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The effects of vibration on fringe projection systems

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Abstract
Mechanical vibration noise is a significant source of error in precision measuring instruments. Errors due to vibration can be detected in measurement signals, and so methods to control mechanical vibration must be considered throughout the design process. Fringe projection (FP) is a fast, non-contact and non-destructive measurement technology, that allows for the rapid form measurement of engineering components. There is an increasing demand in industry for low-intervention, factory-friendly FP systems. Vibration is reported to be a significant source of mechanical error in FP measurements, and so in order to design an effective metrology solution, it is vital to first understand the FP systems' sensitivity to vibrational noise. In this research, a methodology for assessing the effects of vibration on the measurement accuracy and repeatability of a low-cost FP system is presented. The research includes a theoretical investigation of the effects of vibration on FP measurements using a computational simulation technique, as well as an experimental study, which is compared with the simulated results. The methodology presented here allows for the rapid benchmarking of a given FP system operating in any configuration, and can be used to define the required vibrational performance parameters of the system.

Fringe projection, metrology, vibration, error source, sensitivity

1. Introduction

Fringe projection (FP) is currently a prominent research area in the field of optical metrology as it offers a fast, accurate and non-destructive method to measure the form of a part. FP is also a relatively cheap solution, as the only hardware required is a computer, a digital light projector (DLP) and a camera. As such, FP has seen a marked rise in application [1], including areas such as part geometry checking and fault detection [2] and in-process monitoring [3]. As a result there continues to be an increasing demand for low-intervention, factory-friendly FP systems.

Current commercial FP systems can achieve form accuracies in the region of 10 µm, depending on the measurement volume, surface texture and part size [1]. However, as with many precision measurement systems, FP has many error sources which limit accuracy and repeatability including optical sources such as gamma distortion, shot noise and lens distortion, and mechanical errors such as vibration. Whilst there have been several contributions which have proposed methods for minimising optical phase errors (see Ma *et al*. [4] for a comparison of these minimisation techniques), in contrast, there has been little published on the effects of significant mechanical error sources, such as vibration [5]. There are a number of vibration sources in industrial environments including: manufacturing equipment, operating machinery, air conditioning and human activity. Therefore, in order to design an effective metrology solution, it is vital to first understand the FP systems' sensitivity to vibrational noise.

This paper presents a theoretical investigation of the effects of vibration on FP measurements using a computational simulation technique, and an experimental study, to verify and compare with the simulated results. The methodology presented allows for the rapid benchmarking of a given FP system operating in any configuration, and can be used to define the required vibrational performance parameters of the system.

2. Computational simulation

Vibrational noise can affect the values of both the pixel intensity of the projected fringe patterns and the perceived pixel intensity in the captured images, which can cause errors when extracting the phase and absolute height information extracted from intensity values. In order to investigate the expected theoretical behaviour, and verify the experimental results, it was first necessary to create a mathematical model which was capable of simulating vibrational effects on a FP measurement.

2.1 Simulation method

A simulation was created to generate sinusoidal phase shifting fringe patterns, and determine the measurement errors caused by vibration across a range of amplitudes and frequencies when attempting to measure a flat plane. During the generation of the three sinusoidal phase shifted patterns, the effects of vibration were simulated by combining each generated pattern with a normalised pseudo-random noise signal. The combined signals were then used to generate simulated noisy captured images. Without noise/errors the measurement would reconstruct a perfectly flat plane, therefore, any distortions from a flat plane in the noisy images will have been caused by the errors which are present due to the introduction of the vibration signal.

Each simulated 'noisy' FP measurement was compared to the ideal measurement on a pixel by pixel basis, from which an average pixel distortion was calculated across the measurement. The simulated process was performed for a range of different amplitudes of vibration, and repeated 500 times at each amplitude in order to find the mean response at each of the varying levels of vibration.

2.2 Simulation results

The simulation results in figure 1 show there are clear trends between increasing vibration and average phase error. There is a sharp increase in the average phase errors >0.52 rad, as the vibration amplitude is larger than the phase shifts between patterns, which affects the phase unwrapping process. The simulation results match well with the expected behaviour, and so confirms the method proposed as an effective way to investigate the theoretical effects of vibration on FP measurements.

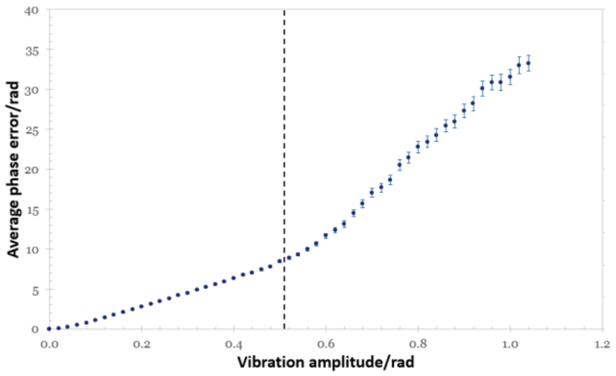

Figure 1. Increasing the amplitude of a model mechanical noise causes an increase in the measured phase error.

3. Experimental method and results

A simple experimental setup was designed to mount a projector and camera, and a vibrator was used to apply vibration to the setups. The designed setups allowed us to investigate the vibrational effects on three different FP system configurations: two isolated setups where either only the camera or the projector are vibrating, and one setup with both components vibrating (figure 2).

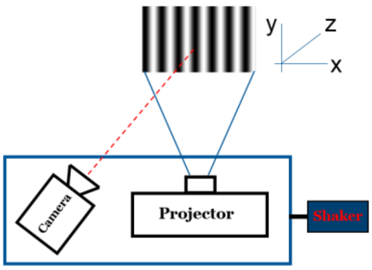

Figure 2. Schema of the experimental setup using an (a) iCODIS G1 pico projector (b) Raspberry Pi 2 with an 8 MP camera module, and (c) Smart Shaker K2007E01 which provides the vibration to the setup.

The effects of vibration were studied experimentally by using a baseline measurement comparison method whereby:

- Ten baseline measurements of a flat 250 mm by 250 mm plane with no applied vibration were taken, and the mean found to give the 'averaged baseline measurement'.
- Ten repeat measurements were taken at each varying level of vibration/excitation applied to the structure.
- A pixel by pixel comparison was performed to find the distortion error between each measurement and the averaged baseline measurement.
- Using the pixel by pixel comparison, the mean phase error across the measurement was calculated, and the mean response of the repeated measurements found.

The frequency response curves in figure 3 show the largest responses in both configurations are between 30 Hz to 40 Hz. These peaks occur as the frequency of the forced vibrations approach the natural frequency of the setups, and so the structure exhibits a resonance and vibrates with much larger amplitudes. Above the resonant frequency, the driving force of the vibrometer is out of phase with the oscillation of the structure and so the amplitudes of the responses decrease, where the small peaks present are harmonics of the natural frequency. It was decided that the experimental testing would be performed at 30 Hz to investigate the effects of vibration with the largest responses in the experimental setups.

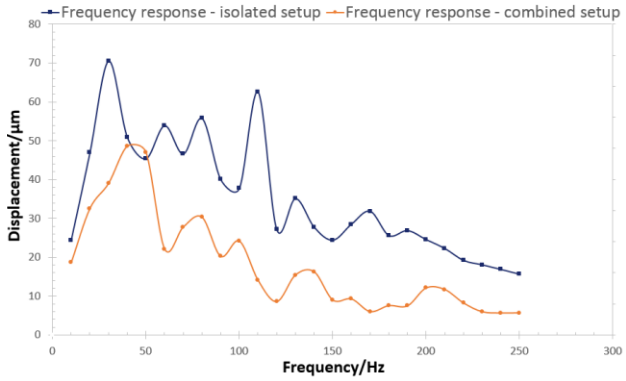

Figure 3. Frequency response of both configuration setups to varying vibration frequencies applied to the system.

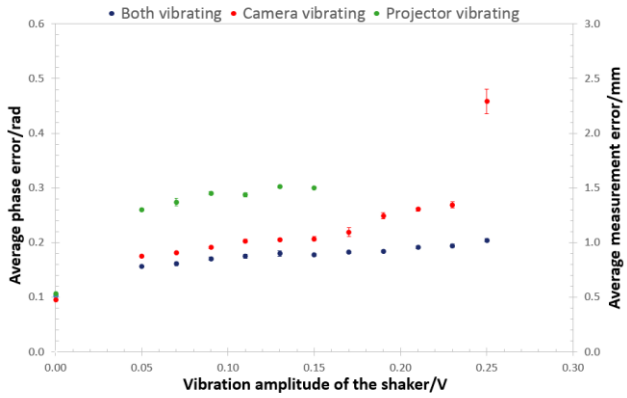

Figure 4. Increasing the amplitude of vibration on three experimental FP setups shows an increase in average measurement error.

The experimental results in figure 4 follow a similar trend to the simulated results. The average error has a near linear response with increasing vibration amplitude, and clearly demonstrates how the FP measurement quality decreases as the vibration levels are increased. The results also show that the FP system is more sensitive when the vibration effects are present in only one component in the system.

4. Conclusion

A method for assessing the effects of vibration on the measurement accuracy of a FP system has been presented. The method includes a theoretical investigation using a computational simulation technique, as well as an experimental study, to verify the simulated behaviour. The methodology presented is an important process to enable the rapid benchmarking of a given FP system operating in any configuration, and can be used to define the required vibrational performance parameters of the system and guide the design of an effective metrology solution. The authors would like to acknowledge Alex Jackson-Crisp as well as the support provided the EPSRC grants EP/M008983/1 and EP/L016567/1.

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