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Development and test of the Point Ahead Angle Mechanism for space gravitational wave detection

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空间引力波探测超前瞄准机构研制与测试

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摘　要：探测低频引力波需要脱离地缘噪声干扰，在空间搭建激光干涉引力波探测装置。太极、LISA、天琴等空间引力波探测任务，计划在几十万到几百万公里量级的臂长上实现皮米级的位移测量精度，以满足引力波探测的要求。在探测任务中，考虑轨道季节性变化和星间激光传输时间等因素，发射光束需要一个超前角度，确保远端望远镜能够接收到光束，从而完成星间激光干涉。针对发射光束需要超前角度的需求，设计并研制了一款用于激光干涉链路中提供超前角度的光束指向机构，即超前瞄准机构。该机构基于将偏转轴配置在反射镜面上的设计理念，采用柔性铰链和杠杆配合的结构形式，利用压电陶瓷自闭环进行驱动控制，实现光束一维高精度偏转。对该机构进行仿真分析，验证其力学特性以及偏转范围。对所研制的机构进行了一系列实验测试，结果表明，该机构偏转范围可达到709.4 μrad，偏转精度可达到0.44 μrad，机构偏转引起的光程差优于10 pm/$\sqrt{\text{Hz}}$ (1~10 Hz)。从而验证了该机构设计的可行性，为实现光束超稳高精度偏转提供一定的参考。

关键词：空间引力波探测；　超前瞄准机构；　柔性铰链；　光程差
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0　引　言

引力波有望提供一种电磁波探测所不及的、新的窗口观测和认识宇宙，因此引力波探测具有十分重要的意义。空间引力波探测计划目前主要包括中国的“太极”计划[1]、“天琴”计划[2] 和欧洲航空局的 LISA 计划[3]。引力波能够在空间引起时空应变，周期性地改变所有天体之间的距离[4]。空间引力波探测计划通过在空间搭建激光干涉仪来探测两个“自由悬浮的检验质量 (Proof mass)”之间距离的变化，进而获取引力波“信号”。在绕日或绕地轨道上构建相距几十万或几百万公里的三个卫星组成的等边三角形星座。每一个卫星都由两个望远镜组成，分别接收和发射激光光束。因为引力波“信号”很微弱，即使干涉臂长达到百万公里，干涉测量系统的绝对测量精度也要达到皮米量级。

由于轨道力学会引起三角形星座形状发生周期性变化，加上星间激光传输需要时间，发射光束需要一个超前角度，使得远端望远镜能够准确接收到光束，完成星间激光干涉。超前瞄准机构[3,5](the Point Ahead Angle Mechanism, PAAM) 是被放置在光学平台上提供超前角度的一类机构。国外欧洲航空局的空间引力波探测计划 LISA 发展较早，已有了一些研究成果。目前已有两家欧洲公司分别为 LISA 计划设计了超前瞄准机构 (PAAM)，均满足 LISA 计划的总体设计要求。瑞士 RUAG 公司的 Simon Henein 等[6−7]为 LISA 引力波探测项目设计了一种超前瞄准机构 (PAAM)，该机构由行走式压电驱动，电容传感器测量角度误差。其偏转范围为±412 μrad，光程差满足 LISA 计划要求10 pm/$\sqrt{\text{Hz}}$ (0.1 mHz~1 Hz)。荷兰 TNO 公司的 N. Rijnveld 等[8] 也为 LISA 设计了一种超前瞄准机构。该机构驱动器为两个压电陶瓷，相互备份。

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经过微小柔性机构传动,带动柔性铰链运动,以达到偏转的目的。该机构的偏转范围为±412 μrad。光程差小于10 pm/$\sqrt{\text{Hz}}$ (0.1 mHz~1 Hz),角度抖动小于8 nrad/$\sqrt{\text{Hz}}$ (0.1 mHz~1 Hz),测试结果均满足 LISA 计划的要求。

国内目前还没有相关公开的研究成果。文中基于空间引力波探测太极计划的初期要求设计并研制了一种超前瞄准机构。对该机构进行了仿真分析与实验测试,验证了该机构的可行性,为日后相关研究奠定基础,具有一定的借鉴价值。

根据轨道力学计算[9],面外超前角变化较大,需要调整,而面内超前角变化较小,小于激光发散角,不需要调整,所以超前瞄准机构采用一维偏转设计。由于太极计划与 LISA 计划在总体光学设计方案等方面(特别是望远镜倍率)有差异[1,9],文中设计的超前瞄准机构关键指标要求如下。

(1) 偏转范围: 500 μrad (机械运动范围);

(2) 偏转精度: 2 μrad;

(3) 引起的光程差: 10 pm/$\sqrt{\text{Hz}}$ (0.1 mHz~1 Hz);

(4) 使用非磁性材料和组件。

1 设计原理

由于柔性铰链具有无机械摩擦、无间隙、易维护、高分辨率和一体化加工等优点[10],几乎所有的光束指向机构都采用了柔性铰链。图 1 所示为传统的快速反射镜,其柔性铰链的偏转中心与镜面中心不重合[11],从而导致出射光路发生平移,不仅会影响其指向精度[12],而且会引入附加光程差。

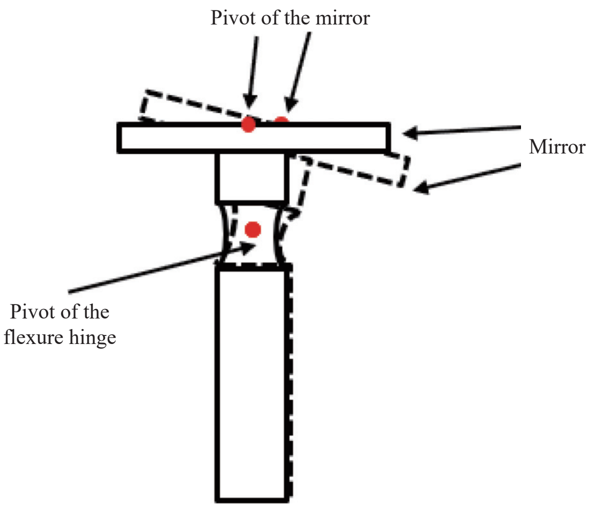
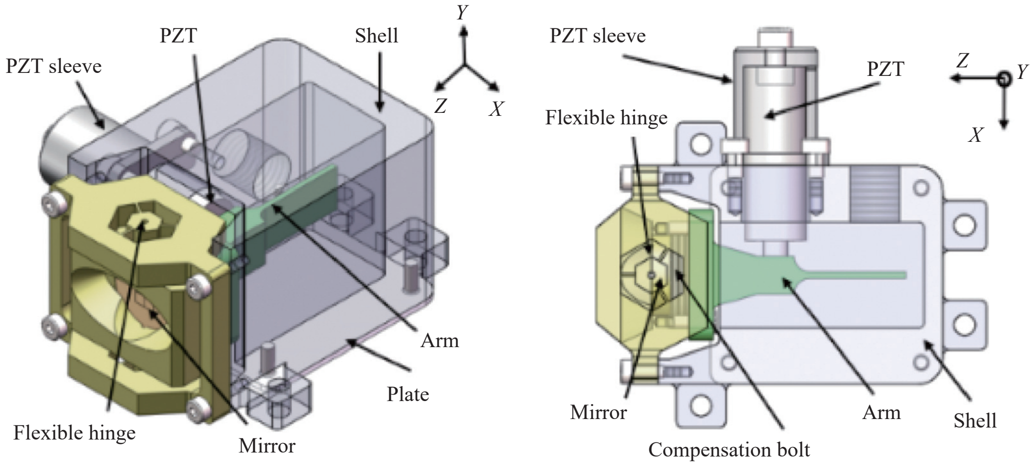


图 1 传统光束指向机构简图

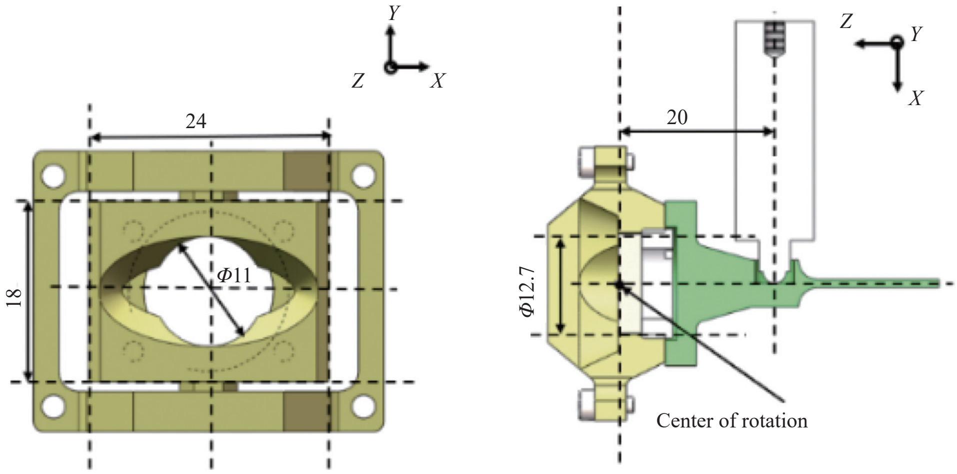
Fig.1 Schematic diagram of a traditional beam pointing mechanism

为了保证偏转中心与镜面中心重合,且柔性铰链具有较高的谐振频率,提高指向精度,减少附加光程差,设计了一种新型的光束指向机构。该机构由柔性铰链 (TC4)、反射镜 (K9)、摆臂 (TC4)、补偿螺钉、外壳 (AL6061)、压电陶瓷、驱动套 (AL6061) 和底板 (AL6061) 组成,图 2(a)、(b) 分别为该机构的轴测图和俯视图。机构采用柔性铰链与杠杆相结合的结构形式,通过压电陶瓷驱动摆臂带动反射镜绕着柔性铰链中心连线进行偏转。柔性铰链中心连线经过反射镜表面竖直中心线。柔性铰链与杠杆设计如



(a) 轴测图
(a) The axonometric view

(b) 俯视图
(b) Top view



(c) 柔性铰链正视图
(c) Front view of the flexible hinge

(d) 柔性铰链杠杆设计图
(d) Design drawing of a flexible hinge and lever

图 2 超前瞄准机构设计图

Fig.2 Design drawing of the PAAM

图 2(c)、(d) 所示，其中柔性铰链中间可旋转部分通过直角型柔性铰链单元上下连接，反射镜通过补偿螺钉进行固定。压电陶瓷 (芯明天 PSt150/5/20 VS10) 头部选用球头，与摆臂点接触，能够有效减小偏转误差。

利用电阻应变片对压电陶瓷进行自闭环控制，实现压电陶瓷精准位移输出，有效补偿压电陶瓷的蠕变和迟滞现象引起的误差[13]。不同的驱动电压信号使得压电陶瓷的伸长量不同，引起应变片阻值变化。通过桥式电路测量应变阻值变化对应的电压信号，经过控制算法来调节驱动电压大小，形成压电陶瓷自闭环。根据压电陶瓷自闭环控制位移分辨率为1 nm，推算出偏转角分辨率为50 nrad，满足偏转精度要求2 μrad。

该机构的偏转方式为一维单向偏转，其简化运动状态如图 3 所示。要想实现一维双向偏转，可以将图 3(b) 所示状态设为偏转零点。减小电压，可以实现绕 Y 轴逆时针偏转，如图 3(a) 所示；增大电压，可以实现绕 Y 轴顺时针偏转，如图 3(c) 所示。

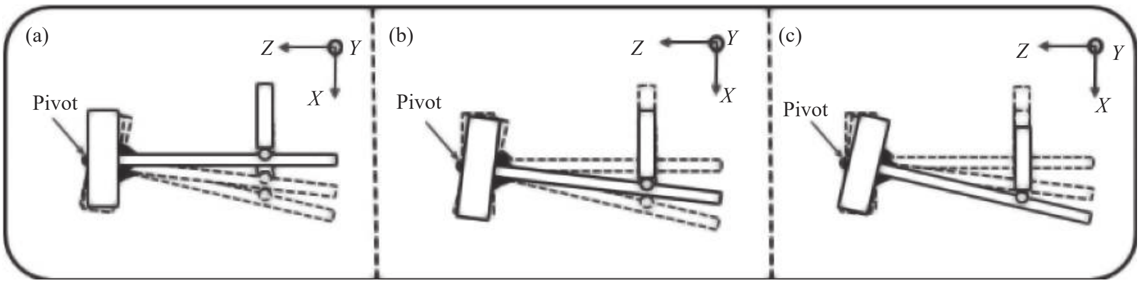


图 3 简化运动状态

Fig.3 Simplified motion state

2 仿真分析

为研究机构是否满足设计要求，利用仿真软件对其进行有限元仿真分析。

2.1 模态分析

首先对其进行模态分析[14]，仿真结果如图 4 所示，得到其一阶模态为 1 157.4 Hz，模态频率较高，六阶模态频率如表 1 所示。进行模态仿真分析能够在设计控制系统时避开相应模态频段，防止共振。

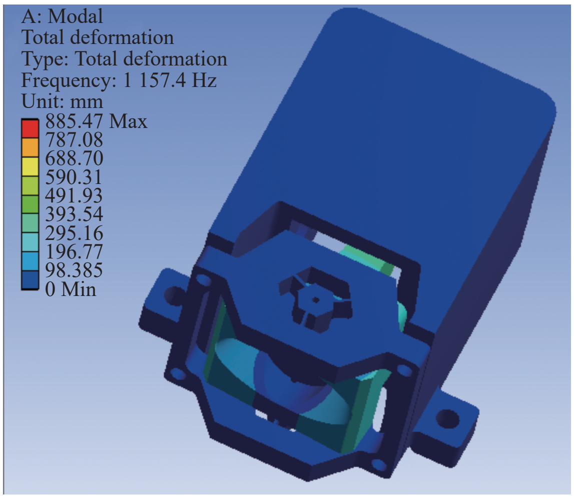


图 4 超前瞄准机构模态分析

Fig.4 Modal analysis of the Point Ahead Angle Mechanism

表 1 6 阶模态频率

Tab.1 Sixth order modal frequency

Modal order	Modal frequency/Hz	Modal shape
1	1 157.4	Rotating around Y
2	3 178.6	None
3	3 483.3	None
4	3 532.5	None
5	5 553.1	None
6	6 855.7	None

2.2 应力仿真

对柔性铰链进行应力分析。柔性铰链选用钛合金 (TC4) 材料，仿真结果如图 5 所示，偏转角度为 779 μrad时最大应力为62.7 MPa，满足钛合金材料应力特性要求。

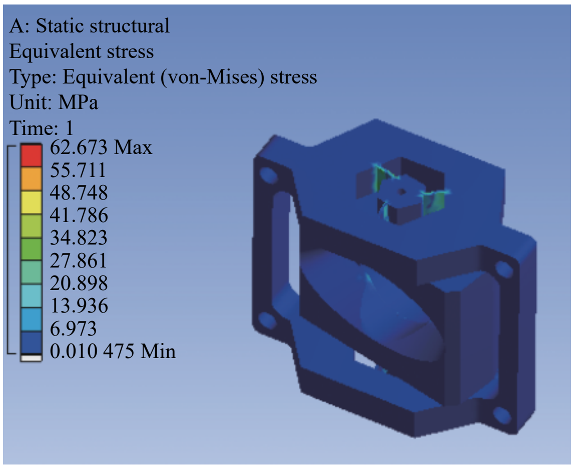


图 5 柔性铰链应力图

Fig.5 Flexible hinge stress diagram

2.3 驱动位移与偏转角度仿真

给予压电陶瓷不同驱动位移，得到不同偏转角度，绘制如图 6 所示的曲线图，可以看出其斜率约为 48.7 μrad/μm，位移为16 μm时，得到的偏转角度为 779 μrad，满足500 μrad设计目标。

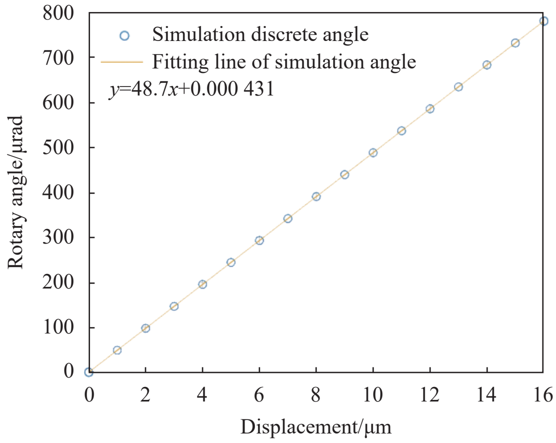


图 6 不同驱动位移下偏转角度拟合曲线图

Fig.6 Rotation angle fitting line under different driving displacements

3 实验测试

根据设计方案研制一套超前瞄准机构，主要特性如表 2 所示。对该超前瞄准机构进行一系列测试实验。

表 2 整体设计的主要特性

Tab.2 Main features of the overall design

Design features	Values
Volume	56 mm × 35 mm × 32 mm
Material	TC4; AL6061; K9
Quality	About 150 g
Mirror size	Φ10 mm
Surface accuracy	λ/30 (RMS; λ = 632.8 nm)

3.1 偏转特性测试

首先，对偏转角度和偏转精度进行了验证。在常温常压相对湿度 60% 的环境下，利用自准直仪对机构的偏转特性进行验证，测试原理如图 7 所示。超前瞄准机构采用压电陶瓷自闭环控制，自准直仪 (ELCOMAT-3000) 的可读精度设置为0.1 μrad。测得其偏转范围大于500 μrad，可达到约709.4 μrad (压电陶瓷驱动位移16 μm)。偏转范围与仿真分析结果相差约70 μrad，相对误差约为 9.8%，这与零件加工精

度、装配误差等有关。在自闭环控制下，对该机构在不同驱动位移下 (0~16 μm) 的偏转角度进行了线性拟合，如图 8(a)、(b) 所示，得到最大残差为0.44 μrad，满足设计初期目标偏转精度2 μrad。

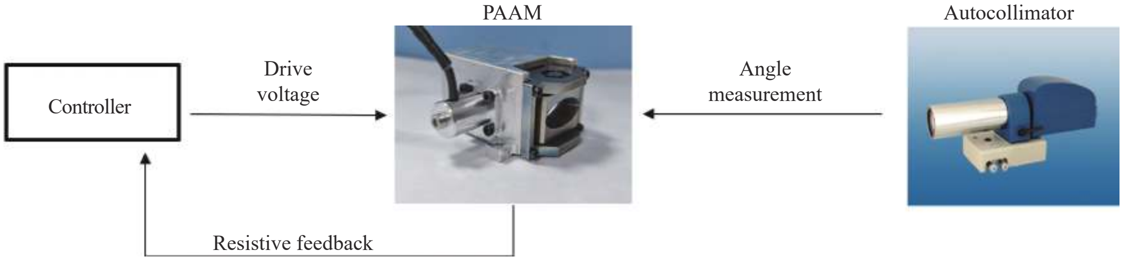
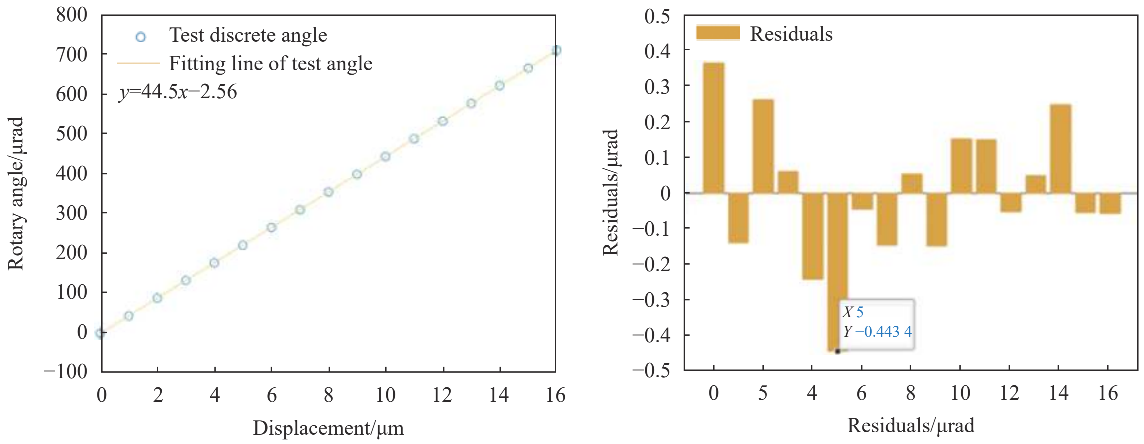


图 7 偏转特性测试原理图

Fig.7 Schematic diagram of rotation characteristic test



(a) 不同驱动位移下偏转角度拟合曲线
(a) Rotation angle fitting line under differen driving displacements

(b) 残差图
(b) The residual graph

图 8 偏转特性测试结果

Fig.8 Test results rotation characteristic

3.2 光程差测试

光程差 (Optical Path Difference, OPD) 是指激光经过超前瞄准机构前后，由于机构本身的抖动引起的光程变化误差[8, 15]。利用激光干涉原理搭建了光程差测试装置，再通过相位计读出相位信息[16]，解算出光程差，如图 9 所示。测试实验使用的相位计相

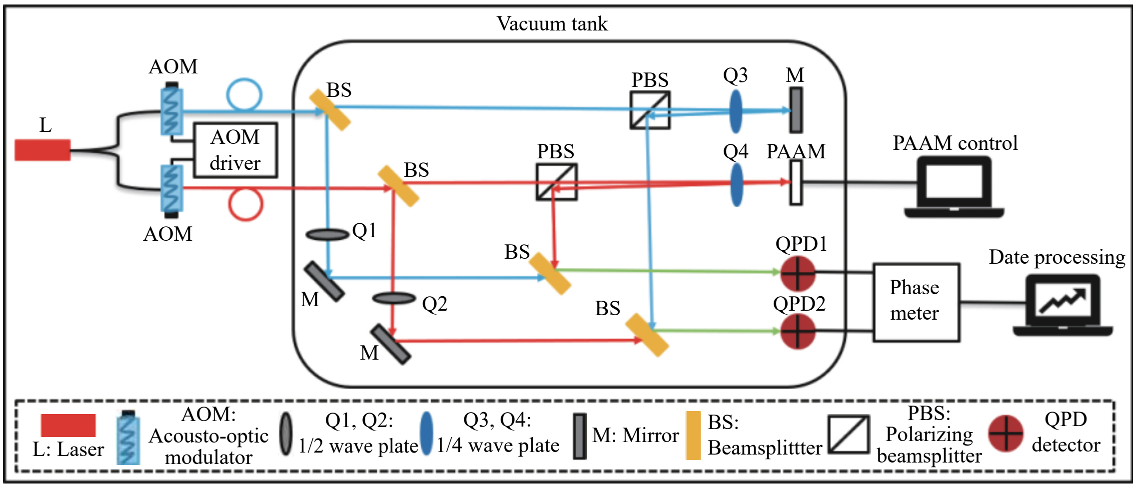
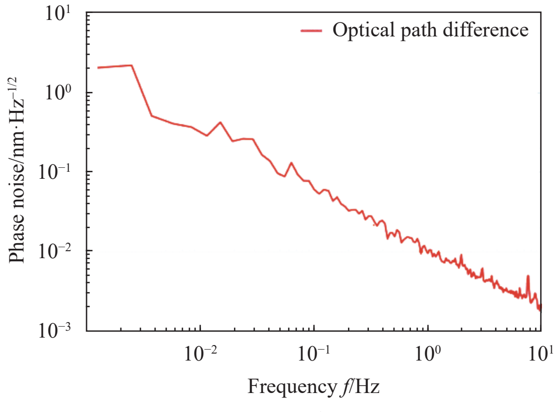


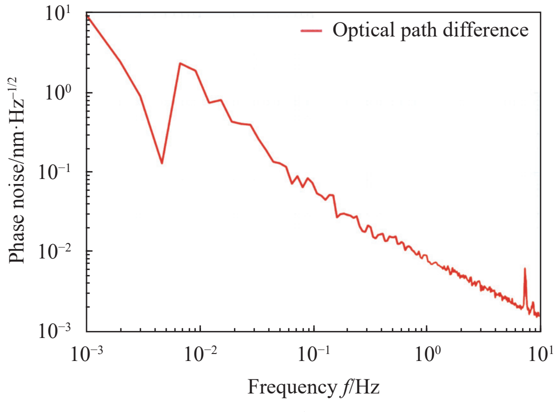
图 9 光程差测试装置原理图

Fig.9 Schematic diagram of optical path difference test device

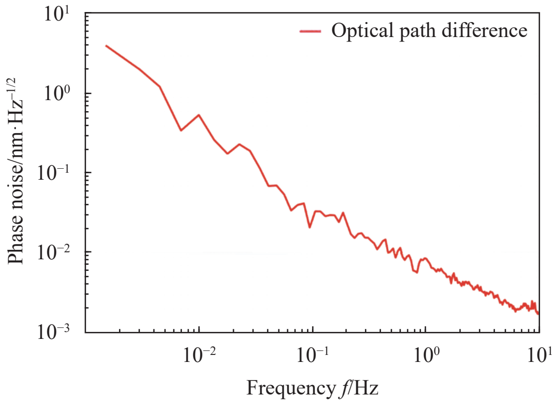
位分辨率为0.5 μrad，经过理论计算，得到理论探测光程分辨率约为0.04 pm(激光波长1 064 nm) 能够用于探测皮米级光程差。因为超前瞄准机构选择驱动位移为8 μm时为动态偏转零点来实现一维双向偏转，所以分别选择驱动位移为0 μm、8 μm和16 μm时，测试其光程差。为确保光斑位置与反射镜面中心轴位置重合，将机构安装在位移调整台 (LY60-C/L/R，位移精度10 μm) 上进行调节。在常温 (24 ℃) 真空环境下 (小于50 Pa)，输入驱动位移为 0 μm、8 μm 和 16 μm 测试了超前瞄准机构的光程差，最后测得的数据经过处理得到结果如图 10(a)~(c) 所示。从图中可以看出，得到的光程差测试结果相似，当频率在 1~10 Hz 时的光程差小于10 pm/ $\sqrt{\text{Hz}}$。而当频率在 1 mHz~1 Hz 时的光程差大于10 pm/ $\sqrt{\text{Hz}}$，这主要与测试环境中温度变化等影响有关[8]。后续针对这些因素，采取诸如主动精密温控等措施进一步优化测试方案。



(a) 驱动位移为 0 μm
(a) When driving displacement is 0 μm



(b) 驱动位移为 8 μm
(b) When driving displacement is 8 μm



(c) 驱动位移为 16 μm
(c) When driving displacement is 16 μm

图 10 光程差测试结果

Fig.10 Test results of optical path difference

因为环境温度变化缓慢，所以温度变化会在低频区域对光程差测试结果产生影响。针对温度变化对光程差测试实验带来的影响，对不同温度下镜面中心点法向位移进行仿真分析，结果如图 11 所示。从图中斜率可以得到温度变化对位移影响明显，为3.5×10^5 pm/℃，要想达到皮秒级测试精度，需要控制环境温度波动在10^{-6} ℃ 量级。

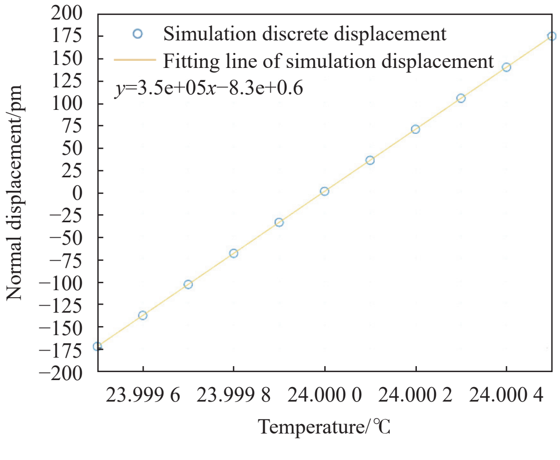


图 11 温度变化对位移的影响

Fig.11 Effect of temperature change on displacement

4 结束语

文中设计并研制了一种用于空间引力波探测装置的超前瞄准机构，并完成了相应指标的测试，验证了该机构原理设计的合理性。该机构是一维双向偏转，偏转范围最大可达 709.4 μrad，偏转精度约

0.44 μrad，均满足预期设计要求。当频率在 1~10 Hz 时该机构引起的光程差优于10 pm/ $\sqrt{\text{Hz}}$，而当频率在 1 mHz~1 Hz 时的光程差大于10 pm/ $\sqrt{\text{Hz}}$。所研制的超前瞄准机构光程差指标与国外先进水平和设计要求存在差距，需要对机构进行优化，同时在光程差测试中重点考虑温度等对光程差测试带来的影响。

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Development and test of the Point Ahead Angle Mechanism for space gravitational wave detection

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Abstract:

Objective To detect low-frequency gravitational waves, it is necessary to eliminate the interference of geo-noise and build a laser interference gravitational wave detection device in space. Taiji, LISA, Tianqin and other space gravitational wave detection missions have been planning to achieve pm-sensitivity on the arm length of several million kilometers to meet the requirements of gravitational wave detection. Because of orbit evolution and time delay in the interferometer arms, the direction of transmitted laser beam changes, consequently, a remote telescope cannot receive the laser beam to complete the inter-satellite laser interference. Aiming at the need for the point ahead angle of the emission beam, a beam pointing mechanism that provides the point ahead angle in the laser interference link is designed and developed for the space gravitational wave detection device, called the Point Ahead Angle Mechanism.

Methods Based on the design concept of aligning the rotary axis on the mirror surface, the Point Ahead Angle Mechanism employs the structural form of flexible hinges and lever (Fig.2), and the control scheme of piezoelectric ceramic self-closing loops to achieve one-dimensional high-precision beam rotation (Fig.3). Mechanical properties are verified by the simulation analysis (Fig.4-5). Rotary range of the mechanism is verified by the simulation analysis (Fig.6). Under the condition of normal temperature and pressure with a relative humidity of 60%, the rotary characteristic test is carried out by using an autocollimator (Fig.7). And under the conditions of normal temperature (24 ℃) and vacuum environment (less than 50 Pa), a special interferometer is built to test the optical path difference (Fig.9).

Results and Discussions A series of experiments are conducted on the mechanism, and the results show that the rotary range of the mechanism is 709.4 μrad, rotary accuracy is 0.44 μrad, and the results meet the requirements (Fig.8). The optical path differences are better than $10\ \mathrm{pm}/\sqrt{\mathrm{Hz}}$ when the frequency is between 1 Hz and 10 Hz, and the results meet the requirement (Fig.10). But when the frequency was between 1 mHz and 1 Hz, the optical path differences are greater than $10\ \mathrm{pm}/\sqrt{\mathrm{Hz}}$. After simulation analysis, they are mainly related to the influence of temperature changes in the experimental environment (Fig.11). This is also the direction of further research. In short, it is proven that the principal design of the mechanism is feasible, and it is a reasonable reference for achieving ultra-stable and high-precision beam rotation.

Conclusions In this study, the Point Ahead Angle Mechanism for space gravitational wave detection is designed and developed, and the corresponding index tests are completed, which verify the rationality of the mechanism design. The mechanism is a one-dimensional and two-way rotation, the maximum rotary range can reach about 709.4 μrad, and the rotary accuracy can reach about 0.44 μrad, all of which meet the expected design requirements. When the frequency is between 1 Hz and 10 Hz, the optical path difference caused by the mechanism is better than $10\ \mathrm{pm}/\sqrt{\mathrm{Hz}}$, and when the frequency is between 1 mHz and 1 Hz , the optical path difference is greater than $10\ \mathrm{pm}/\sqrt{\mathrm{Hz}}$. The optical path difference of the Point Ahead Angle Mechanism developed in this paper still has a gap with the foreign advanced level and design requirements, and the mechanism needs to be optimized. At the same time, the influence of temperature on the optical path difference test should be considered in further research.

Key words: space gravitational wave detection; Point Ahead Angle Mechanism; flexible hinge; optical path difference