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Analysis of Noise in Phase Stepping Interferometry

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Abstract: - **In Optical Interferometric Sensors, it is important to precisely monitor changes in fringes which give change in phase information of a signal. The detection of a change in phase provides information on measurable physical parameters like change in displacement, temperature, strain, etc. These parameters may change with respect to time therefore; it is needed to monitor continuously changes in phase. The stepping interferometer technique is one of the most widely used techniques for phase detection. During this technique, the phase is continuously modified with known step size and therefore the detector integrates the intensity at every point over a range of phases. The various algorithms have been reported like 3-point, 4-point and much more for measuring phase shift with their own advantages and disadvantages. The various system errors like quantization of the detector signal, miscalibration of the phase shifter, detector nonlinearities, aberrations in optics of measuring device, vibrations and air turbulence can affect the phase measurement. In this paper, the effect of such noises on phase detection has been analyzed to provide the least error on the measurement of phase information with high-speed measurements. It has been observed that 4-point & 5-point methods have less effect of noises interface during phase detection with noise interface 1-5% in detected signal.**

Index Terms- **Phase detection, Interferometry, Stepping.**

I. INTRODUCTION

Interferometry and fringe projection profilometry techniques are gaining attention in various fields of science because of their precise measurement capability. The measured and reference wave-fronts have been checked to a high degree of accuracy using interferometry [1]. These techniques encode the information of measured phase of a two-dimensional fringe pattern. The interference fringes are analysed to achieve these accuracies with phase resolution greater than 0.001 fringes.

Phase Measurement Interferometry can be greatly affected by vibration and air turbulence from which optical system must be isolated. The other factors like non-linearity and phase shifter decrease with increase in the range of measurements.

There are various techniques such as Fourier transform, fringe skeletonization, phase locking, phase-stepping, phase-shifting, temporal and spatial heterodyning which are used for phase extraction. Equation 1 represents the fringe intensity which is given below:

$$I(x,y,t) = u(x,y) + v(x,y)cos[\Phi(x,y) + \varphi_r(x,y,t)] \qquad (1)$$

Here, $\Phi(x,y)$ = surface to be measured

$\varphi_r(x,y,t)$ = reference phase at time t

$u(x,y)$ = variation of the background illumination

$v(x,y)$ = noise and contrast variations

II. PHASE DETECTION TECHNIQUES

A. Fringe Skeletonization Methods

Over the last thirty years, the image can be automatically analyzed with digital Interferometric fringe patterns. In this method, fringes are analysed by eye on basis of tracking fringe minima or maxima across the field which depends upon image brightness distribution. One digitised interferogram is needed for temporal drifts of the experimental arrangement. As computation time is high, its accuracy is about λ/10 thus there is no suppress noise between the frames [2]. Since the change in intensity is equal for each positive and negative gradient so it is generally difficult to consign the appropriate sign to phase gradients.

B. Fourier Transform Methods

In this technique the reference phase $\varphi_r(x,y,t)$ of Fringe patterns arising from one interference pattern can be randomly set to zero. The phase of Fringe patterns can be measured from Equation 2

$$\varphi(x,y) = \tan^{-1}\frac{\Im[c(x,y)]}{\Re[c(x,y)]} \qquad (2)$$

When phase is evaluated, there is phase discontinuity in interferogram which can be resolved by adding another interferogram of reference phase shifted up to π.

C.Temporal Heterodyning Methods

An alternate method of fringe analysis is based on temporal fringe processing in which the phase estimates are derived from a stack of multiple phases shifted fringe patterns. Temporal fringe pattern analysis is invaluable in transient phenomena studies but imposes long processing times. The time-varying interferogram used by this technique is given by Equation 3[3]

$$I(x,y,t) = u(x,y) + v(x,y)\cos[2\pi f_0 t + \Phi(x,y)] \quad (3)$$

Where u(x, y) = background intensity,

v (x,y) = fringe amplitude,

$\Phi(x, y)$ = phase to be determined, and

f_0 = temporal-carrier frequency introduced by a frequency-shifting device.

The phase-shift interferometry shows discrete-time version of the interferogram which is sampled at different time interval as given by Equation 4 - 5.

$$\Delta t = 1/Nf_0 \quad (4)$$

$$I(x,y;\ n\,\Delta t) = u(x,y) + v(x,y)\cos[2\pi n/N + \Phi(x,y)] \quad (5)$$

D. Spatial Heterodyning Methods

The spatial-carrier technique uses a single interferogram represented by Equation 6

$$I(x,y,t) = u(x,y) + v(x,y)\cos[2\pi f_0 x + \Phi(x,y)] \quad (6)$$

Where, f_0 = spatial-carrier frequency which is generated by tilting the reference wave front.

The advantages of spatial versus temporal techniques are as follows:

1. Only one image is needed in special technique instead of 3-5 images separated in time as in the case of temporal heterodyning technique.
2. Spatial technique requires a special device to shift the phase whereas in temporal technique, phase shifting device is required.

SPM technique requires stringent requirements on detector than TPM techniques. This is because the large numbers of fringes are resolved by detector array and the sensitivity should be homogeneous over the whole array. The single interferogram used in SPM techniques in usually obtained using tilt between the beams which in turn introduces unwanted aberrations in the wave front measurement increasing the systematic error [4]. The major errors reported in TPM techniques are phase-shifter miscalibration and nonlinearities in the detection system.

In current work, we analyzed the effect of such errors found in phase detection in various techniques used to see which one provide the least error on the measurement of phase information with high-speed measurements.

E. Phase Stepping Method

The fringe patterns can also be analyzed by other method called as phase stepping method which is relatively simple as compared to other technique like Fourier fringe analysis.

Phase stepping methods have been used since 1974 and have been further investigated by many researchers. Many different variants of this phase stepping algorithms have been developed, such as three-frame, four-frame, five-frame and the "2+1" techniques [5, 6, 7]. In this method minimum three steps are required for phase determination. The algorithms are selected accordingly with the intensity bias and fringe contrast. However, the algorithms using five or more intensity-step values is comparatively more efficient towards phase measurement as well as these least error prone so it is a better choice to implement.

For a reference beam having phase φ, the intensity (I_r) at any point in the interferogram is given by equation

$$I_r = I_0 + I_0 V\cos(\varphi_r - \varphi) \quad (7)$$

The range of π (-π/2 to π/2) represents the value of φ.

III. PHASE STEPPING TECHNIQUES BY QUADRANTS SIGNALS

A. Two Point Phase –Stepping Technique

Two Point Phase –Stepping method first used by Santoyo et al. [8] only two measurements I0, I1 are used to improve contrast at first step and calculate using

$$\varphi(x,y) = \arctan^{-1}\left[\frac{I_1}{I_0}\right] \quad (8)$$

The phase step θ be exactly π/2.This method is complicated to achieve the phase by this method.

B. Three Point Phase-Stepping Technique

The phase shift of 90° between intensity signals which correspond to detector element is use for detection of change in phase with respect to three unknown irradiance of interferogram. In this case phase at a pixel is written as

$$\varphi_a = \tan^{-1}\left(\frac{I_2 - I_1}{I_0 - I_1}\right) \quad (9)$$

$$\varphi_b = \tan^{-1}\left(\frac{I_3 - I_2}{I_1 - I_2}\right) \quad (10)$$

Here φ_a and φ_b are two different technique of three point phase stepping method used for phase measurement.

C. Four Point Phase-Stepping Technique

The most common technique for recovering the phase, utilize a phase shift of 90° between the intensity signals which correspond to detector elements chosen to be one-fourth of the interference fringe width. The algorithm is given by equation 11

$$\varphi = \tan^{-1}\left(\frac{I_3 - I_1}{I_0 - I_2}\right) \quad (11)$$

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D. Five Point Phase-Stepping Technique

A 5- point technique introduced by Hariharanet. al.[9], claiming to be most insensitive to various systematic errors, uses 5 data points with relative phase shift of 90°. It provides more accuracy as compared to other algorithms for phase detection. The phase is obtained from

$$\varphi = \tan^{-1}\left(\frac{2\,[I_1 - I_3]}{2[I_2 - I_4 - I_0]}\right) \quad (12)$$

IV. ERROR ANALYSIS

The accuracy and repeatability in Interferometric measurements can be increased by phase-measuring interferometry. The measurement system error in phase is due to miscalibration or nonlinearity of the piezoelectric transducer. There is some source of errors in phase-shifting interferometry like Systematic errors, random errors with and without phase dependence. In systematic errors, the signal phase varies sinusoidal in which frequency is twice the signal frequency whereas amplitude and phase are constant. The errors can be cancelled out for those algorithms which are displaced 90° with sampling point by averaging the measurement of two algorithms. Random errors with phase dependence become more susceptible to random noise and give larger random errors in the phase. The value of Random errors without phase dependence errors is independent of the phase of the measured signal [10].

Experimental system errors during measurement:

Some experimental factors also effect the phase measurement before algorithm execution.Some other factors such as phase-shifter errors; non-linearities due to the detector and quantization of the detector signal are also affected during phase measurement. The calibration error decrease as the range of measurements will increase.

A. Phase-Shifter Miscalibration and Nonlinearities

If the phase-shifter device response is not linear or it is not well calibrated, the objective phase shifts (α) is not the real phase shift (α′) as represented by Equations 13-15.

$$\alpha'_n = \alpha_n(1 - \varepsilon_1 - \varepsilon_2\,\alpha - \varepsilon_3\,\alpha + ...) \quad (13)$$

$$= \alpha_n + (\varepsilon_1 - \varepsilon_2\,\alpha - \varepsilon_3\,\alpha^2 + ...)\,\alpha_n \quad (14)$$

$$= \alpha_n + \Delta\alpha_n \quad (15)$$

Where α = reference value of phase shift

α′ = real value

ε = normalized error.

We need to add an extra linear term so the total linear error [11] coefficient becomes:

$$\varepsilon_1 = -\varepsilon_2\alpha_n \quad (16)$$

This function minimized the error caused by the nonlinear phase shifter.

B.Error due to Detector Nonlinearities

Another source of phase errors is introduced due to the non linear response from a detector [12].

The initial intensity I_{int}, is linearly related to actual intensity I (equation 17)

$$I_{int} = \beta I \quad (17)$$

Here β is a constant. For certain detectors there are non – linearity of second and third orders also present. The measured I_{int} can be written as

$$I_{int} = \beta I + \rho\, I^2 + \gamma\, I^3 + ... \quad (18)$$

At least four measurements are required for phase calculation, once 2nd order non one-dimensionality is present in the fringe intensity, the effects of 3rd order is larger than the 4th order nonlinearity. More than 3 order non-linearities are negligible.

C.Error due to Phase Stepper

Phase-stepper error is the most important error of PSI technique. In Phase stepping interferometry for 3 and 4 position techniques a known and fixed phase step size of π/2 is used. However, non-linearities in the movement of a PZT performing the phase-stepping and due to miscalibration of phase step size the calculated phase to be in error.

The calculated phase of interferogram at each point (x, y) is

$$\emptyset'r = \emptyset r + \varepsilon_r \quad (19)$$

Where, ∅ r is the intensity at a point for phase step angle, ∅′r is the achieved phase step and ∅r is the correct phase step.

$$I_r = I_0 + I_0\,\gamma\cos(\Phi - \emptyset_r) \quad (20)$$

$$I'_r = I_0 + I_0\,\gamma\cos(\Phi - \emptyset_r + \varepsilon_r) \quad (21)$$

Phase-stepper error is linear which one is difficult to remove when we apply one phase step miscalibration.

V. SIMULATION RESULTS

The phase measurement interferometer calculation depends on the algorithm used. The phase is calculated by the fringe pattern which can be detected by the CCD detector. The large amount of noise interface occurs during obtaining sequence of images for phase detection.

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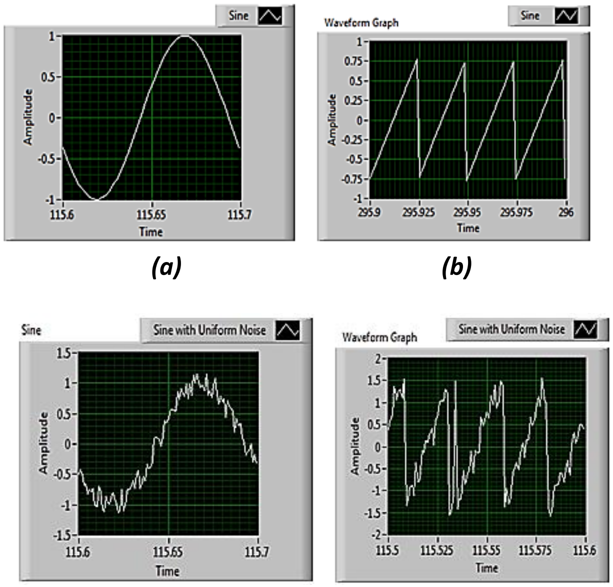

Fig.1 (a) sine without noise, (b) phase profile without noise, (c) sine with uniform noise and (d) phase profile with noise.

Detector grabs the real image of 8 bit through NI-PCI – 1405. The simulation is done in LabVIEW software. The acquired image is noisy so we select some part of the image by using the region of interest. In this simulation, we compared the three-point, four-point, and five-point technique. The change in the root mean square error value of various phase detection technique is shown in figures as per noise interface in signals from 1% to 5%.

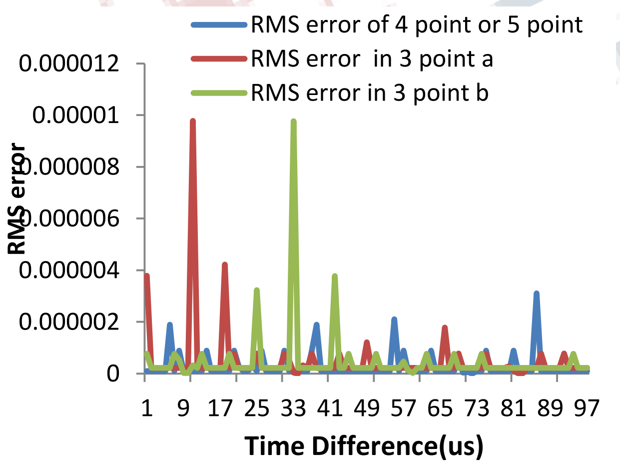

Fig.2. Change in RMS error of 3 point a, 3 point b and 4 point or 5 Point phase detection techniques with 1% noise interface

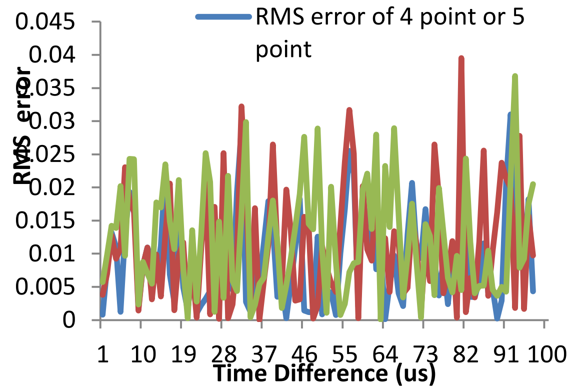

Fig.3. Change in RMS error of 3 point a, 3 point b and 4 point or 5 Point phase detection techniques with 2% noise interface

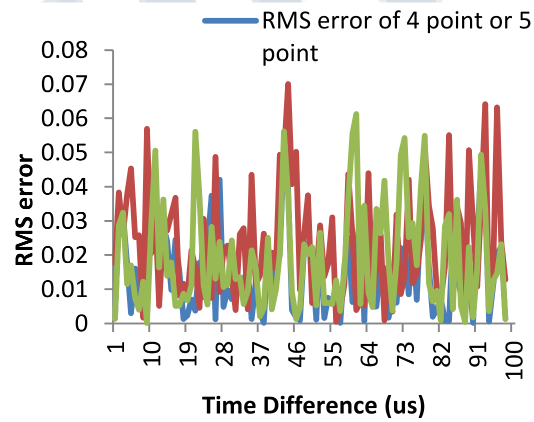

Fig.4. Change in RMS error of 3 point a, 3 point b and 4 point or 5 Point phase detection techniques with 3% noise interface

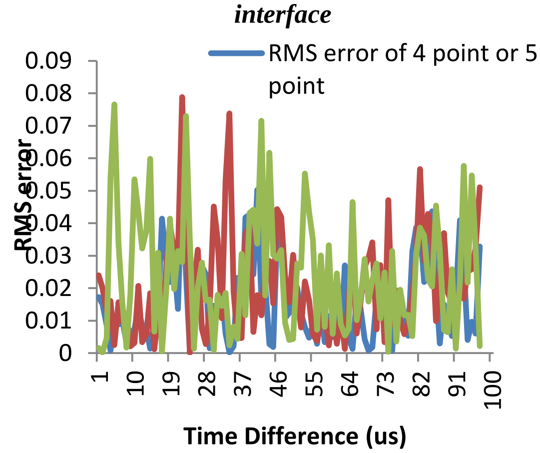

Fig.5. Change in RMS error of 3 point a, 3 point b and 4 point or 5 Point phase detection techniques with 4% noise interface

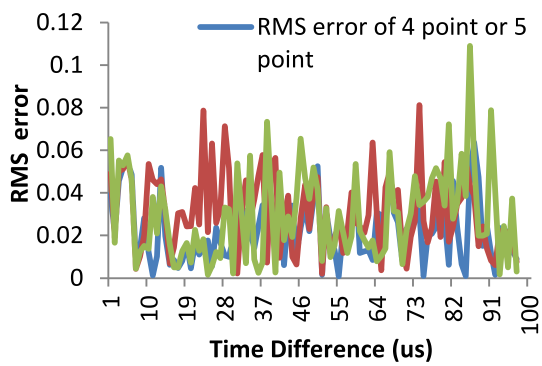

Fig.6. Change in RMS error of 3 point a, 3 point b and 4 point or 5 Point phase detection techniques with 5% noise interface

As per shown various graphs increase in noise during detection of signals introduce more error in phase measurement by phase stepping interferometer. The simulation study showed that the four-point and five point's techniques are best four reduce the error effects. A maximum number of n numbers give less error to the system.

VI. CONCLUSION

In phase measurement interferometry there are many techniques like phase stepping interferometry, Fast Fourier transform, phase shifting interferometry etc. for phase detection of fringes. But during real-time continuous measurement phase detection from Fast Fourier Transform is difficult. So we used phase stepping interferometry technique for phase detection. There are 3 points, 4 points and 5 point algorithm for detection of phase change. We have calculated phase value from continuous varies signal with noise interface from 1% to 5%. Also we calculated noise interface during detection of phase from phase stepping method varies as 3 points, 4 points and 5 point algorithm. Finally, we found that 4 point and 5 point method provides less error in phase detection as compared to another method. These methods are less complex and consume small execution time.

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