# MEASUREMENT NOISE OF A COHERENCE SCANNING INTERFEROMETER IN AN INDUSTRIAL ENVIRONMENT

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## INTRODUCTION

Coherence scanning interferometry (CSI) has seen a rapid uptake in manufacturing industry for use in quality control of parts that require surface texture to be controlled to the micrometre and nanometre levels. This uptake is largely due to the relative speed of measurement of CSI compared to other techniques, as well as its claimed potential for nanometric height accuracy [1].

In some applications of CSI, the user's understanding of the operating principles of the instrument can be low – technicians who are not specialised metrologists will often use the instrument as a "black box". As with all metrology instruments, CSIs can be sensitive to changes in measurement conditions. With the increase in interest in surfaces controlled to nanometric tolerances, the potential for unknown effects is likely to become an increasingly serious issue for the CSI users.

Efforts have been made by various national measurement institutes (NMIs) and standardisation bodies to provide guides and standard operating procedures for CSI users (see for example, [2] [3]). The intention of these guides is to educate non-specialists in some of the aspects of the instrument and its use that need to be considered, such as the measurement noise.

The fact that the work towards guides commonly takes place within the NMIs, means that the guides are largely compiled using instruments in very stringent conditions; frequently housed away from as many sources of noise as possible. This is done so as to provide the most accurate measurements possible and enables NMIs to identify only issues implicit within the machine itself.

This approach to guide development, whilst essential, fails to take into account that the majority of the metrology work carried out using CSIs in industrial applications does not take place within specialised, isolated laboratories. CSIs used in industry are frequently housed with a host of other manufacturing machines in workshops, possibly close to areas where manufacturing work is being carried out [4].

The industrial situation has the result that the measurement data obtained from industrial CSIs can be significantly less accurate than those acquired from CSIs in the NMIs. For example, in the work towards ISO metrological characteristics at the National Physical Laboratory, UK, the measurement noise when measuring an optical flat was in the sub-nanometre range [5]. However, we have found that, with just a small increase in the ambient vibration level, it is easily possible to have measurement noise levels exceeding 20 nm.

A significant component of the measurement noise comes from environmental disturbances in the form of, for example, ground vibration or acoustic noise. These disturbances are observed at a much greater magnitude in an industrial workshop compared to an NMI's laboratory.

At the time of writing, and to the best of the authors' knowledge, there has yet to be any guide published which deals with the issues faced when attempting to obtain areal surface texture data close to the nanometre level in an industrial environment, although some manufacturers have addressed the issue using software and hardware modifications [6]. This paper aims to identify issues introduced by taking measurements in a common working environment. Specific attention is paid to identifying issues causing the increased levels of measurement noise observed in industry and to outlining steps that can easily be taken by technicians or users to reduce the noise levels.

## MEASUREMENT NOISE

Measurement noise comprises all the noise signals that add to the output signal of an instrument when the instrument is used in normal operating conditions [7]. Noise can be caused by both the internal noise of the instrument (for example, electronic instability) and environmental noise (for example, ground vibration, air turbulance, temperature fluctuations). In this study, the measurement noise associated with CSI under industrial conditions will be quantified. Both a subtraction and an averaging method (see [5] for details) will be used to estimate the instrument noise used in industrial conditions. Both the substraction and the averaging methods use an *Sq* parameter, which is the root mean square (RMS) value calculated from the departure of heights from a mean reference plane. Two repeated measurements in quick succession are required by the subtraction method. From the two repeated measurements, the surface topography data of one measurement is substracted from the surface topography data of the other measurement. The subtraction process is used to remove the effect of roughness and the residual flatness error of the surface topography from the noise calculation. The subtraction method combines the surface topography variance of two indentical probability distributions of the two measurements and is formulated as:

$$Sq_{noise} = \frac{Sq}{\sqrt{2}} \qquad (1)$$

where $Sq_{noise}$ is the estimated measurement noise of the instrument.

In the averaging method, the assumption is made that the measurement noise contribution decreases (converges to a lower value) when averaging two or more surface topography data captured at the same location on the optical flat. The basic idea of the averaging method is that the calculated *Sq* on the optical flat surface is constituted by the sum of square of the instrument noise ($Sq_{noise}$) and the optical flat roughness ($Sq_{flat}$), and is formulated as:

$$Sq = \sqrt{Sq_{flat}^2 + Sq_{noise}^2} \ . \qquad (2)$$

The $Sq_{noise}$ will be reduced after *n* repeated measurements by the square root of *n*, while the the $Sq_{flat}$ is constant (measured at the same location on the optical flat). *n* measurements are taken and equation (2) gives the RMS of the averaged topography data:

$$Sq_{mean} = \sqrt{Sq_{flat}^2 + \frac{1}{n} Sq_{noise}^2} \qquad (3)$$

Hence, the $Sq_{noise}$ can be derived as follows:

$$Sq_{noise} = \sqrt{\frac{Sq_{flat}{}^2 - Sq_{mean}{}^2}{1 - {}^1/_n}} \ . \qquad (4)$$

Theoretically, both the subtraction and the averaging methods to calculate the measurement noise should have close agreement if all the measured surface topographies have an identical probability distribution; under so-called stationary conditions. The stationary condition of the surface data, obtained over a series of surface acquisitions at the same location on the optical flat, is characterised by constant statistical properties, for example, mean and variance, as they come from the same probability distribution.

Figure 1 shows an example of a measurement noise map calculated by using the subtraction method.

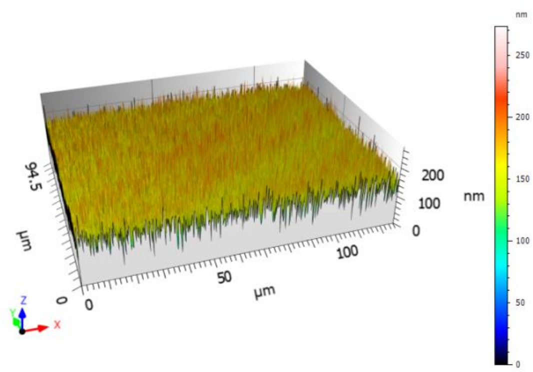


*FIGURE 1. Surface after the subtraction method for calculating measurement noise was applied to an optical flat.*

In this study, the CSI used is placed under an air conditioning fan blower and is housed in a room with a scanning electron microscope (SEM) instrument with a vacuum compressor. The CSI is mounted on a vibration isolation table. The specification of the vibration isolation table states that the table can isolate low-frequency ground vibration at frequencies less than 4 Hz. The room which houses the CSI instrument is in a manufacturing facility building containing several conventional and non-conventional material cutting machines.

For the measurement noise experiment, a 50× magnification objective lens with a numerical aperture (NA) of 0.55 was used. The objective lens is a Mirau interference objective. The artefact measured is an optical flat. The lowest measurement speed was applied to vertically scan the optical flat surface through the surface focus position. The measurement noise experiment was carried out in two conditions with the air conditioning fan on and off. The vacuum compressor of the SEM was on in both conditions (it was not possible to switch it off for this work).

## RESULTS AND DISCUSSION

Both the subtraction and the averaging methods were applied to estimate the CSI's measurement noise. The results from the averaging method did not converge to a lower noise value. Averaging up to ten measurements of the optical flat surface topography did not reduce the $Sq_{noise}$. These diverging noise values suggest that the surface data from several measurements do not have an identical probability distribution and are in a non-stationary condition.

The reason for the non-stationary condition could be either due to measuring different locations on the optical surface or due to invalid surface reconstruction by the instrument (i.e the measured surface topography is different to the real surface topography of the optical flat). As can be seen in figure 2, a sinusoidal (ripple) pattern is observed on the measured surface topography. This ripple pattern is an artificial artefact and is not a representation of the real optical flat surface. The ripple pattern on the measured surface topography suggests that the non-stationary condition is caused by invalid surface reconstruction of the real surface.

The reason of the invalid surface reconstruction is that the environmental noise from the ground and acoustic sources combines into the fringe data while the CSI scans the optical flat and negatively affects the fringe demodulation algorithm of the CSI instrument to reconstruct the surface topography. The environmental noise effects cause invalid features (artefacts) on the measured surface topography and hence induce a non-stationary condition.

Due to the non-stationary property, only the subtraction method is used to estimate the measurement noise. Figure 3 shows the effect of non-stationary surface data to the subtracted surface. In figure 3, a ripple pattern which has a high deviation from the reference surface has been observed. It is worth noting that the ripple pattern is not found in a subtracted surface from two statistically stationary surfaces as shown in figure 1.

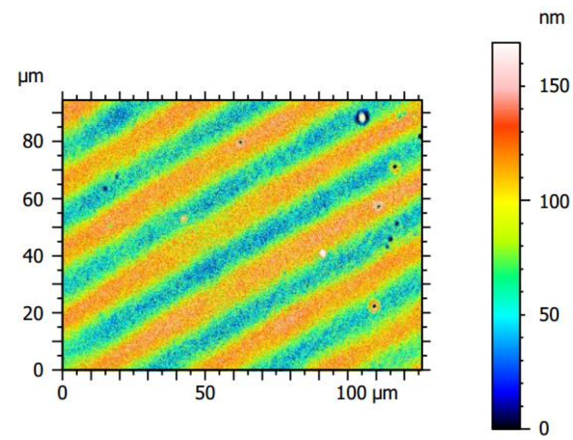


*FIGURE 2. The measured surface while the air conditioner's fan blower is on.*

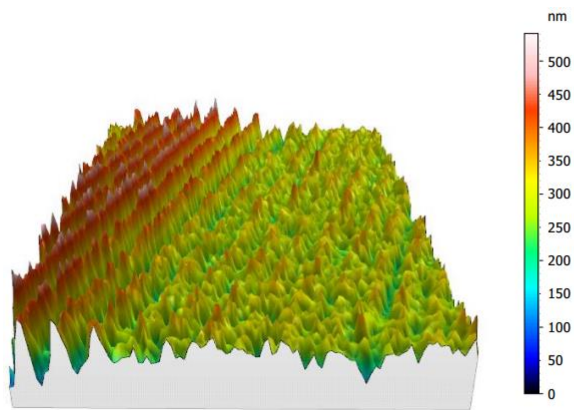


*FIGURE 3. Effect of statistically non-stationary surface data to the subtraction between two consecutive surface data.*

The measurement noise from the two measurement conditions (air conditioning on and off) shows a significant difference. Eliminating one of the vibration sources (the air conditioning fan) reduces the measurement noise. Table 1 shows the estimated measurement noise for both conditions of the air conditioning fan. The average value of the measurement noise when the air conditioning fan was on is 36.3 nm ± 6 nm (1σ) and when the air conditioning fan was off is 27 nm ± 2.3 nm. By reducing the vibration source from the air conditioning fan, a 40 % improvement of the measurement noise is obtained. However, the improved noise of 27 nm is still two orders of magnitude higher compared to the noise value of 0.6 nm (a CSI with 50× magnification lens) obtained in a strict laboratory environment by Giusca et al [4].

*TABLE 1. Results of measurement noise from two measurement conditions.*

| Air conditioner's fan | Measurement noise /nm | | |
|---|---|---|---|
| | 1 | 2 | 3 |
| On | 32.4 | 43.3 | 33.3 |
| Off | 26.7 | 29.5 | 24.9 |

Due to a significant environmental vibration noise contribution, the sinusoidal (ripple) pattern on the surface data becomes apparent. In fact, this sinusoidal pattern is also found in the measurement using phase-shifting interferometry in the presence of vibrations [8]. As per our results, figure 2 shows a significant sinusoidal pattern on the obtained surface data measured when the air conditioning fan was on. A less apparent sinusoidal pattern is observed in figure 4. In figure 4, the surface was measured when the air conditioning fan was switched off. The sinusoidal pattern in figure 2 has a maximum amplitude up to around 100 nm.

To further investigate the vibration sources, an accelerometer sensor was used to measure the vibration during the measurement. The accelerometer sensor was attached to the CSI base table. The CSI's objective lens was set on top of the sensor close to the accelerometer sensor top surface to simulate the real measurement run. The air conditioning fan was switched on and off during the vibration measurement. The signal received from the accelerometer sensor was analysed in the frequency domain to decompose the vibration signal into its single frequency constituents. The frequency spectrum of the measured signal is shown in figure 5. Figure 5 shows the frequency spectrum of the obtained signal recorded from one of the series of vibration measurements.

From figure 5, the frequency spectrum of the measured vibration reveals that the air conditioning fan is not the dominant source of the vibration. The vibration from an air conditioning fan commonly vibrates at frequency around 50 Hz. Because the air conditioning fan is not the dominant vibration source, the vibration noise affecting the measured surface topography is still significant so that the measurement noise is still considered high when the air conditioning fan was switched off, even though the noise can be improved up to around 40 %. As shown in figure 5, the lower frequency vibration is the dominant vibration source.

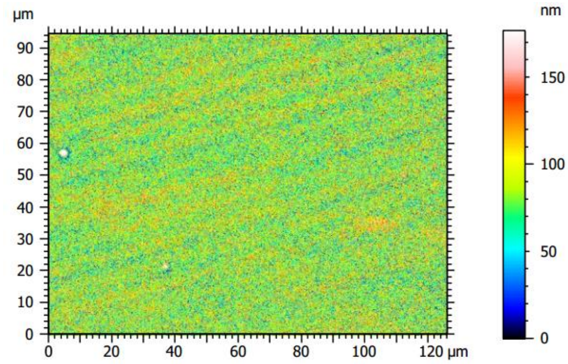


*FIGURE 4. The measured surface while the air conditioner's fan blower is off.*

To analyse the frequency spectrum, a pick-peaking algorithm, to automatically detect the maximum peak of the signal, was used to find the frequency with the highest amplitude. From a sequence of ten vibration measurements with the air conditioning fan switched on and off, the average frequency having the highest amplitude is 15.1 Hz ± 1 Hz (1σ). The vacuum compressor of the SEM instrument was working when the vibration was measured. A maximum rotation of 1450 rpm can be performed by the compressor of the SEM instrument. The rotation of the compressor at 1450 rpm corresponds to a 24.17 Hz vibration frequency.

By comparing the frequency with the highest amplitude of the measured vibration signal and the frequency of the vacuum compressor at its maximum rotational speed, a frequency difference of 9 Hz is observed. The vibration frequency difference may be due to the vibration frequency exhibited by the vacuum compressor being attenuated when the vibration of the vacuum compressor propagated to the CSI instrument. The attenuation of the vibration is possibly due to a non-linear damping and isolation effects of the floor concrete and joints through which the vibration propagates. A certain amount of vibration energy dissipates during the travelling of the vibration wave from the vacuum compressor to the CSI. From the comparison of the frequency of compressor motor and the most dominant measured vibration frequency, the compressor motor possibly contributes, to a certain degree, to the vibration noise during the measurement of the optical flat and causes the increase of measurement noise of the CSI.

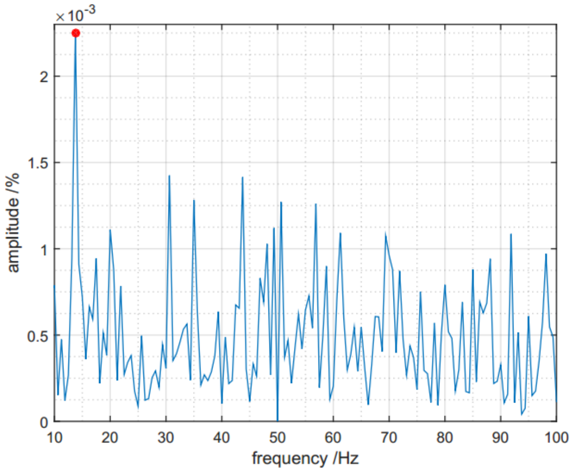


*FIGURE 5. The frequency spectrum of the measured vibration signal.*

In addition to the vibration noise, the measurement noise of the CSI is significantly affected by the optical flat's surface orientation (surface tilting) with respect to CSI's objective lens. Figure 6 shows the effect of the surface orientation of the estimated measurement noise. As figure 6 suggests, a larger measurement noise is observed when the orientation (tilting) angle of the optical flat increases. It can be argued that the limited numerical aperture (NA) of the objective lens causes a positive correlation between the tilting angle of the optical flat and the estimated measurement noise. The reason is possibly due to the higher tilting angle of the optical flat surface causing some reflected light outside NA limit of the objective lens and causing speckle in the reflected signal to the objective lens [9]. The speckle introduces higher frequency components in the reflected light signals that are outside the bandwidth limit of the CSI [10]. The higher frequency components outside the bandwidth limit will be cut off and cannot pass the optical system. Due to the frequency cut off, some information of the real surface topography is lost.

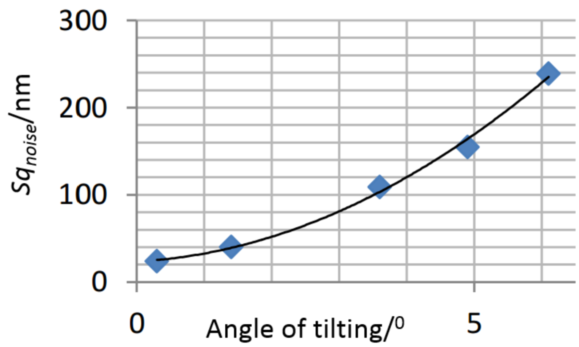


*FIGURE 6. The effect of surface tilting to the measurement noise.*

The general rules to reduce vibration are by reducing the vibration sources, isolating the vibration sources and/or isolating the instrument. From this study, if low-noise operation is required, a CSI should not be placed together with rotating equipment or another instrument that may generate vibration. Moreover, an air flow system inside the CSI's room should be carefully planned. Finally, the placement of the sample to be measured should be as flat as possible.

## CONCLUSION AND FUTURE WORK

This study investigates the measurement noise of a CSI when it is used in an industrial environment. A significantly high measurement noise is observed when the measurement is carried out in the industrial environment as compared to the strictly controlled laboratory environment. The increase of measurement noise is not significant on a rough surface (*Sa* > 0.1 µm) since the sinusoidal pattern noise amplitude observed in the measured surface data due to vibration is around 100 nm. The results suggest that it is important to evaluate the measurement noise of a CSI and other instruments in the actual environment where the instrument will be operated [11]. Continuous improvement, especially by the commercial CSI instrument manufacturers, should be conducted and existing knowledge related to vibration noise on measurements should be published more openly (for example, as can be found in [12]).

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