems is inevitable. To solve the instability of light-beam in vibration environment, a new scheme of light-beam stabilizing control is presented and the corresponding experimental setup is established. The experimental results show that the pointing direction errors can be effectively compensated, thus the newly proposed stabilizing technique is feasible.

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