西安光机所高精度跟瞄光学系统视轴稳定技术研究取得新进展

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近日，机械系统与信号处理领域国际顶级学术期刊Mechanical Systems and Signal Processing在线发表了中国科学院空间精密测量技术重点实验室在高精度跟瞄与视轴抖动主动抑制方面最新研究成果。论文第一作者为重点实验室成员吕涛，通讯作者为西安光机所阮萍研究员，合作作者为重点实验室成员姜凯、井锋。该成果为重点实验室承担的“引力波探测”重点专项项目开展提供了重要理论支撑。

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Modeling and analysis of fast steering mirror disturbance effects on the line of sight jitter for precision pointing and tracking system

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ABSTRACT

Fast steering mirrors (FSMs) are typically applied for beam stabilization for precision pointing and tracking systems (PPTSs) owing to their high-bandwidth, high-resolution, and high accuracy. In addition to the advantages, the presence of the residual momentum which caused by FSMs' operation usually has noticeable effects on the stabilization of the line of sight (LOS) for PPTSs. Hence, it is necessary and momentous to estimate the effects of these disturbances to give insight into the FSM specification and the PPTS structural performance. However, the characteristic of multidisciplinary coupling makes it a challenge to measure the LOS jitter caused by FSMs. We approach this problem by establishing an integrated model for estimating the LOS jitter. A dynamic model of an FSM is firstly built to value the unbalanced momentum generated from its motion. Then a finite element model for the structure of the tracking system is established to predict the dynamic response excited by the disturbances from the FSM. In addition, with a linear optical model, the system optical performance under the FSM's disturbances is determined. Finally, a test is conducted to verify the validity of the model and the analysis. This paper focuses on estimating the disturbances effects of the FSM on the LOS jitter for a PPTS, and providing potential approaches for reducing these effects.

1. Introduction

PPTSs play crucial roles in numerous applications, such as free-space optical communication, target pointing, surveillance, and laser manufacturing [1–5]. In order to achieve mission objectives, PPTSs must provide precise LOS tracking and pointing capabilities with suppression of LOS jitter. Traditional gimbals with large mass and inertia are not qualified to meet high-performance requirements of aiming, tracking, and pointing [6], and FSMs with high-resolution, high-precision, and high-bandwidth are utilized for decades to stabilize the LOS of PPTSs.

Over the years, this area has seen significant advances in estimating and eliminating the LOS jitter for complex tracking and image stabilization equipment. Some researchers aimed at finding out what the jitter source was, how the factors affected the jitter, and how the jitter was eliminated with FSMs and isolation devices. In the early 1960s, A. W. Lohmann and D. P. Paris from IBM Corporation compared longitudinal and transversal vibrations, and they analyzed the influence of longitudinal vibration on image quality which has received little attentions before [7]. J. M. Hilkert et al. from Texas Instruments addressed the effects of image motion on the performance of electro-optical imaging systems. In addition, they investigated alternate methods of specifying the allowable image

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科学观测、深空光通信以及引力波探测等任务对跟瞄光学系统的视轴指向精度及其稳定性提出了达到亚urad乃至nrad的高要求。来自系统内外部的动态振动扰动是影响视轴精度的主要因素，因此抑制动态振动扰动成为了领域内最具挑战性的关键问题之一。在一些高精度、高稳定性的应用场合，会采用快速控制反射镜等运动部件作为视轴的精确指向与稳定的关键单元，但其引入的寄生扰动却是制约系统精度与稳定性进一步提升的重要因素。该项研究通过创新性建立的光-机-电多学科交叉耦合的系统级视轴指向与抖动评估预测模型，针对快速控制反射镜在精密光束控制中产生的寄生扰动的问题，通过不确定性分析、时频域比对等手段，定量分离寄生扰动分量，结合预测模型，提出破解寄生扰动的补偿方法及视轴抖动综合整治思路，经外场测试，试验数据充分验证了模型的有效性。

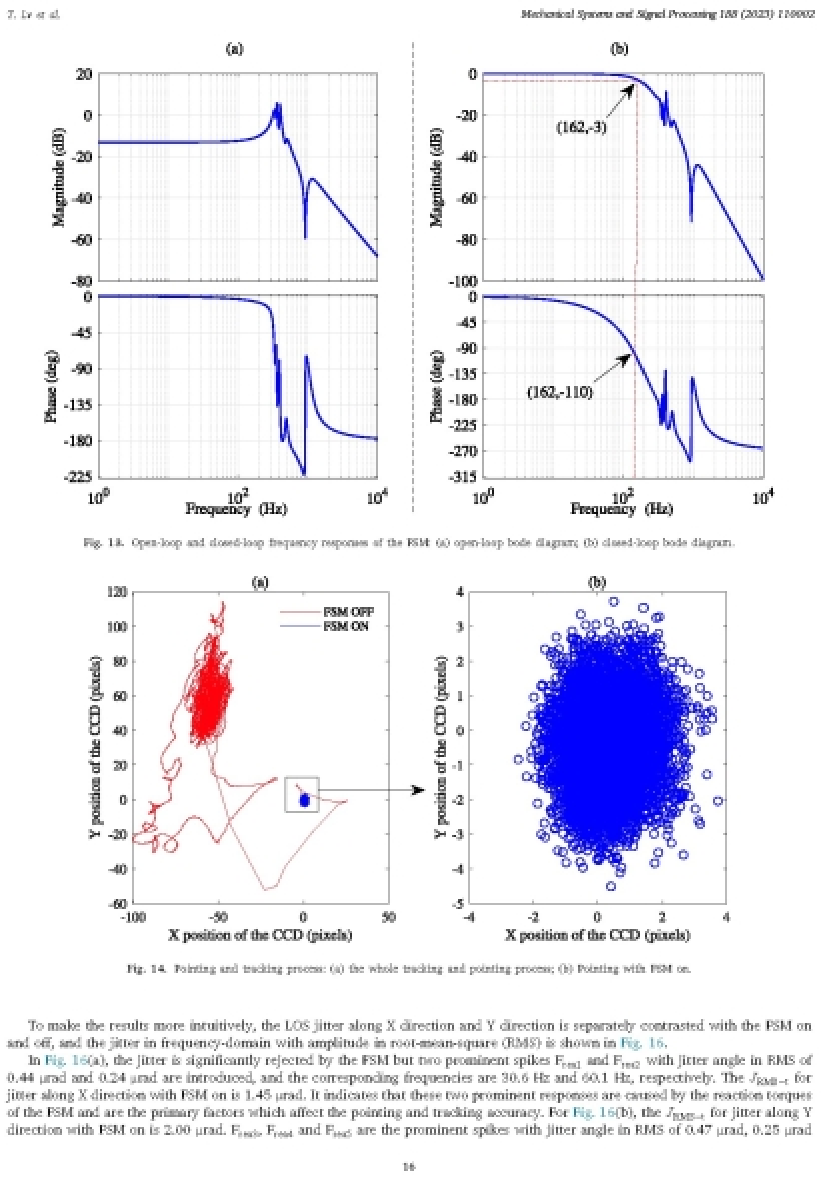

Fig. 13. Open-loop and closed-loop frequency responses of the FSM: (a) open-loop bode diagram; (b) closed-loop bode diagram.

Fig. 14. Pointing and tracking process: (a) the whole tracking and pointing process; (b) Pointing with FSM on.

To make the results more intuitively, the LOS jitter along X direction and Y direction is separately contrasted with the FSM on and off, and the jitter in frequency-domain with amplitude in root-mean-square (RMS) is shown in Fig. 16.

In Fig. 16(a), the jitter is significantly rejected by the FSM but two prominent spikes F_{res1} and F_{res2} with jitter angle in RMS of 0.44 µrad and 0.24 µrad are introduced, and the corresponding frequencies are 30.6 Hz and 60.1 Hz, respectively. The J_{RMS-t} for jitter along X direction with FSM on is 1.45 µrad. It indicates that these two prominent responses are caused by the reaction torques of the FSM and are the primary factors which affect the pointing and tracking accuracy. For Fig. 16(b), the J_{RMS-t} for jitter along Y direction with FSM on is 2.00 µrad. F_{res3}, F_{res4} and F_{res5} are the prominent spikes with jitter angle in RMS of 0.47 µrad, 0.25 µrad

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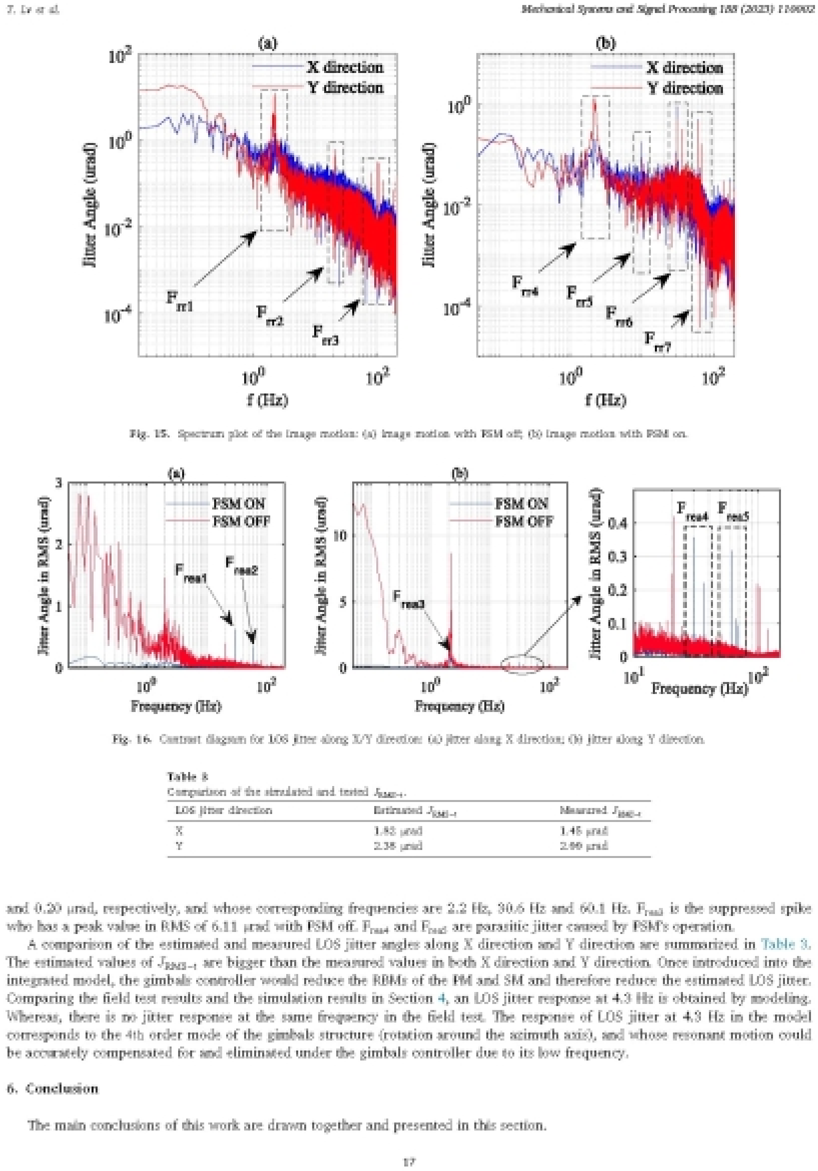
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Fig. 15. Spectrum plot of the image motion: (a) image motion with FSM off; (b) image motion with FSM on.

Fig. 16. Contrast diagram for LOS jitter along X/Y direction: (a) jitter along X direction; (b) jitter along Y direction.

Table 3
Comparison of the simulated and tested J_{RMS-t}.

LOS jitter direction	Estimated J_{RMS-t}	Measured J_{RMS-t}
X	1.82 μrad	1.45 μrad
Y	2.38 μrad	2.00 μrad

and 0.20 μrad, respectively, and whose corresponding frequencies are 2.2 Hz, 30.6 Hz and 60.1 Hz. F_{res3} is the suppressed spike who has a peak value in RMS of 6.11 μrad with FSM off. F_{res4} and F_{res5} are parasitic jitter caused by FSM's operation.

A comparison of the estimated and measured LOS jitter angles along X direction and Y direction are summarized in Table 3. The estimated values of J_{RMS-t} are bigger than the measured values in both X direction and Y direction. Once introduced into the integrated model, the gimbals controller would reduce the RBMs of the PM and SM and therefore reduce the estimated LOS jitter. Comparing the field test results and the simulation results in Section 4, an LOS jitter response at 4.3 Hz is obtained by modeling. Whereas, there is no jitter response at the same frequency in the field test. The response of LOS jitter at 4.3 Hz in the model corresponds to the 4th order mode of the gimbals structure (rotation around the azimuth axis), and whose resonant motion could be accurately compensated for and eliminated under the gimbals controller due to its low frequency.

6. Conclusion

The main conclusions of this work are drawn together and presented in this section.

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该项成果为高精度跟瞄光学系统的系统级集成设计、分析与优化提供了高效数值分析模型，也为有效满足国家空间精密测量领域的相关需求提供了新的思路和手段。（院空间精密测量技术重点实验室　　供稿）

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