光学学报

基于动态全息的面内微振动测量系统

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摘要 为了实时测量高频、微小面内振动,利用硅酸铋(BSO)晶体的光折变特性搭建了基于动态全息的面内微振动测量系统。通过粗糙表面的散射信号光携带面内振动信息,与参考光在晶体内干涉形成动态全息并实时衍射,参考光的衍射光和信号光的透射光之间形成新的干涉,通过光电探测器对干涉信号进行解时域或频域的探测,即可得到振动信息。以剪切式压电陶瓷驱动的散射片为被测物,实验测量了0.5～240 kHz的亚微米量级的面内振动。

关键词 测量；动态全息；面内振动；硅酸铋(BSO)晶体；振动测量

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1 引 言

高频、微小面内振动的测量在航空航天、微机械、材料科学和生物医学等领域扮演着重要角色。为了避免对器件的干扰和损坏,具有高精度、非接触等优点的光学测量法被广泛使用[1-9],其中散斑干涉测量法最为典型,但由于其光源照射与成像处理过程受CCD高速性能的限制,其测量频率无法提高。

基于光折变晶体的动态全息测振法因具有波前匹配、低频截止等优点被逐渐重视。Georges等[10]研究了光折变晶体如何有效应用于全息干涉测量,展示了无损检测、位移和振动计量测量结果,并表明它可能是高要求应用中传统散斑技术的良好替代品。赵书安等[11]分析了应用光折变晶体的准实时、离面微振动测量方法,并给出了计算机模拟结果,结果表明此法易实现且精度高。段昌琪[12]基于硅酸铋(BSO)晶体搭建了自适应的双波混合干涉仪进行振动测量,讨论了光强比、总光强、外加电压对灵敏度的影响,并成功测量了超声探头的微小离面脉冲振动。

包括上述研究在内,基于光折变晶体干涉测振的研究几乎都是针对离面振动,信号光垂直照射在被测物表面即可受到离面振动的调制,但难以受到面内振动的调制。本文研究了基于BSO晶体动态全息的面内振动测量系统,通过信号光照射粗糙表面携带面内振动信息,并利用BSO晶体的多通道复用,让信号光的多束散射子波与参考光在晶体内形成动态全息,每一束散射子波的透射光都会与参考光的衍射光发生干涉,用透镜收集多束干涉信号以提高系统灵敏度。实验测量了0.5～240 kHz的面内振动,并与商用测振仪对比,验证了系统的可行性。

2 测量原理

2.1 动态全息

测量原理如图1所示。实验时,受到振动信号调制的信号光射入光折变晶体后与参考光发生干涉,由于晶体具有光折变特性,其折射率在空间调制光强的辐照下发生了相应的变化[13],生成布拉格光栅,两束光都满足布拉格条件。参考光经过光栅后的衍射光与信号光的透射光发生干涉,通过探测器接收干涉信号并进行解调即可得到振动信息。晶体内的动态全息过程使得参考光的衍射光与信号光的透射光具有波前自适应特性,相比传统干涉仪,基于动态全息原理的系统更加适于粗糙表面的测量。

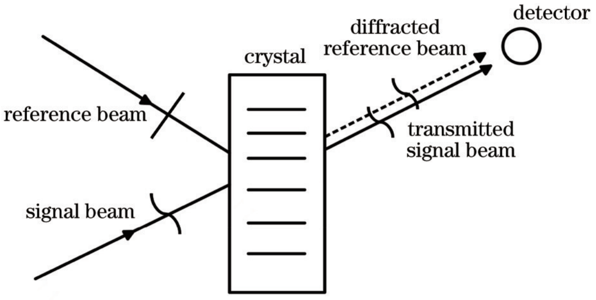

图1 动态全息原理

Fig. 1 Principle of dynamic holography

2.2 面内振动测量

振动可以分为振动方向垂直于物体表面的离面振

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动分量和平行于物体表面的面内振动分量。如图 2 所示，将振动位移量D分解后，可得

$$D_{\text{out-plane}}=(D_1+D_2)/(2\cos\theta),\tag{1}$$

$$D_{\text{in-plane}}=(D_1-D_2)/(2\sin\theta),\tag{2}$$

式中：$D_{\text{out-plane}}$表示离面振动分量；$D_{\text{in-plane}}$表示面内振动分量；D_1、D_2表示振动在探测器方向上的分量；θ为探测器方向与离面方向之间的夹角。因此，对于一般激光干涉测振方法，单束激光垂直照射振动物体表面，可直接获得离面振动信息。以一定角度照射时，可获得面内振动信息。

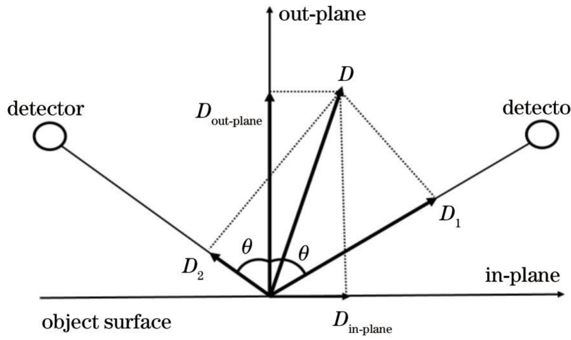

图 2　面内测振原理

Fig. 2　Principle of in-plane vibration measurement

3　实验及结果

3.1　实验装置

基于动态全息的面内微振动测量系统的实验装置如图 3 所示。光源选用输出功率为 150 mW、波长为 532 nm 的单纵模连续固体激光器，光折变晶体采用 5 mm×5 mm×5 mm、(001)切割的 BSO 晶体，被测振动物体为一散射片，由剪切压电陶瓷(shear PZT)驱动，产生具有横向位移量的面内振动，最大位移量为 1.3 μm。激光出射后经准直扩束，再通过 1/2 波片和偏振分光棱镜(PBS)被分成信号光与参考光，1/2 波片结合 PBS 可调整两束出射光之间的光强比。参考光进入 BSO 晶体前经过一个 1/4 波片，其作用是引入一个相位差，以满足信号光与参考光干涉所需的π/2 相位匹配条件，增强干涉信号。信号光先通过 1/2 波片使其与参考光的偏振方向一致，随后照射在由剪切压电陶瓷驱动的散射片上，并受到散射片面内振动的调制。利用 BSO 晶体的多通道复用性，使多束信号光的散射光通过透镜会聚在 BSO 晶体内，并与参考光发生干涉，形成动态全息。参考光的衍射光与信号光的透射光再次发生干涉，干涉信号被探测器接收。利用示波器和频谱仪即可观察到干涉信号并解调出振动信息。

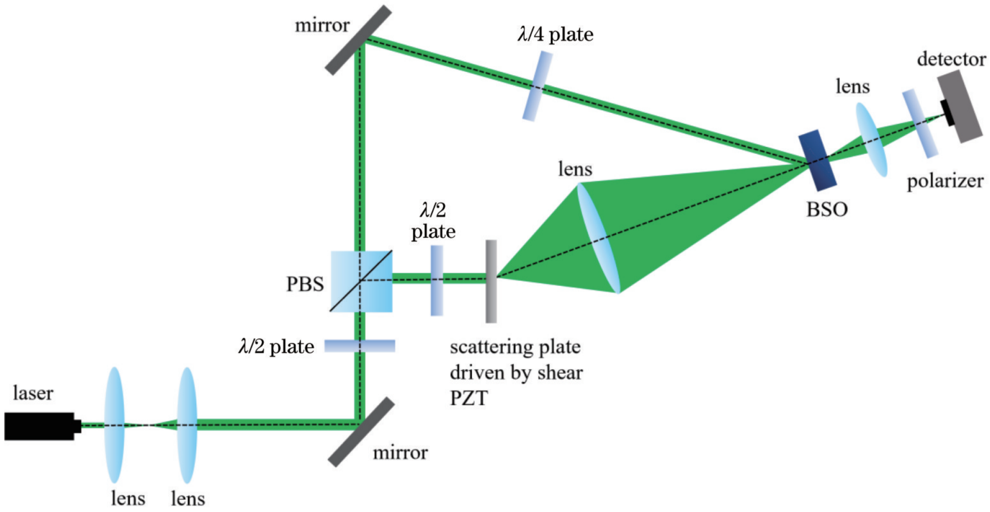

图 3　实验装置图

Fig. 3　Schematic of experimental setup

3.2　实验结果

3.2.1　衍射效率

对于 BSO 晶体内的动态全息，参考光和信号光的夹角在 20°～40°范围内，衍射效率较高，在 30°时衍射效率达到最高[14]。使信号光主光线与参考光的夹角为 30°，调节 PBS 前的 1/2 波片来改变参考光和信号光的光强比。遮挡参考光后，通过观察示波器上的信号幅值变化来判断衍射光强。当激光光源功率为最大值 150 mW 时，衍射信号幅值与光强比的关系如图 4 所示，可以看出，当参考光与信号光的光强比为 5:1 左右时，衍射强度最大。

3.2.2　振动测量结果

信号光主光线与参考光的夹角为 30°，激光器功率为 150 mW，光强比为 5:1，剪切压电陶瓷加载 1 kHz、80～200 V 的正弦电压驱动。在散射片侧面粘贴一张反光贴纸，用 PDV100 测振仪(德国 Polytec 公司)测量散射片的离面振动，亦为本系统直接测量的散射片的面内振动，结果如图 5 所示。将两者测量结果进行对比，结果如图 6 所示，测量结果呈高度线性相关。

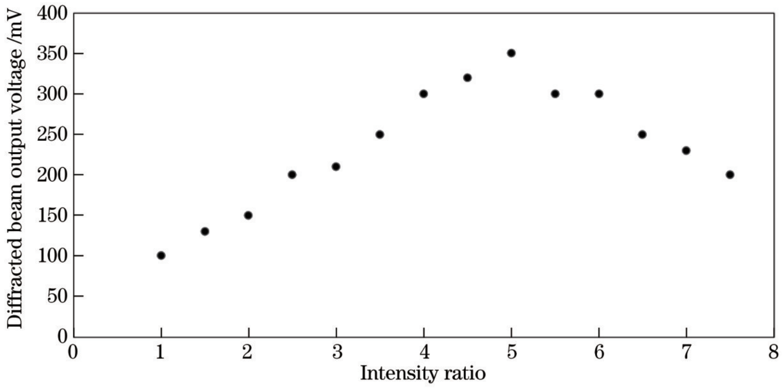

图 4　衍射信号与光强比的关系

Fig. 4　Diffracted output voltage versus intensity ratio of reference beam to signal beam

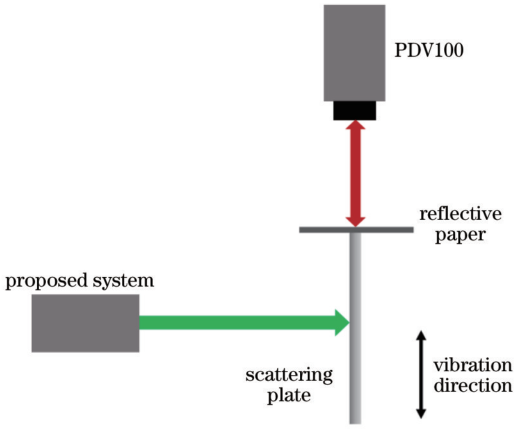

图 5　所提系统与PDV100测振仪进行对比的实验布局

Fig. 5　Layout of the comparison experiment of proposed system with PDV100 vibrometer

剪切压电陶瓷由 200 V、500～5000 Hz 的正弦信号驱动，得到的时域对比测量结果如图 7 所示。信号 1 为本系统测得信号，信号 2 为 PDV100 测得信号，两者的测量结果一致，验证了本系统的可行性。根据 PDV100 测振仪给定的输出电压信号与振速之间的比例因子，并利用振幅与振速的换算关系，得到振动频率为 5 kHz时的振幅为 0.11 μm。

PDV100 测振仪的最高测量频率仅为 20 kHz，因此利用本系统单独测量了 20～240 kHz 的面内振动，通过频谱仪的解调得到频域信号，结果如图 8 所示，可以看出测得的振动频率与加载在剪切压电陶瓷上的信号频率一致。

4　结论

微振幅高频振动的检测在无损检测、质量控制和状态监测等领域具有较高的应用价值，特别是被测振动表面通常为粗糙表面，导致传统激光干涉方法的测量灵敏度较低。不同于较易测量的离面振动，本文研究了一种针对面内振动的动态全息测量系统，信号光透过散射片后受到其面内振动的调制，散射光与参考光在 BSO 晶体内形成动态全息。通过 BSO 晶体的散射光的透射光与参考光的衍射光发生干涉，对干涉信号进行解调可以获得面内振动信号。BSO 晶体的光折变特性，使其能够记录动态全息并实时衍射，使得两干涉光束具有波前自适应特性，适于测量粗糙表面的振动。结合其低频截止的特性，能够获得更高的测量灵敏度，更加适于微小振幅的高频振动测量。通过与商用测振仪的测量结果对比，证实了本系统的可行性。以散射片为被测物，目前最高可测得频率为 240 kHz

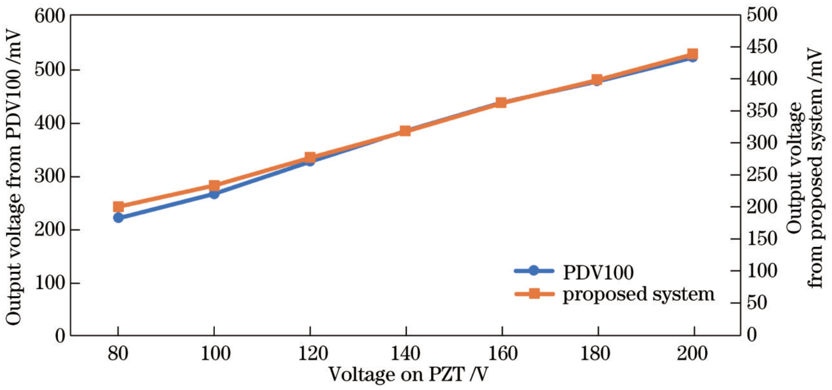

图 6　所提系统与PDV100测量结果对比

Fig. 6　Comparison of the measurement results by proposed system and PDV100

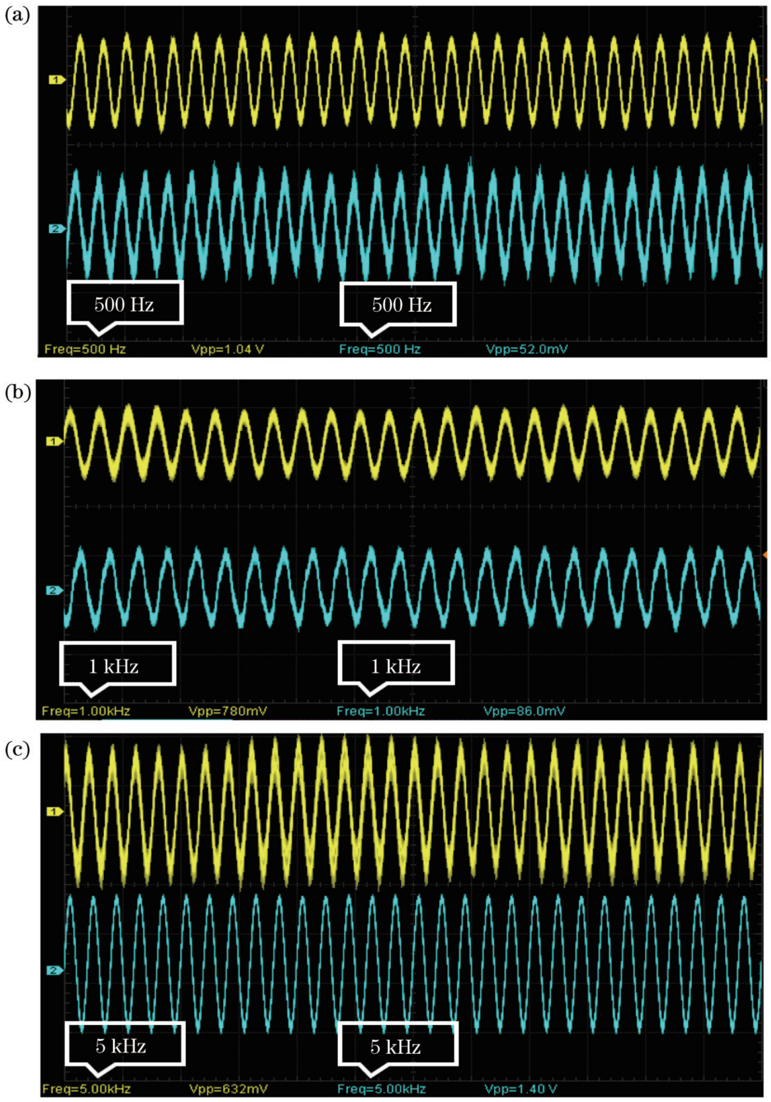

图 7　不同频率下的对比结果。(a)500 Hz；(b)1 kHz；(c)5 kHz

Fig. 7　Comparison results at different frequencies. (a) 500 Hz; (b) 1 kHz; (c) 5 kHz

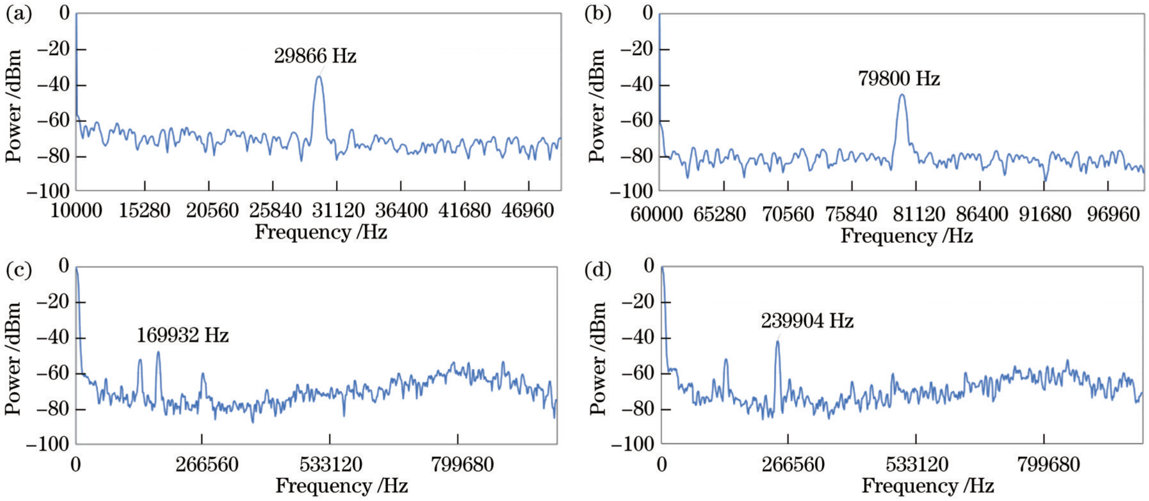

图 8　不同频率下所提系统的测量结果。(a)30 kHz；(b)80 kHz；(c)170 kHz；(d)240 kHz

Fig. 8　Measurement results of proposed system at different frequencies. (a) 30 kHz; (b) 80 kHz; (c) 170 kHz; (d) 240 kHz

的亚微米级面内振动。

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In-Plane Micro-Vibration Measurement System Based on Dynamic Holography

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Abstract

Objective The measurement of high frequency and micro-vibration plays a critical role in multiple fields, such as nondestructive testing, micro machinery, materials science, biomedicine, and aerospace. Optical measurement methods with high accuracy, non-contact, and other advantages are widely applied to avoid device interference and damage. Compared with out-of-plane vibration measurement, in-plane vibration measurement is difficult because the measured light cannot be incident parallel to the in-plane vibration direction. Speckle interferometry is the most commonly used method for in-plane displacement measurement. However, owing to the high-speed performance limitation of the charge-coupled device (CCD) in the imaging process, its measurement frequency cannot be increased. In addition, the measured vibration surface is typically rough, leading to low measurement sensitivity for traditional laser interferometry. The dynamic holographic vibration measurement method based on a photorefractive crystal has attracted increasing attention due to advantages such as wavefront matching and low-frequency cutoff. In this study, a dynamic holographic in-plane vibration measurement system based on bismuth silicate (BSO) crystal is examined, which measures high frequency and small in-plane vibration in real time. It has strong anti-interference ability and is suitable for rough surfaces.

Methods The laser beam emitted from the source is split into a reference beam and a signal beam. The signal beam carrying in-plane vibration information passes through a scatterer driven by shear piezoelectric ceramics. Both beams interfere in a BSO crystal. According to the photorefractive properties of BSO crystal, a refractive index grating is formed on the crystal which is equivalent to the interference recording in holography. The grating automatically meets the Bragg condition, and the reference beam generates Bragg diffracted beam in real time, which is equivalent to the diffraction reproduction in holography. The diffracted beam of the reference beam passing through the grating interferes with the transmitted beam of the signal beam. Vibration information can be obtained by receiving the interference signal and demodulating it through the detector. The relationship between the intensity of the diffraction signal and the light intensity ratio of the two interference beams is measured to obtain a better interference signal. A commercial out-of-plane laser vibrometer PDV100 (Polytec, Germany) is used for comparison, and the feasibility of the proposed system for measuring in-plane micro-vibration is verified. The capability of the proposed system to measure high-frequency vibration is also verified by demodulating the loading frequency beyond the measurement upper limit of PDV100. To this end, the demodulation frequency is obtained directly by the spectrum analyzer.

Results and Discussions First, the relationship between the intensity of the diffraction signal and the light intensity ratio of the two interference beams is measured (Fig. 4). The highest diffraction efficiency is established, which obtains a better interference signal. PDV100 and the proposed system are placed in a mutually vertical structure relative to the measured object, and the out-of-plane vibration measured by PDV100 is the in-plane vibration measured by the proposed system. When the measured object is driven by sinusoidal voltage with the same frequency and different voltage (1 kHz, 80–200 V), the measurement results of the proposed system demonstrate a highly linear relationship with those of PDV100 (Fig. 6). When the measured object is driven by sinusoidal signals with the same voltage and different frequencies (200 V, 500 Hz–5 kHz), the time domain signal measurement results of both measurement systems are consistent, which verifies the feasibility of the proposed system (Fig. 7). According to the relevant calibration of the PDV100 and the conversion relationship between amplitude and vibration velocity, the amplitude is 0.11 μm when the vibration frequency is 5 kHz. In addition, as the upper measurement limit of the PDV100 vibrometer is 20 kHz, the in-plane vibration of 20–240 kHz is also measured. The frequency domain signals are obtained by the spectrometer (Fig. 8), and the measurement results are consistent with the signal frequency loaded on the shear piezoelectric ceramics.

Conclusions In contrast to out-of-plane vibration which is straightforward to measure, this paper proposes a dynamic holographic measurement system for in-plane vibration. The signal beam is modulated by the in-plane vibration of a scatterer after passing through it. The signal and reference beams form dynamic holography in a BSO crystal. Interference between the transmitted scattered beam and the diffraction beam of the reference beam occurs, and the in-plane vibration signal is obtained by demodulation of the interference signal. Photorefractive properties of the BSO crystal enable it to record dynamic holography and diffract in real time. As a result, the automatic wavefront match of the two interference beams can be achieved, which is suitable for measuring the vibration of rough surfaces. Combined with the low-frequency cutoff of BSO crystals, higher measurement sensitivity can be obtained and it is more suitable for high-frequency vibration measurement with small amplitude. The feasibility of the proposed system is verified by the comparison with the measurement results of a commercial vibrometer. With the scatterer as the object, the submicron in-plane vibration with a frequency of 240 kHz can be measured.

Key words measurement; dynamic holography; in-plane vibration; bismuth silicate (BSO) crystal; vibration measurement