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A non-contact distance sensor with spectrally–spatially resolved white light interferometry

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ABSTRACT

A non-contact distance sensor with spectrally-spatially resolved white light interferometry (SSRI) is proposed. With a charge coupled device (CCD) camera and a beam splitter added to the typical experimental setup of spectrally resolved interferometry (SRI), the spatial white light interferogram and the spectrum are recorded simultaneously. The two interferograms are used to measure distances in different measuring ranges. Adopting the proposed method, the dead zone of SRI measuring range is eliminated by analysing the shift of zero-order interference fringe in CCD camera field. In addition, the distance sign (positive or negative) of SRI is determined by analysing the nonlinear spectral phase caused by a dispersive plate, leading to the double extension of the measuring range. An experiment is performed to verify the advantage of this method. The root mean square (RMS) of 20 consecutive distance measurement errors is 0.013 μm and the measuring range is successfully extended to −160 to 160 μm from 8 to 160 μm, which demonstrates that the new method is effective to overcome the measuring range limits of SRI.

1. Introduction

Distance measurement plays a crucial role in a variety of applications, such as micromanufacturing, precision alignment, position monitoring, vibration analysis and optical profilometry [1–3]. During the past few decades, a number of sensors have been developed to meet the ever-increasing requirements of distance measurement. These sensors are classified as contact and non-contact sensors depending on their operating mode. For a contact distance sensor, which is usually a mechanical probe, measurement is time consuming because the probe must be picked up after each measurement to avoid scratching the surface. In addition, the radius of the curvature of the probe and the lateral force of the probe may introduce additional measurement errors. To overcome these drawbacks, various types of non-contact distance sensors have been studied, including sensors based on laser triangulation, atomic force microscopy, spectral confocal principles and low-coherence interferometry. Among these sensors, low-coherence interferometry has been widely used for ambiguity-free measurement of profiles of discontinuous structures, with nanometre accuracy.

Two methods of low-coherence interferometry are mainly studied: one is vertical scanning white light interferometry (VSWLI) [4–7], which requires a large number of optical path difference (OPD) scans along the height axis to determine the profile variation over the object field, and the other is often referred to as spectrally resolved interferometry (SRI) [8–10]. By using a multichannel spectrometer, the interferogram is analysed in the spectral domain, and the target phase can be extracted from a single spectral interferogram. The main advantage of SRI is that no mechanical or electrical scanning process is required, thus, measurements can be performed in real time. In addition, the measurement range of SRI is greatly expanded compared to that of VSWLI.

Researchers have developed various types of sensors based on SRI. Hlubina adopted a Michelson interferometer of spatial distribution to measure different physical quantities such as distance [11], thickness [12] and dispersion [13]. Debnath introduced a microstructure based on phase shifting interferometry for measuring optical profiling [14]. In some cases, the slope of specimens varies as the position changes, and a microscopic structure is necessary to collect more reflected light and make the contrast of the recorded interference signal good enough. Srivastava used a fibre-optic spectral-domain low-coherence interferometry to measure refractive index [15]. However, most of these studies focused on the applications of SRI and not SRI itself.

Typically, SRI can measure distances in the range of a few micrometres (L_{min}) to a few hundred micrometres (L_{max}), which was

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first described by Schnell et al. [16]. Two limitations exist in SRI measurement: distances less than L_{min} are difficult to measure [17] and only the absolute value of OPD can be detected [18–20]. Joo [21] adopted an optical comb in SRI to extend the maximum measurable value, and the spectral resolution was also improved by the discrete broad spectrum, this method did not deal with the problem of dead zone. Another research by Joo [17] put forward a dichroic spectrally resolved interferometry to overcome the measuring range limitations of the traditional SRI. A dual reference mirror structure was adopted so as to acquire two distances simultaneously, the direction was determined and the dead zone was eliminated based on the relationship between the two distances. The relative position of two reference mirrors need to be decided according to the condition in advance.

In this article, a non-contact distance sensor based on spectrally-spatially resolved white light interferometry (SSRI) method is studied. Adopting the proposed method, the measuring range limits of SRI is efficiently overcome. With a charge coupled device (CCD) camera and a beam splitter (BS) added to the typical SRI setup, spatial white light interference fringes can be recorded with spectral interferograms simultaneously. The distance in the dead zone is measured by analysing the shift of zero-order fringe in CCD camera field while the sign of the distance measurement results with SRI method is decided by analysing the nonlinear spectral phase caused by a dispersive plate.

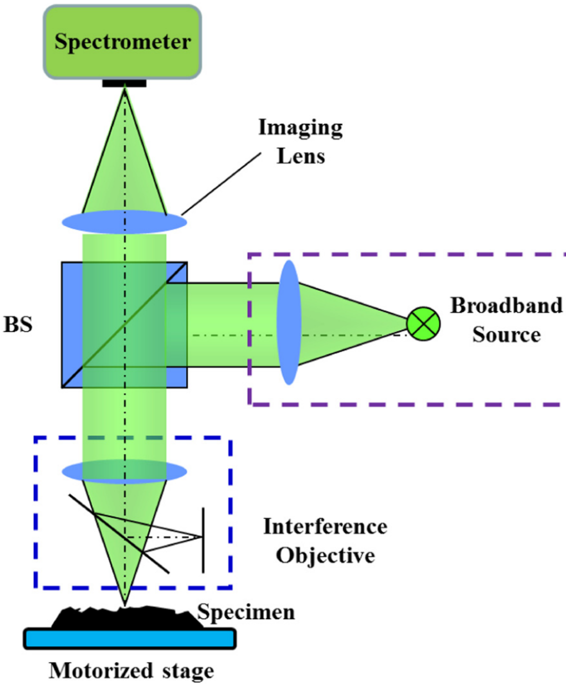

Fig. 1. Optical layout of SRI with a Michelson interference objective.

2. Theory

2.1. Measuring range limitations of SRI

Fig. 1 gives out the optical layout of SRI with a Michelson interference objective, the interferogram is spectrally decomposed by passing it through a spectrometer. The recorded spectral intensity $S(k)$ can be expressed briefly as follows:

$$S(k) = A(k) + B(k)\cos(2\pi k\Lambda) \tag{1}$$

Here, $A(k)$ and $B(k)$ are the baseline and the contrast spectra, respectively, and $k = 1/\lambda$ and $\Lambda = 2Z$represent the OPDs, where Z is the desired distance. By processing a single spectral interferogram with a proper method, for instance, the fast Fourier transform (FFT) method [22,23], the distance can be determined.

By using the synchronous sampling technique, Schnell [16] derived the minimum (Z_{min}) and maximum (Z_{max}) measurable distances of SRI theoretically as follows:

$$\begin{cases} Z_{min} = \dfrac{\lambda_0^2}{\Delta\lambda} \\ Z_{max} = \dfrac{\lambda_0^2}{6\Delta\lambda_{sr}} \end{cases} \tag{2}$$

where λ_0 is the central wavelength, $\Delta\lambda$ is the bandwidth of light source and $\Delta\lambda_{sr}$ is the resolution of the spectrometer. For typical SRI devices, the measurable range available is a few micrometres to a few hundred micrometres. The application of SRI is restricted by two measuring range limitations: (1) there exists a dead zone in the range of zero to the minimum measurable distance and (2) the sign of the extracted distance cannot be decided.

To illustrate this problem, the specimen is moved gradually towards the optical axis of the system device from a position far from the interference objective, as shown in Fig. 2(a). Fig. 2(b) shows different distance measuring ranges. The optical axis is chosen for establishing the z axis; the Z values, which represent the distances, are the distances between the specimens and the plane of zero OPD. In general, the traditional SRI measurements have mostly been implemented in the range of $[-Z_{max}, -Z_{min}]$ or $[Z_{min}, Z_{max}]$ with an unknown sign. The interval $[-Z_{min}, Z_{min}]$ is the dead zone of SRI measuring range.

2.2. System configuration of the distance sensor by SSRI method

Fig. 3(a) shows the system configuration of the distance sensor by the SSRI method. Light from a broadband source is incident on a beam splitter (BS1) before entering into the interference objective, where the light is reflected from the reference mirror, and the specimen goes back into BS1 along the former path, thus resulting in an interference. The interference pattern is recorded by a spectrometer and a CCD camera simultaneously after the light beams are split by another beam splitter (BS2). This interference pattern is modulated by a cosine function that is determined by the OPD. In the dead zone of $[-Z_{min}, Z_{min}]$, distance measurement is realized with a spatially resolved white light interferometry, which will be discussed in detail in Section 2.3; in the range of $[-Z_{max}, -Z_{min}]$ or $[Z_{min}, Z_{max}]$, distance measurement is realized with SRI method, the sign is decided by analysing the nonlinear spectral phase caused by a dispersive plate, which will be discussed in detail in Section 2.4.

Fig. 3(b) shows the schematic diagram of the desired distance; R′ is the symmetric plane of the reference mirror with respect to the BS, which represents the plane of zero OPD. The distance Z to be measured is the distance between R′ and the test specimen, which is half the OPD. It is worth mentioning that the measuring spot on specimen is usually a tiny area, which means that the OPD varies with spatial positions. Therefore, the extracted distance is defined as the distance between the central point of the measuring spot and the plane of zero OPD on condition that the measuring area can be regarded as a tiny plane.

2.3. Elimination of the dead zone with (spatially resolved white light interferometry) SWLI method

In VSWLI, white light interference fringes are localized in the vicinity of zero OPD. When the distance is located in the dead zone $[-Z_{min}, Z_{min}]$, spatial fringes can be captured using a CCD camera on the image plane, which can be written as follows [22]:

$$I(x,y,z) = I_r + I_t + 2\sqrt{I_r I_t}\, g(x,y,z)\cos(\phi(x,y,z)) \tag{3}$$