RESIDUAL GRATINGS REMOVAL IN MOIRÉ PATTERN USING AUTOENCODER

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DECLARATION

I hereby declare that the work presented in this thesis is the result of my own work. Acknowledgement is credited to materials taken from various sources, either published or unpublished by giving explicit references.

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LIST OF ABBREVIATIONS

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HFMF	**High Frequency Moiré Fringes**	**42**
LFMF	**Low Frequency Moiré Fringes**	**42**
OFRMF	**One Fringe Real Moiré Fringes**	**42**
TFRMF	**Three Fringes Real Moiré Fringes**	**42**

ABSTRAK (BM)

Corak moiré adalah corak gangguan terbentuk apabila dua jeriji dengan pic-picnya sedikit serupa bertindih bersama. Ia ada kelebihan luar biasa iaitu tidak invasif dan tanpa sentuhan. Akibatnya, ia digunakan luas dalam pelbagai aplikasi seperti pengukuran pertumbuhan retak, penjajaran wafer dalam fotolitografi, pengenalpastian kemunculan komponen nano dalam gambar mikroskopi elektron penghantaran (TEM) dan pembentukan topogram moiré yang digunakan untuk mendiagnosis pelbagai penyakit asimetri postur seperti Scoliosis. Kebelakangan ini, Yen dan Ratnam mencadangkan kaedah analisis grafik (GAM) sebagai kaedah alternatif kepada transformasi Fourier pantas (FFT) untuk mengatasi had pengiraan dengan kerumitan yang tinggi. GAM mengalami kehilangan perincian pinggir moiré kerana operasi pengembangan morfologi telah mengurangkan ketepatan walaupun pengukuran ketepatannya tinggi. Oleh itu, autoencoder denoising tersusun (SDA) dicadangkan dalam kerja ini untuk mengatasi masalah GAM sambil mengekalkan kelebihannya iaitu ketepatan tahap tinggi dan pengiraan sederhana. Empat jenis corak moiré dan seumpamanya, pinggir moiré digunakan untuk melatih SDA supaya meningkatkan julat penggunaannya. Corak moiré termasuklah corak moiré kekerapan tinggi (HFMP), corak moiré kekerapan rendah (LFMP), satu pinggiran corak moiré sebenar (OFRMP), tiga pinggiran corak moiré sebenar (TFRMP) di mana corak moiré simulasi diperoleh dengan menggunakan MATLAB dan SOLIDWORKS sementara corak moiré sebenar diperoleh dari set data GAM. Pinggiran moiré yang dibina semula dinilai secara kualitatif pada kawasan menarik (RoI) pinggiran moiré bulatan dan secara kuantitatif dengan memeriksa ketepatan pengukuran berdasarkan hasil statistik diperoleh dari pengeluaran operasi pemasangan lengkung. Penilaian kualitatif menunjukkan SDA berjaya mengekalkan perincian pinggiran moiré dengan baik sementara penilaian kuantitatif dengan tahap keyakinan 95% menunjukkan SDA mempunyai tahap ukuran ketepatan yang tinggi yang setanding dengan GAM seperti kadar ralat rendah 0.1970 ± 0.2869 titik, 0.0027 ± 0.0060 mm , -0.0045 ± 0.0029 mm dan -0.0034 ± 0.0020 mm dalam magnitud eksentrik dan 0.0004 ± 0.0332^{o}, -0.9432 ± 0.3023^{o}, -0.3023 ± 1.2872^{o} dan 1.5287 ± 0.7821^{o} dalam arah eksentrik masing-masing bagi HFMP, LFMP, OFRMP dan TFRMP. Kebolehgunaan dan kepraktikalan SDA terbukti dalam demonstrasi pembinaan semula pinggiran moiré rawak dengan berjaya membina semula pusat pinggir moiré.

ABSTRACT (BI)

Moiré pattern is an interference pattern that is formed when two gratings with similar pitch superimposed together. It has exceptional advantage of non-invasive and contactless properties. As a result, it is widely utilized in various applications such as measurement of crack growth, wafer alignment in photolithography, identification of presence of nano components in Transmission Electron Microscope (TEM) images and formation of moiré topogram which is used to diagnose various posture asymmetry disease such as Scoliosis. Recently, Yen and Ratnam proposed Graphical Analysis Method (GAM) as an alternative method to Fast Fourier Transform (FFT) to overcome its limitation of high complexity computations. GAM suffered the loss of fine details of moiré fringes due to morphological dilation operations which eventually penalized the accuracy in spite of its high precision measurements. Hence, stacked denoising autoencoder (SDA) is proposed in this work to overcome the aforementioned problem in GAM while preserving its advantages of high level precision and simple computation. Four types of moiré pattern and their corresponding moiré fringes were used to train the SDA to increase its range of applicability. These moiré pattern include High Frequency Moiré Pattern (HFMP), Low Frequency Moiré Pattern (LFMP), One Fringe Real Moiré Pattern (OFRMP), Three Fringes Real Moiré Pattern (TFRMP) where simulated moiré pattern were obtained by using MATLAB and SOLIDWORKS while real moiré pattern were obtained directly from GAM's dataset. Reconstructed moiré fringes were evaluated qualitatively on Region of Interest (RoI) of circular moiré fringes and quantitatively by examined on the precision of measurement based on statistical results derived from outputs of curve fitting operation. Qualitative evaluation showed that SDA successfully preserved the fine details of moiré fringes while quantitative evaluation with 95% level of confidence showed that SDA has high level precision measurement that is comparable to GAM such as low error rate of 0.1970 ± 0.2869 point, 0.0027 ± 0.0060 mm, -0.0045 ± 0.0029 mm and -0.0034 ± 0.0020 mm in eccentricity magnitude and 0.0004 ± 0.0332^o, -0.9432 ± 0.3023^o, -0.3023 ± 1.2872^o and 1.5287 ± 0.7821^o in eccentricity direction for HFMP, LFMP, OFRMP and TFRMP respectively. The applicability and practicality of SDA were proven in the demonstration of reconstructing random moiré fringes by successfully reconstructed the center of moiré fringes.

CHAPTER 1
INTRODUCTION

1.1 Introduction

Moiré pattern phenomena occurs in daily life which can be viewed from the surroundings such as folded netting, folded nylon curtain, railing of a bridge viewed from a far distance and screen recording. In fact, moiré methods had played an important role for many decades in the metrology field due to its several advantages such as contactless, full-field measuring, high resolution, low equipment cost, low sensitivity to external noise as well as ability to magnify surface deformation without distortion [1], [2]. Moiré metrology is utilized in various applications such as semiconductor, nanotechnology and particularly in medical field where it is being applied as medical imaging tool in clinical diagnostics to identify postural deviations diseases such as Scoliosis owing to its fast-trial and non-invasive properties [3].

In moiré metrology, two periodic gratings structure with 1D lines called reference grating and object grating superimpose to form moiré fringe [4].In fact, moiré pattern can also be generated using any periodic or quasi-periodic pattern of dots, lines, circles, arcs, spirals etc. [5]. Gratings generally can be categorized into linear gratings and non-linear gratings while the first one remains the popular gratings to be used in displacement sensing and measurement due to the simplicity of the moiré pattern formation as it consists of only a set of parallel lines [6].

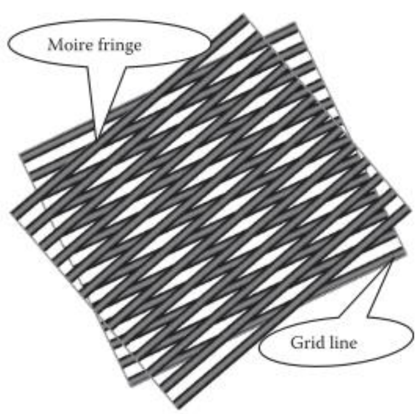

Figure 1.1: Superposition of two grid lines and moiré fringe. (Source: Adapted from [4])

Typical moiré methods included geometric moiré, shadow moiré, projection moiré, reflection moiré and moiré interferometry which is used in the measurement of surface topography, deformation, in-plane displacement, out-of-plane displacement, strain measurement and vibrations [1], [2], [7], [8].

Yen and Ratnam [6], [9] compared FFT and GAM to determine the in-plane two-dimensional (2D) displacement components from transformed circular moiré patterns. Researchers found that FFT was unable to be applied to low frequency circular moiré patterns whose transmittance is not sinusoidal. Thus, GAM was proposed as alternate method to FFT. This method overcomed the aforementioned problem and proved to give high accurate output with lower error rates compared to FFT. Downside is it remove fine details of the moiré fringes in a series of preprocessing steps to remove residual gratings and noise which eventually causes uncertainty and errors in the measurement.

Inspired by the great success of stacked sparse denoising autoencoder on image denoising task and blind image inpainting task [10]. SDA was proposed as alternate method to FFT and GAM in this work where the residual gratings were treated as unwanted “noise” and the goal is to reconstruct the moiré fringes by denoising operations. Theoretically, an autoencoder consists of an encoder and a decoder where encoder works by compressing the input data into low dimensionl latent space representation while the decoder reconstruct the output data by expanding the low dimensional encoded representation into same dimensional as input data. Information is lost due to compression by gradual decrease and increase of size of layers in encoder and decoder respectively, forcing the autoencoder to learn most salient features of the moiré pattern, thus allow it to reconstruct the images consisting only moiré fringes. The autoencoder approach is expected to reconstruct the image which consists only the moiré fringes for all types of circular moiré pattern presented in this work. Concurrently having results with precision comparable to GAM while preserving the fine details of the moiré fringes. Succesful implementation of this method may unlock the possibility to replace both FFT and GAM in moire metrology in future.

1.2 Problem Statement

Yen and Ratnam (2011) proved that GAM can be applied on low frequency circular moiré patterns whose transmittance is not sinusoidal and gives outputs with high accuracy and low error rates. The morphological grayscale dilation operation was used to eliminate the residual gratings and preserve moiré fringe in the processing steps. It functions by outputting pixel intensity which is the maximum among the pixels within the 1-D line structuring element in the input image. Consequently, part of the moiré fringes was removed in the process and causes error and uncertainty to the results. Hence, a SDA model is proposed in the work to overcome the aforementioned problem by reconstructing the moiré fringes from input images without using the morphological grayscale dilation operation.

1.3 Objectives

i. To develop an autoencoder model for residual gratings removal in moiré pattern without removing the fine details of the moiré fringes.

ii. To evaluate the applicability and effectiveness of an autoencoder model for residual gratings removal in moiré pattern.

CHAPTER 2
LITERATURE REVIEW

2.1 Introduction

Moiré pattern held high esteem ever since late 19^{th} century and early 20^{th} century in silk industry. Through rapid evolutionary of technology, it is now playing an important role in various industrial applications and especially in medical field. Various applications of moiré pattern in the past decades are reviewed in this chapter. Different types of existing moiré analysis methods together with their advantages and limitations are also discussed. Recent published research based on deep learning approaches in moiré pattern applications will be given special attention for their contribution in moiré metrology.

2.2 Dual Moiré and Laser Interferometer as a Metrology Tool

Recent advancement of moiré metrology tool includes the use of hybrid combination of conventional moiré methods and other methods to achieve greater performance and precision of measurement compared to conventional moiré methods alone in moiré metrology.

Abolbashari et al. [11] attempted to address the challenge of combining the moiré methods and laser interferometry in a single measurement capable of measuring physical parameters at both macro and micro level as both of the methods are mutually exclusive. The researchers introduced a hybrid measurement method by combining projection moiré method and laser interferometer as a single metrology tool. This method allows the overall form and shape of the object to be measured while analyzing the detailed surface texture of a small region on the surface of the object.

The moiré method employed is moiré projection technique and the laser interferometer is Michelson interferometer.

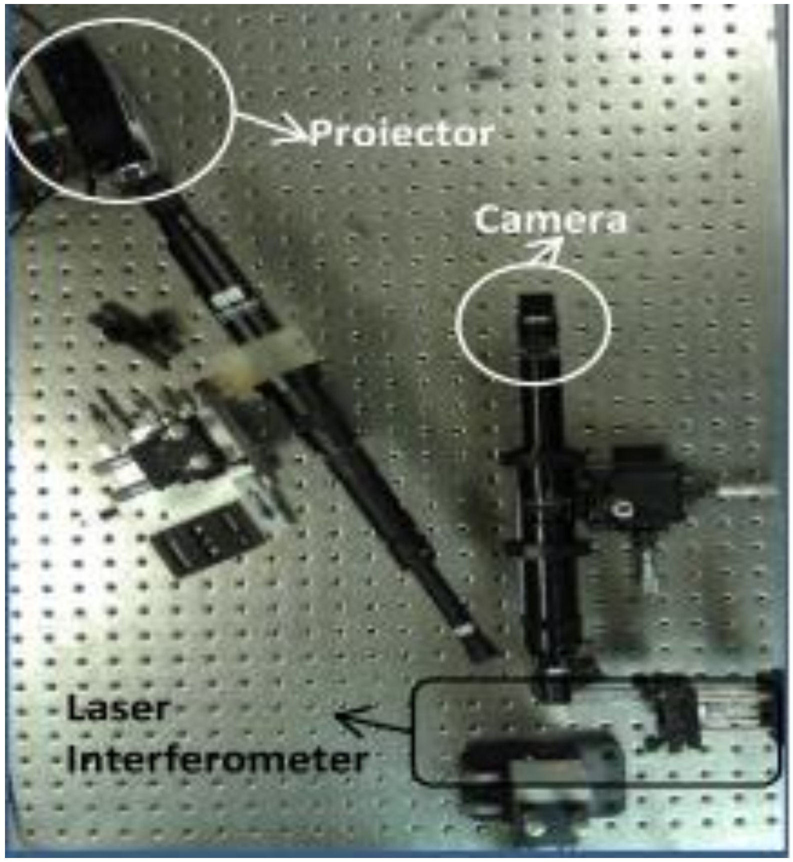

Figure 2.1: Dual moiré and laser interferometer. (Source: Adapted from [11])

In the work, the interferogram from moiré method and laser interferometer were first acquired simultaneously to obtain image consisting of detail surface texture at macro and micro scale respectively. Stitching algorithm was then applied to combine the image as an overall image which consists of all the detailed surface texture of the object. Simulations of both methods were done in MATLAB environment where fringe projection was done using ray-tracing method while simulation of laser interferometer was done by means of mathematical approach with some noise introduced into the system to reflect the system in real world application.

The method showed an error percentage below 0.6% for both fringe projection and laser interferometer under various zoom level. However, limitation is its precision is extremely sensitive to the external factors such as instability of laser wavelength, air flow and electronic noise.

2.3 Optical Displacement Metrology in Photolithography

Moiré pattern is also used in semiconductor industry for precision alignment of wafer in photolithography process. K. Suwa et al. [12] implemented alternating direction moiré (ADM) method in the optical registration metrology system (ORMS) to improve its precision during wafer alignment process. This method has advantage over conventional method in reducing measurement error where it does not require slow moving of wafer stage.

Theoretically, alternate direction moiré pattern was created using two gratings having opposite phases and implemented into bar-in-bar method in OMRS. Utilizing alternating direction moiré, mask with chromium line having an inclination angle with respect to second mask superimpose with each other to create wedge-shaped photoresists pattern which forms the moiré pattern which was then used in measurement of exposure displacement error.

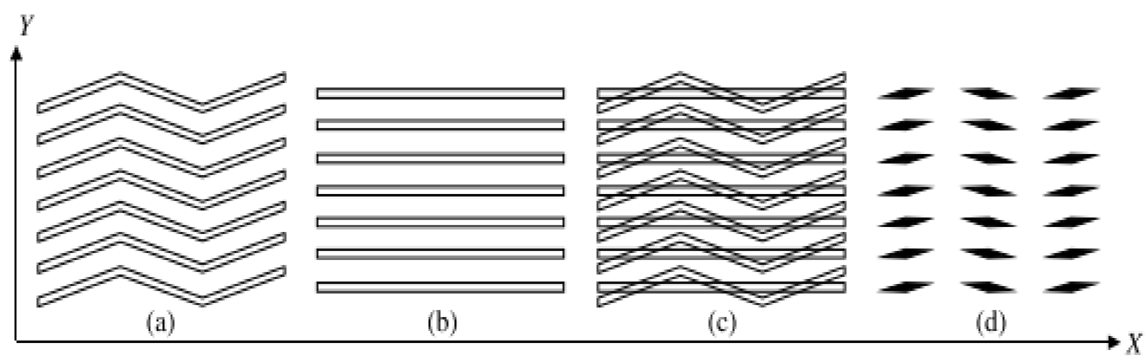

Figure 2.2: Combination of moiré photoresist patterns. (a) The first mask pattern. (b) The second mask pattern. (c) Double exposed image. (d) Patterns after development used for ADM. (Source: Adapted from [12])

Alternating direction moiré proved to significantly increase the OMRS measurement precision by a factor of 32 compared to conventional methods due to error being reduced in inverse proportion to moiré magnification.

2.4 TEM Nano-Moiré Pattern Analysis

Moiré pattern has also found an application in nanotechnology field. Jay and Tu [13] utilized the presence of moiré pattern found in TEM images to identify the presence of single walled carbon nanotube (SWCNT) within copper matrix. Moiré fringes was induced in copper-single walled carbon nanotube (Cu-SWCNT) due to disrupted atomic arrangement in copper-single walled carbon nanotube (Cu-SWCNT) metal nanocomposite. The following crystallographic analysis regarding the presence of SWCNT in the work was coupled with the analysis of diffraction patterns generated via FFT.

Researchers cannot derive conclusion solely based on the presence of moiré fringes as it could also be induced by other factors such as dislocation of atoms as proven in the analysis on pure copper samples with or without laser surface implanting (LSI). Therefore, lattice spacing and overlapping angle derived from mathematical approach are used to distinguish the formation of moiré fringes from other factors such as dislocation of atoms or presence of impurities to identify the presence of SWCNT.

By separating the pure copper atoms from the rest of the detected moiré fringes based on lattice spacing of copper atoms, together with the verification from the analysis on pure copper atoms as well as diffraction patterns, researchers concluded that the presence of SWCNT can be identified based on moiré fringes distinguished from others by overlapping angle of periodic arrangements.

Limitation is the analysis method using lattice spacing and overlapping angle are subjected to human error and hardware limitation. Error may be induced in the process of manual measurement, measurement tools being used as well as insufficient sharpness and resolution of TEM images.

2.5 3D Measurement of Human Plantar Foot

In medical field, moiré metrology plays an important role in many medical imaging applications such as constructing medical topogram.

Figure 2.3: Moiré topogram. (Source: Adapted from [14])

Such scenario is shown in the work of Del Vecchio et al. [15]. Researchers carried out 3D measurement of human plantar foot by using both projection moiré technique combined with temporal phase-shifting (TPS) method, and coordinate measuring machine (CMM) to compare the accuracy of both results taking latter method as benchmark as the method has low uncertainty of ±0.01 mm.

In the work, four digital grating patterns being displaced by one fourth of the grating pitch to introduce mutual phase steps of ninety degrees, are projected using liquid crystal display (LCD) projector onto the specimen surface.

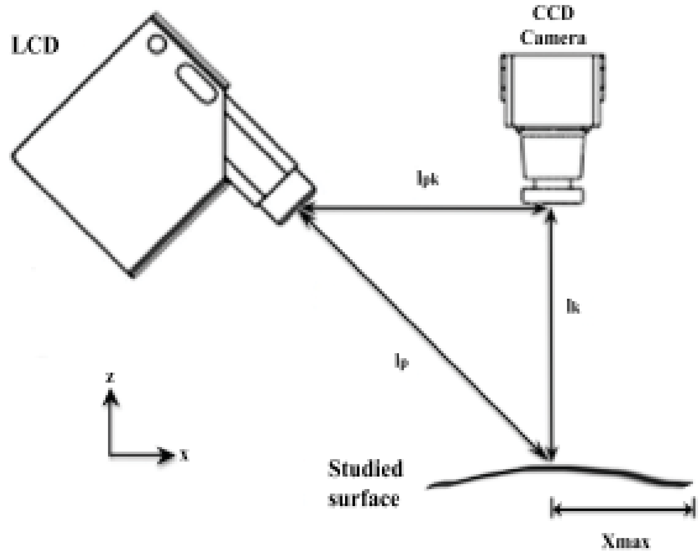

Figure 2.4: Sketch of optic-mechanical system configuration.

(Source: Adapted from [15])

A total of eight images were captured composed of each four images of reference plane and specimen surface. The signal presented in the images is further enhanced by applying Butterworth filter. Since the signal presented discontinuities for every 2π interval changes in phase, unwrapping operation was carried out to join the signal at each discontinuity point. After relative phase from reference images and foot images were obtained, phase difference was computed and rebuilt while Butterworth filter was applied to remove the high frequency noise exist in projected fringe patterns. The process was completed by final unwrapping process on the phase difference to compute the 3D profile.

Results showed that projection moiré technique had around 6% uncertainty of measured contour value. Major advantage of described technique over CMM is its simplicity and low cost equipment.

2.6 Moiré Imaging using an X-Ray Phase-Contrast Talbot–Lau Interferometer

Seifert et al. [16] employed a piecewise reconstruction technique called sliding window reconstruction (SWR) for moiré imaging by using an X-ray phase-contrast Talbot-Lau interferometer to significantly speed up the image acquisition process without using conventional phase stepping method.

Measurement samples of synthetic sponge with constant thickness, step wedge made from Polymethyl methacrylate (PMMA) and PMMA wedge with constant slope are chosen for examination of dark field signal, behavior of attenuation image and differential phase signal respectively. The setup of experiment consists of three major gratings where the first gratings was used to split the polychromatic X-ray source into multiple slit sources which all behaves as coherence sources independently while the second and third gratings were superimposed together to form moiré pattern.

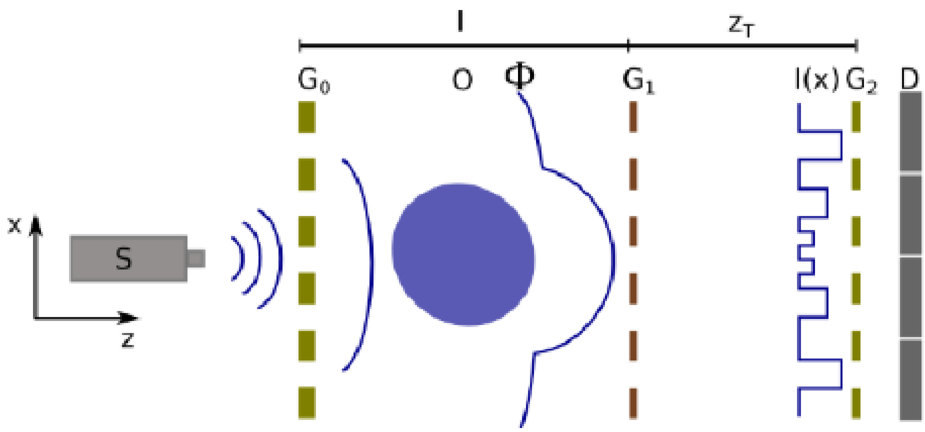

Figure 2.5: Setup of a Talbot–Lau interferometer. (Source: Adapted from [16])

The main idea of SWR was to reconstruct the region of interest by using predefined size of small windows where the size was carefully chosen so that the moiré period at the edges of image can be detected. Each of the windows were overlaid with neighboring windows to avoid margin artifacts and Hanning filter [17] was applied to solve the discontinuities issues at the windows' margin. Hence, an artifact-free image can be reconstructed by taking the inner third of the reconstructed window into account to join the image together.

Contrast to noise measurement technique was employed to quantitatively evaluate the performance of SWR algorithm while the reconstructed image of human finger was qualitatively examined. Judging from the quality of the reconstructed image, moiré imaging has lower spatial resolution and low signal area was more emphasized even though the algorithm showed comparable results with that of phase-stepping method. Quantitative evaluation of contrast to noise ratio (CNR) values showed that the results of both SWR and phase-stepping technique were comparable to each other.