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AN IMPROVED REAL-TIME ROCKING MOTION MONITORING SYSTEM

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Most primary accelerometer calibrations, or absolute calibrations, are currently performed using laser interferometry under the guideline of the international standard (ISO 16063-11, 1999). The laser interferometric method measures the displacement amplitude of a moving surface with an accelerometer mounted. To achieve high accuracy in the measurement of acceleration it requires a piston-like and distortion-free vibration of the accelerometer at calibration frequencies and amplitudes. Unfortunately, vibration shakers usually present high levels of rocking motion. Rocking motion is an unwanted phenomenon exhibited by vibration shaker. It is usually manifested in oscillatory back and forth, side to side, or rotatory movements. It causes the measurements of accelerometer sensitivity deviating from each other for up to a few percent. To reduce the effect of rocking motion, measurements may be performed at multiple incidence points equally spaced along the border of the accelerometer on the mounting surface and the corresponding average is then estimated. Recently, mechanical filters have been used to decouple the rocking motion from vibration shaker to accelerometer. To obtain the best results, the filter should be optimized for a specific type of reference accelerometer. For this purpose, a real-time rocking motion monitoring system was developed at the National Research Council Canada. This paper describes the improvements of the system since it was developed and reported and presents the measurement results of rocking motion for different conditions.

1. Introduction

Most primary accelerometer calibrations, or absolute accelerometer calibrations, are currently performed using laser interferometry under the guideline of the international standard (ISO 16063-11, 1999)[1]. The laser interferometric method measures the displacement amplitude of a moving surface with an accelerometer mounted. To achieve high accuracy in the measurement of acceleration it requires a piston-like and distortion-free vibration of the accelerometer at calibration frequencies and amplitudes. Unfortunately, vibration shakers usually present high levels of rocking motion. Rocking motion is an unwanted phenomenon exhibited by vibration shaker. It is usually manifested in oscillatory back and forth, side to side, or rotatory movements. It causes the measurements of accelerometer sensitivity deviating from each other for up to a few percent.

The international standard ISO 16063–11 states that transverse, bending and rocking acceleration shall be sufficiently small to prevent excessive effects on the calibration results. There are many ways reported in the literature to achieve this goal. Among them averaging is the most commonly used method[2]. An alternative solution to this problem has been devised in the form of mechanical filters that break up the structure to remove the high frequency bending modes of the shaker plus accelerometer structure[3]. Instead of passively filtering an active-controlled system was developed that minimizes the undesirable movements of the moving element of an electro-dynamic exciter using piezoelectric actuators[4]. To verify the effectiveness of these methods, a real-time rocking motion monitoring system was developed at the National Research Council (NRC) Canada[5]. This paper describes the improvements of the system since it was developed and reported and presents the measurement results of rocking motion for different conditions.

2. Rocking motion and its measurements

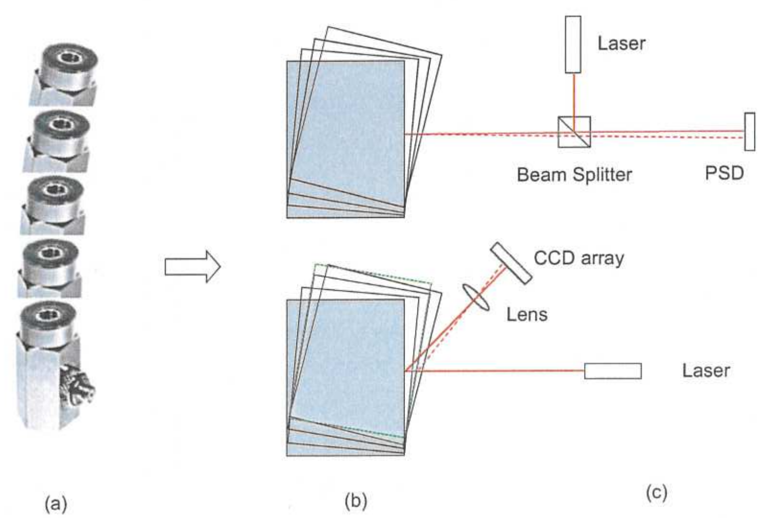


Figure 1. Rocking motion modeling and measuring. (a) Rocking motion of accelerometer. (b) Rocking motion modeling. (c) Rocking motion measurement methods.

The rocking motion of an accelerometer (Fig. 1a) can be modeled as the rocking motion of a rigid rectangular block as shown in Fig. 1b. This is a free stand rocking as the block-like body allows to uplift or rock while resting on a base which shakes. The rocking motion of an accelerometer can be studied experimentally. As a first step a real-time rocking motion monitoring system is needed. The rocking motion can then be studied for different conditions. Figure 1c illustrates the methods for measuring the rocking motion of an accelerometer. An earlier system shown in the upper part of Fig. 1c uses a position sensitive device (PSD) to measure the tilting angle due to the rocking motion. The current system shown in the lower part of Fig. 1c uses a charge coupled device (CCD) array to measure the displacement due to the rocking motion. The later system does not require dummy accelerometers with mirror finish surfaces[5] to be made for the study.

3. Rocking motion monitoring system

The schematic diagram of the rocking motion monitoring system is shown in Fig. 2. Modifications for an earlier system[5] to achieve improvements are discussed here. The PSD used in the earlier system is replaced by the CCD array (LD1607-0.5, Micro-Epsilon). The actual accelerometer is used instead of a dummy accelerometer. Thus, the rocking motion due to accelerometer housing is part of the study.

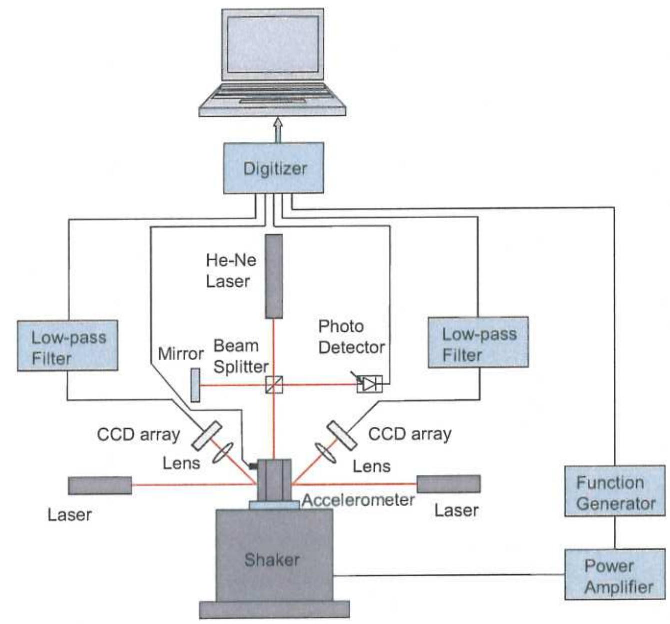


Figure 2. An improved real-time rocking motion monitoring system.

3.1 Laser triangulation system

Laser triangulation systems use laser lights to sense the shape of an object or the position of a target. The triangulation laser project a spot of light on the object and its reflection or scattering is focused via an optical lens on a light sensitive device or an imaging device. Depending on how far away the laser strikes a surface or the position of the target, the reflected laser spot appears at different places on the active area of the light sensitive device. Such a system can be used to measure the displacement of the side of an accelerometer due to the rocking motion of the accelerometer.

3.1.1 Operating principle

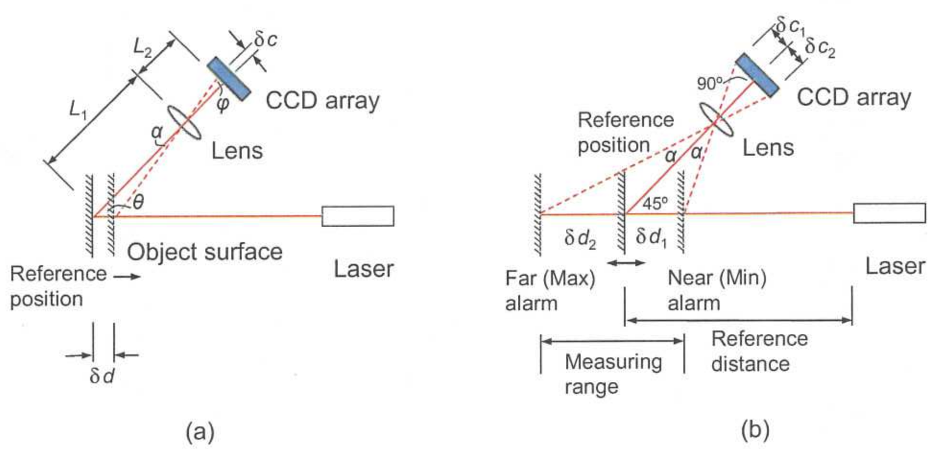


Figure 3. Measuring principle of laser triangulation. (a) Object moves towards laser source. (b) Object moves towards laser source reaching near-end measuring range and away from laser source reaching far-end measuring range.

The operating principle of a laser triangulation system for displacement measurement is shown in Fig. 3a. For this application a single laser spot is used to shine the object surface. The scattering light from the object surface is received by a CCD array via an optical lens forming an imaging spot on the surface of the CCD array. When the object moves towards the laser, this causes the laser spot moving towards the laser. The laser image spot on the CCD surface will also move accordingly. According to the law of sines in trigonometry, the following equation can be obtained:

$$\delta d = \frac{L_1 \delta c \sin\varphi}{L_2 \sin\theta + \delta c \sin(\varphi - \theta)} \tag{1}$$

where L_1 and L_2 are the distances from the lens centre to the laser spot on the object surface and the imaging spot on the CCD surface, respectively, when the object is at the reference position, δd and δc are the displacements of laser and image spots on the object surface and the CCD surface, respectively, when the object moves towards the laser, θ is the angle between the incident light and the scattering light, and φ is the angle between the scattering light and the CCD surface. For the object moves away from the laser a similar equation can be obtained as follows:

$$\delta d = \frac{L_1 \delta c \sin\varphi}{L_2 \sin\theta - \delta c \sin(\varphi - \theta)} \tag{2}$$

Equations 1 and 2 establish the relationship between the displacement of the laser spot from a reference position and the deviation of the image spot from a specific (normally centre) position with known L_1, L_2, θ, and φ.

3.1.2 Reference position

To maintain L_1, θ, and φ with the known values the object has to be placed at the reference position, or the displacement measured is relative to that position. A gauge block can be inserted between the object and the laser emitter to ensure a desired distance. However, this does not work when the object surface is not flat as for most cases. On the other hand, a specific output level of the CCD array can be used as an indication that the scattering image spot is at the desired position (so does the laser spot). But an accurate measurement of the dc output voltage of the CCD array is difficult because of the low frequency noise from environmental vibration and short-term drifting of measuring chain. In this paper, a simple method is proposed to determine the reference position of the object. The method utilizes the far and near alarm features that are available from most laser triangulation sensors.

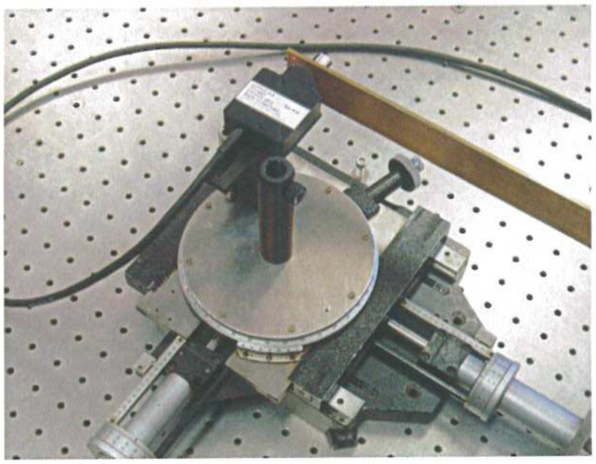
The principle of the method is illustrated in Fig. 3(b). When $\varphi = 90°, \theta = 45°$, and $\delta c_1 = \delta c_2$, the following equation can be obtained according to the law of sines in trigonometry:

$$\frac{\delta d_1}{\delta d_2} = \frac{L_1 + \delta d_1/\sqrt{2}}{L_1 - \delta d_1/\sqrt{2}} \tag{3}$$

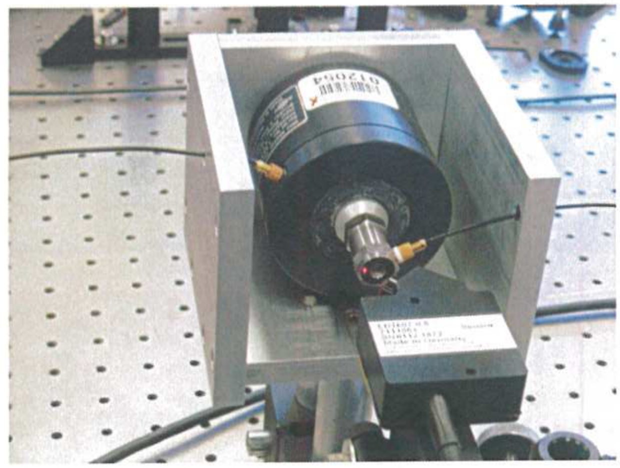
The distance L_1 can be determined from the given reference distance shown in Fig. 3b and the geometrical arrangement of the laser triangulation system. With an additional measurement for $\delta d_1 + \delta d_2$, Eq. 3 can be solved for δd_1 and δd_2, or the reference position of the object.

A linear translation stage with micrometre drive is used to move the laser triangulation system towards or away from the object. The measurement of $\delta d_1 + \delta d_2$ is realized by recording the indications of the micrometre at far alarm and near alarm positions. The calculated δd_1 or δd_2 value is then used to set the object at the reference position or the triangulation system at the reference distance.

An example of using a laser triangulation system for measuring the vibration of a cantilever beam is shown in Fig. 4a. A linear x-y translation plus z-axis rotation stage is used. The x-axis translation is used to measure $\delta d_1 + \delta d_2$ and therefore to find the reference position or reference distance. The y-axis translation controls the laser spot position on the object surface so that a stronger scattering light is received on the CCD array. The z-axis rotation is used to control the light incident angle such that it is perpendicular to the object surface. The CCD array can also be rotated with respect to the incident light to position itself for the strongest scattering light.



(a)



(b)

Figure 4. Application examples of laser triangulation. (a) Measuring the vibration of a cantilever beam at its free end. (b) Measuring the vibration of an accelerometer mounted on a vibration shaker.

3.1.3 Calibration

The calibration of laser triangulation systems can be carried out by using certified artifacts. NRC has developed a portable characterization target kit for this purpose[6]. For rocking motion measurements this task becomes simpler as the dynamic displacement is the only interest. A comparison calibration system can be setup for the task. The system consists of a function generator, a power amplifier and a vibration shaker for generating sinusoidal vibrations, and a calibrated back-to-back accelerometer for comparing its output with that of a laser triangulation system. Figure 4b is a photo of such a calibration system without showing the function generator and power amplifier. When the vibration shaker was vibrating at an acceleration of 20 m/s^2 and a frequency of 160 Hz, the output waveforms of the accelerometer and the CCD array were observed in real-time. A segment of waveforms is shown in Fig. 5 with the accelerometer waveform in red colour and that of the CCD array in white. The CCD array output contains speckle noise that is due to coherent lighting on rough surfaces.

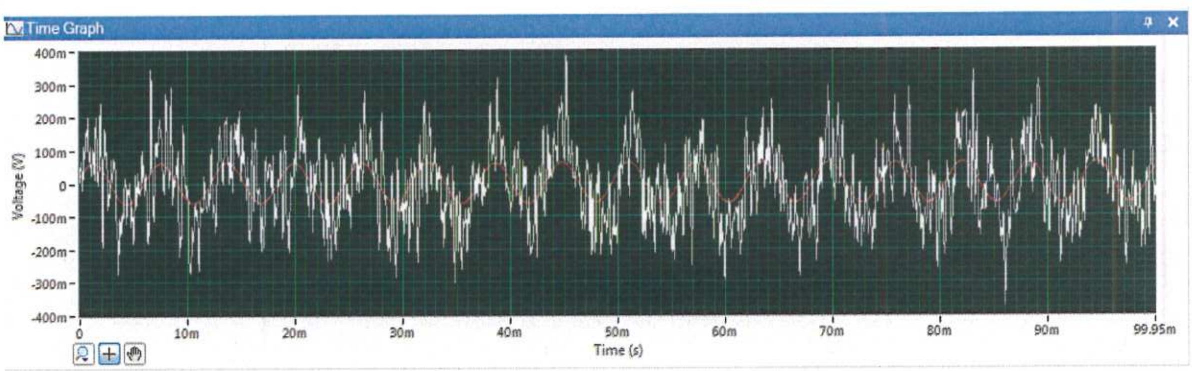
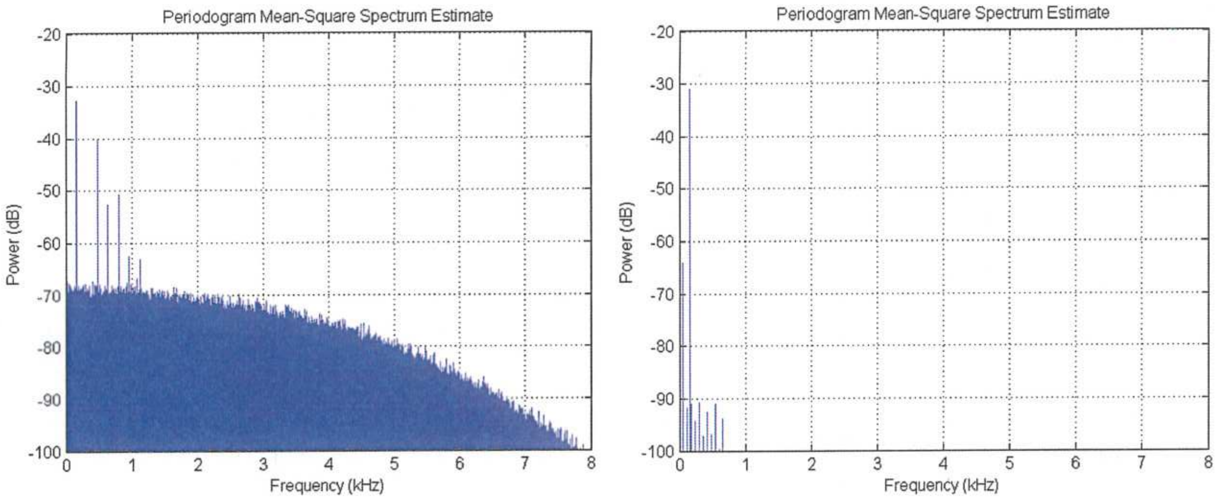


Figure 5. CCD array and accelerometer outputs when the shaker was vibrating at 20 m/s^2 and 160 Hz.

The spectrum estimates of these waveform signals for a period of 20 seconds are plotted in Fig. 6. The noise power spectrum is almost 40 dB below the fundamental of the CCD array output signal. A low-pass (or band-pass) filter can then be added between the CCD array and the digitizer as shown in Fig. 2 to remove the speckle noise. Harmonics were also observed from the spectrum of the CCD array output. This is due to the nonlinear nature of the relationship between the displacements of the laser spot δd and that of the image spot δc given by Eqs. 1 and 2. It is interest to see that the output of the accelerometer contains the power line interference of 60 Hz while that of the CCD array does not.

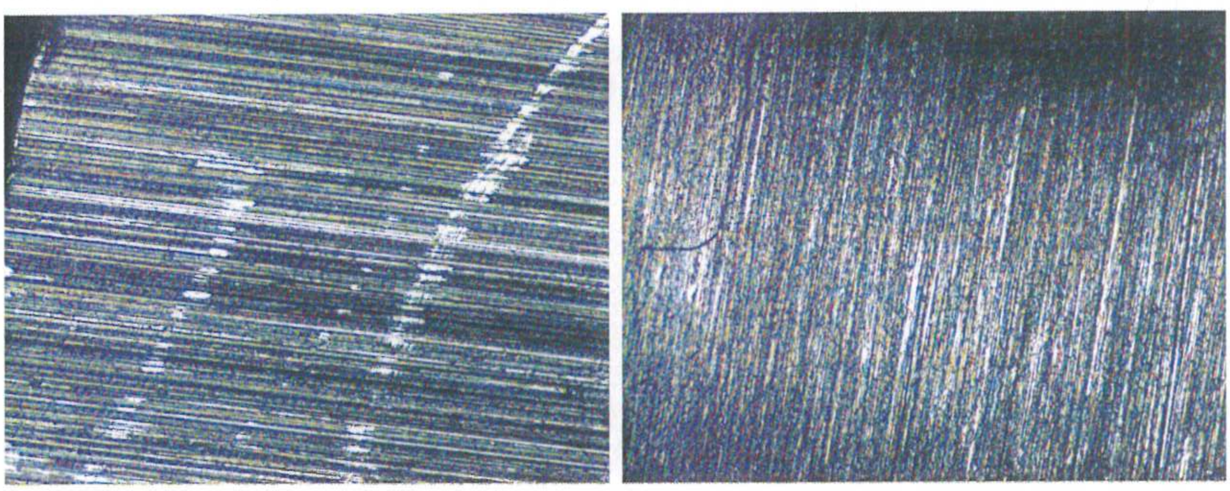


(a) (b)

Figure 6. Plots of spectrum estimates. (a) The spectrum of the CCD array output shown in Fig. 5. (b) The spectrum of the accelerometer output shown in Fig. 5.

3.2 Object surface

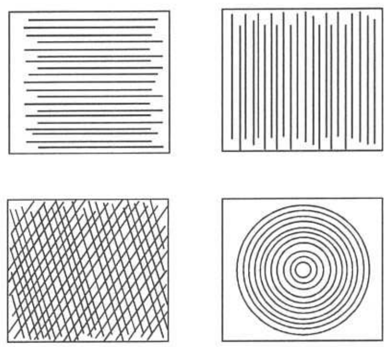
The object surface sensed by the laser triangulation system is the side surface of the accelerometer, which is parallel to its main axis, or the principle vibration axis, as shown in Fig. 1b. This surface is not flat or smooth as decreasing the roughness of a surface will usually increase exponentially its manufacturing costs. Roughness of the surface plays an important role in resulting in scattered reflections of light. Part of scattered reflections (scattering light) can then be received by receiving optics (CCD array). Images in Fig. 8 show the surface roughness of an accelerometer (Type 8305, B&K). Different areas on the side surface show the different lay directions. This information is useful for the arrangement of the laser triangulation system. A detailed discussion is as follows.



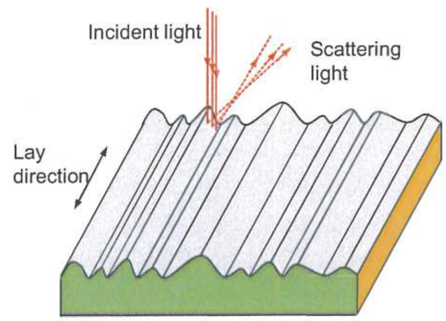
(a) (b)

Figure 7. Images of the surface roughness of an accelerometer. (a) Side surface near the top of the accelerometer. (b) Curved surface of the cylinder part of the accelerometer.

Lay is a measure of the direction of the predominant machining pattern representing of a specific manufacturing operation. Examples of various lay patterns are illustrated in Fig. 9a. Based on these lay patterns, an one-dimensional surface roughness model[7] is used as shown in Fig. 9b. The surface is represented by a continuous distribution of small elementary stripes with different tilts. The analysis is then done by the geometrical optics. In Fig. 9b, the solid red line represents a ray of incident light perpendicular to the surface. The rays of scattering light are represented by the dotted lines. These rays are contained in a plane perpendicular to the lay direction.



(a)



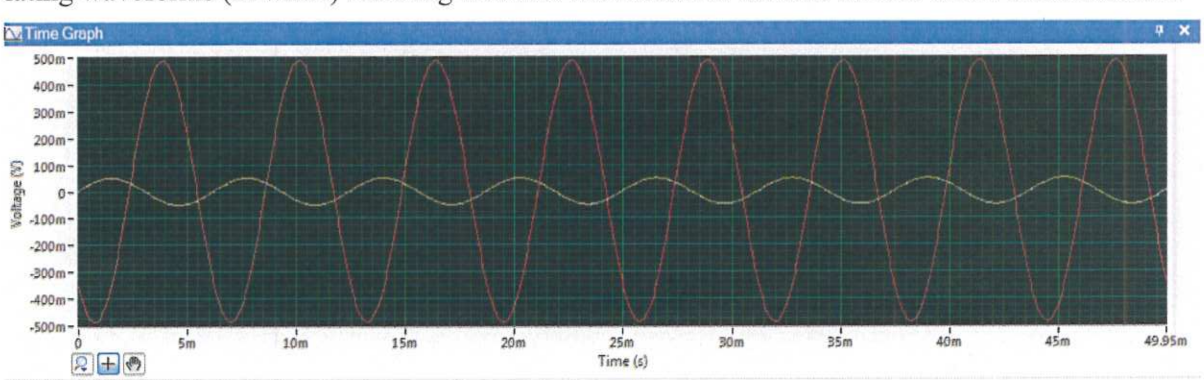
(b)

Figure 8. Lay and surface roughness modelling. (a) Examples of various lay patterns. (b) One-dimensional surface roughness model with incident and scattered light.

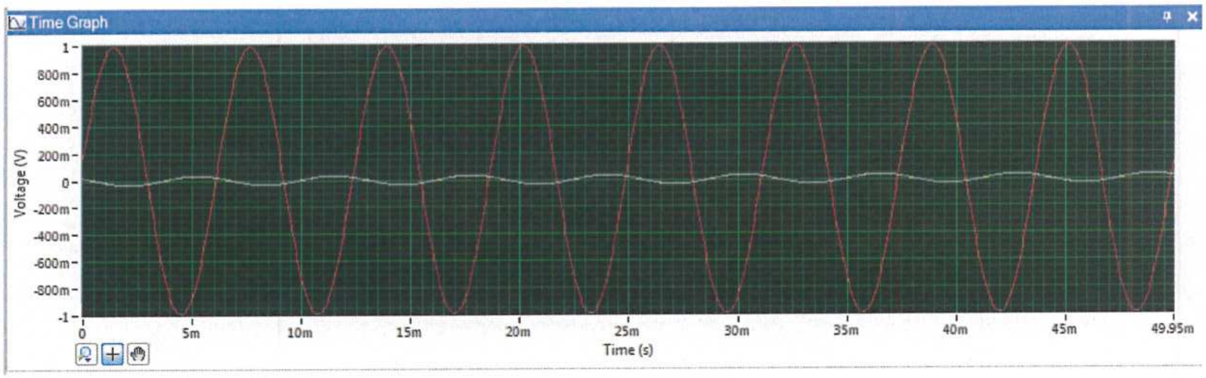
Nowadays metrologists consider slope as the parameter to describe roughness. Optical method can be used for slope measurement. The method measures the direction of the reflected light from the surface with respect to the incident beam. Reversely, if the slope of the roughness profile is known then the direction of the scattering light for the given incident light is known. For the one-dimensional surface roughness model shown in Fig. 9b, the laser triangulation system should be arranged such that the incident light and the scattering light into the CCD array are perpendicular to the lay direction. The y-axis translation moves the incident laser spot so that the light impinges on the elementary stripe with a desired slope resulting in a scattering light with a desired angle.

4. Measurement results

The rocking motion of accelerometer was investigated by vibrating an accelerometer under different cable fastening conditions, different mass loads, different accelerations, and at different frequencies. Some typical results are presented here. Shown in Fig. 9 are the accelerometer and CCD array output waveforms with the shaker vibrating at the frequency of 160 Hz and at the acceleration of 50 m/s^2 or 100 m/s^2. The rocking motion of the accelerometer can be seen from the oscillating waveforms (in white) resulting from the movement of the side surface of the accelerometer.



(a)



(b)

Figure 9. Accelerometer and CCD array output waveforms with the shaker vibrating at the frequency of 160 Hz and (a) at the acceleration of 50 m/s^2, (b) at the acceleration of 100 m/s^2.

Increasing the shaker acceleration does not increase the rocking motion. This is consistent to that discovered with the dummy accelerometer using the earlier system[5]. The rocking motion model shown in Fig. 1b can be used to explain this. The block with dotted lines vibrates twice as large as that with solid lines, but the side displacements of both blocks are the same.

5. Conclusions

An inproved measurement system for monitoring rocking motion of accelerometers in real-time is described. The principle of the system is based on real–time displacement measurements on the side surface of an accelerometer using laser triangulation systems. A simple method to determine the reference position (distance) of a triangulation system is proposed. Surface roughness of accelerometers are studied and then utilized to enhance the strength of scattering light. The system is used to study the accelerometer rocking motion under different operating conditions. It is found that the rocking motion does not increase as the acceleration increases for the vibration shaker under investigation. Thus, choosing higher acceleration level during the accelerometer calibration can prevent excessive effects of rocking motion on the calibration results.

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