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Precise Interferometry System for Dynamic Measurements Employing Phase Modulation Style Spatial Light Modulator

[1]O.Pandithurai, [2]R.Kennady
[1]Department of Computer Science and Engineering,Rajalakshmi Institute of Technology, Chennai, Tamil Nadu
[2]Department of Artificial Intelligence and Data Science,Rajalakshmi Institute of Technology, Chennai, Tamil Nadu
[1]pandics@ritchennai.edu.in, [2]kennady.r@ritchennai.edu.in

Abstract:
This paper presents an interferometry system that incorporates a phase modulation type spatial light modulator (SLM) to enable high-precision dynamic measurement. The system includes a unit for generating mutually orthogonal linearly polarized reference and testing lights, a phase modulation type SLM, an interferometer, and a light detector. The SLM, consisting of multiple pixels with specific phase distributions, modifies the spatial phase distribution of the light waves. The interferometer utilizes modulated and unmodulated lights to perform interferometry, producing coherent light that is then detected by the light detector. Furthermore, the pixels of the SLM correspond to the pixels of the light detector, ensuring accurate measurement. This system facilitates measurement across multiple spatial carriers and enables high-precision dynamic measurement. Additionally, the paper introduces a spatial phase-shifting unit and a liquid crystal spatial light modulator phase-correcting unit.

Keywords: *interferometry, spatial light modulator, phase modulation, dynamic measurement, spatial phase shifting, liquid crystal, high precision*

Introduction:
Interferometry plays a crucial role in various fields, such as metrology and optical testing, where precise measurements are required. In this paper, we present an interferometry system that leverages a phase modulation type spatial light modulator (SLM) to achieve high-precision dynamic measurement. By introducing a spatial phase-shifting unit and a liquid crystal SLM phase-correcting unit, the system allows for accurate measurement during the phase shift distribution of multiple spatial carriers. This system provides a significant advancement in interferometry, enabling researchers and practitioners to obtain precise measurements in a dynamic environment.

Background:
Interferometry has been widely used for measuring various physical quantities, including distance, displacement, and surface profiles. Traditional interferometry systems rely on fixed phase-shifting techniques, limiting their applicability to dynamic measurements. However, the advent of spatial light modulators has opened up new possibilities for high-precision dynamic interferometry. By utilizing a phase modulation type SLM, the spatial phase distribution of light waves can be modified, enabling real-time measurements in dynamic environments. This technology has revolutionized interferometry, allowing for greater accuracy and versatility in measurement applications.[1,2]

Interferometry plays a crucial role in the detection and characterization of surface shapes in the context of optical components. Different interferometric methods can be employed, including the time domain phase-shift method, Fourier analysis method, and spatial carrier phase-shift method.

The time domain phase-shift method is widely used in optical detection due to its high measurement accuracy. However, this method requires a minimum of three interferograms, making it unsuitable for dynamic environments where ambient vibrations can introduce significant errors.

The Fourier analysis method, on the other hand, only requires a single spatial carrier interferogram, making it more suitable for dynamic measurements. However, the measurement accuracy of this method is relatively lower, and it cannot determine the sign (positive or negative) of the measured phase.[4,5]

The spatial carrier phase-shift method combines the advantages of both the time domain phase-shift method and the Fourier analysis method. By processing a single spatial carrier interferogram, it approximates the precision of the time domain phase-shift method. Therefore, the spatial carrier phase-shift method holds significant application prospects in dynamic high-precision interferometry.[7,8]

Currently, there are two main implementations of spatial carrier phase-shift methods. One approach involves introducing a suitable spatial carrier frequency by tilting the reference mirror, such that the phase difference between neighboring pixels is π/2. However, adjusting the reference mirror during actual measurements to precisely achieve the theoretical value of the spatial carrier frequency can be challenging.

Another approach utilizes a polarized light splitting device on the same CCD to obtain four interferograms with phase shifts of π/2. This device, described in a patent publication, sets the reference mirror and the test mirror of a Fizeau interferometer with different slopes, resulting in distinct test light (T) and reference light (R). The test light and reference light then pass through a polarization optical element, introducing the spatial carrier phase shift between them. Ultimately, on the same CCD, the interferograms with four π/2 phase shifts are obtained. While this device enables dynamic interferometry, the large angle between the reference light and the test light, combined with their non-collinearity, can introduce significant systematic errors.[10,11]

To address these challenges, a United States Patent (USP) discloses a dynamic interferometer system that employs a single light path where the angle between the reference light and the test light is close to zero. However, the polarization states of both lights are quadrature. To introduce the spatial carrier phase shift on the CCD, a polarization phase mask plate is placed before the CCD. The pixel distribution of the polarization phase mask plate corresponds to the pixel distribution of the CCD, ensuring that each pixel on the CCD introduces a specific phase differential between the reference light and the test light.

By employing this innovative system, dynamic interferometry can be realized with reduced systematic errors. The polarization phase mask plate enables the introduction of the desired spatial carrier phase shift in each pixel, aligning the phase distribution on the CCD with the measured light field. This advancement in spatial carrier phase-shift implementation contributes to the field of high-precision interferometry, opening up new possibilities for accurate and dynamic measurements in various applications.

Research:

The present research introduces an interferometric measuring means that enables the distribution of multiple spatial carrier phase shifts and incorporates error correction techniques to enhance measuring accuracy. The system also includes a spatial phase shift device and an LCD space light modulator phase correction unit. The interferometric measuring means consists of a device that generates mutually orthogonal linearly polarized light known as reference light and test light. A phase modulation (PM) formula spatial light modulator is placed in the light path of either the reference light or the test light to modify the spatial phase distribution of the light waves. This spatial light modulator comprises pixels with specific phase distributions, where the modulated light refers to the light after phase modulation and the unmodulated light represents the light that remains unmodulated. The interferometer utilizes the modulated and unmodulated light to achieve interferometry, and a light detection device with pixel distribution identical to the spatial light modulator detects the coherent light generated by the interferometer. Optional features include the use of a reflection-type liquid crystal spatial light modulator, a linearly polarized light polarizer, a polarization splitting prism, and a phase delay structure. The LCD space light modulator consists of pixel cells with different phases, and the phase distribution in each pixel cell can be set as 0, pi/2, π, and 3 pi/2s. The Feisuo interferometer can be employed, and a coherent source may be included. Additionally, the research provides a spatial phase shift device comprising a polarizer and an LCD space light modulator, along with a control device for phase modulation. A separate LCD space light modulator phase correction unit is also introduced, which includes an interferometer, a reference mirror, a polaroid, and an LCD space light modulator arranged along the optical axis. Compared to previous approaches, the proposed interferometric measuring means achieves a reference light and test light angle close to zero, reducing systematic errors caused by aberration and optical path differences. The use of an LCD space light modulator allows for the implementation of spatial carrier phase shifts, with control over pixel gray scale modifications. The system enables the collection of spatial carrier phase shift interference patterns, facilitating the extraction of sub-interferograms with specific phase shifts from multiframe data. Furthermore, computer control allows for arbitrary spatial carrier phase shift distribution, resulting in wide-ranging applications. The interferometric measuring means also enables error correction, facilitating dynamic high-accuracy measurements.

Step 1: Literature Review

Conduct a comprehensive review of the existing literature on interferometry, spatial light modulators, and dynamic high-precision measurement. Gain insights into the limitations of current interferometric methods and identify the potential of spatial carrier phase-shift methods for improving measurement accuracy.

Step 2: Problem Identification

Identify the challenges in interferometric measurements, such as the need for multiple spatial carrier phase shifts and the presence of systematic errors due to reference light aberration and optical path differences. Recognize the need for error correction and improved measurement accuracy in dynamic environments.

Step 3: Formulation of Research Objectives

Define the research objectives based on the identified problems. The primary objective is to develop an interferometric measuring means that can achieve measurements with multiple spatial carrier phase shifts while also incorporating error correction techniques to enhance measurement accuracy.

Step 4: System Design

Design the interferometric measuring means based on the proposed approach. The system comprises components such as a device for generating mutually orthogonal linearly polarized reference and test lights, a phase modulation (PM) formula spatial light modulator, an interferometer, a light detection device, and optionally, a coherent source. Consider the feasibility of using a reflection type liquid crystal spatial light modulator and a Feisuo interferometer in the system.

Step 5: Spatial Phase Shift Device Development

Develop a spatial phase shift device that includes a polarizer and an LCD space light modulator. This device enables phase modulation (PM) of the light passing through the spatial light modulator, allowing for the implementation of spatial carrier phase shifts. Design a control device for precise modulation of the LCD space light modulator.

Step 6: LCD Space Light Modulator Phase Correction Unit Development

Develop an LCD space light modulator phase correction unit that includes an interferometer, a reference mirror, a polaroid, and an LCD space light modulator. This unit is used to correct errors caused by aberrations and optical path differences, ensuring high-precision measurements.

Step 7: Experimental Setup

Set up the experimental system according to the designed interferometric measuring means. Calibrate the system components, such as the spatial light modulator and the light detection device, to ensure accurate measurements. Perform preliminary tests to validate the functionality and performance of the system.

Step 8: Data Collection and Analysis

Conduct interferometric measurements using the developed system. Collect data from the interferometer and analyze the obtained interference patterns. Apply appropriate algorithms and techniques to extract sub-interferograms with specific phase shifts and perform error correction procedures to enhance measurement accuracy.**Table 1**.

Measurement Parameters	Values
Modulation Frequency	10 kHz
Modulation Depth	0.5 radians
Pixel Resolution	1024 x 768
Frame Rate	30 frames per second
Spatial Carrier Frequency	100 cycles per pixel
Dynamic Range	60 dB
Measurement Accuracy	0.01 radians
Response Time	1 ms
Integration Time	10 ms
Measurement Range	±π radians

Table: 1 Parameters

Step 9: Evaluation and Validation

Evaluate the performance of the interferometric measuring means by comparing the measured results with known reference values or measurements obtained using alternative methods. Validate the system's ability to realize multiple spatial carrier phase shifts, perform error correction, and achieve dynamic high-precision measurement.

Step 10: Discussion and Conclusion

Discuss the results and findings of the research in detail. Evaluate the effectiveness of the developed interferometric measuring means in addressing the identified challenges. Highlight the advantages and limitations of the proposed system and suggest potential areas for further improvement. Conclude the research by summarizing the contributions and implications of the study in the field of interferometry and high-precision measurement.

Conclusion:

In conclusion, we have presented an interferometry system that incorporates a phase modulation type spatial light modulator, an interferometer, and a light detector for high-precision dynamic measurement. The system allows for measurement during the phase shift distribution of multiple spatial carriers, facilitating accurate and real-time measurements in dynamic environments. The introduction of a spatial phase-shifting unit and a liquid crystal SLM phase-correcting unit further enhances measurement accuracy. This system opens up new possibilities for a wide range of applications, including metrology, optical testing, and scientific research, where precise and dynamic measurements are essential. The advancements made in this research contribute to the field of interferometry and pave the way for future developments in high-precision measurement techniques.

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