Optical detection of ultrasound on rough surfaces using speckle correlated spatial filtering

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Abstract.
　　There are numerous techniques for the optical detection of ultrasound but many of these are of very limited application on optically rough surfaces. Techniques that work on rough surfaces are often complicated, inefficient and expensive. In this paper a new technique for the optical detection of ultrasound on rough surfaces is presented. It is a variation on the knife-edge (KE) technique but adapted for rough surfaces by replacing the knife-edge with a speckle correlated spatial filter (SCSF) which is implemented using a spatial light modulator (SLM). This technique is conceptually and practically simple and may be implemented using relatively low cost components. It is also relatively general and may also be applied to the detection of small displacements in many circumstances.

1. Introduction

There are numerous techniques for the optical detection of ultrasound including: KE detection, homodyne and heterodyne interferometry and Fabry-Perot detection. For reviews of these techniques see [1, 2, 3]. All of these techniques operate on optically smooth surfaces but can suffer from greatly reduced performance on optically rough surfaces.

Optically rough surfaces present a particular problem for optical detection because the reflection of laser light from a rough sample surface is speckled rather than specular. Techniques that work on rough surfaces include: adaptive interferometers, Fabry-Perot detectors and photo EMF based receivers. These techniques suffer from a number of drawbacks, for instance, the Fabry-Perot technique requires a frequency stabilised, single mode laser and an etalon with adaptive feedback in order to operate effectively. These are expensive and fragile items. Adaptive interferometers using two wave mixing in non linear crystals or photoEMF devices need to use a lot of the optical power to establish the adaptive pattern in the the crystal or photo-EMF receiver. Consequently they have expensive light budgets. Several commercial rough surface detectors are available on the market at considerable expense; much of which is due to the cost of the detection laser.

In this paper a simple variation of the KE detection technique is demonstrated on optically rough surfaces. It shares the same sensitivity characteristics as a normal KE detector operating on a smooth sample. The system is optically and conceptually simple, robust and inexpensive to implement. The SCSF detector demonstrated in this paper used a 5mW HeNe laser and an SLM removed from an inexpensive ($300) video projector.

2. Knife edge detectors

In a normal KE detector the presence of an elastic wave under the illumination beam deflects the reflected beam (see figure 1). The reflected beam is partially blocked by a 'knife-edge'. As the beam moves perpendicular to the knife-edge the amount of light passing it and reaching the photodiode changes. In practice the 'knife-edge' is simply a special case of a general spatial filter and may be implemented in a number of different ways, for instance, by using a split photodiode and differential electronics[4].
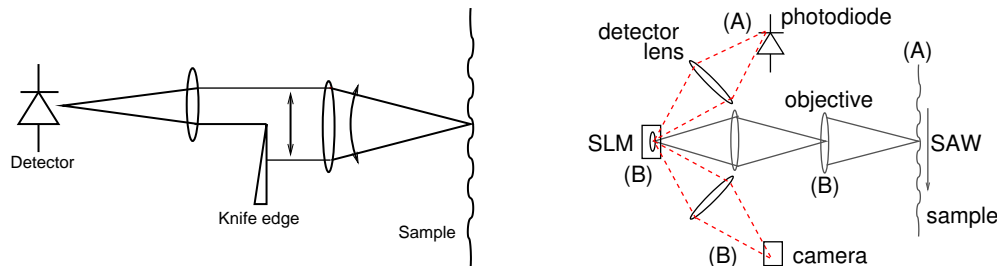
Figure 1. (left) Schematic of a KE detector and (right) the SCSF detector. In both cases the illumination optics have been removed for clarity. As the surface is deflected by the elastic wave the reflected beam is subject to angular deflection. This is transformed into an intensity modulation by the knife-edge (left) or spatial filter (right) and picked up by a photodetector. To gain optimal performance the knife-edge is positioned at the point of peak intensity in the reflected beam. In the SCSF detector an 'edge' is placed at the peak of each speckle. Planes marked (A) are conjugates of each other as are planes marked (B), hence the speckle pattern at the objective lens is imaged onto the SLM and the camera.

In order for the KE detector to work effectively the reflection from the sample surface needs to contain a strong specular component. If the sample surface is optically rough this specular reflection is not present, and only a diffuse speckle pattern enters the detector. In this situation the sensitivity is severely dependent on the location of the individual speckles across the knife-edge. Since the light is spread out over a wide range of solid angle, the transfer of optical power across the knife-edge with angular deflection is reduced leading to reduced sensitivity. The light entering the optical system is also likely to be clipped by the entrance aperture so there is a possibility that the response will change sign. As the speckle will change with the position, the sensitivity is not only reduced but also varies randomly with position.

The new detection method presented here uses an ensemble of 'knife-edges', one 'edge' for each speckle. This ensemble of knife-edges is implemented as pattern displayed on an SLM.

This detection method relies on the fact that, for very small displacements of the sample surface, the observed speckle moves rigidly. A carefully designed spatial filter, correlated to the observed speckle pattern, remains highly correlated to the speckle pattern throughout this small movement. The spatial filter needs to be designed so that it divides each speckle in half (across the direction of motion). The light from the sample is then passed through the spatial filter, collected by a lens and focused onto a photodiode. As the sample surface is perturbed by the acoustic wave the rigid movement of the speckles across the spatial filter is turned into an intensity modulation at the photodiode.

The spatial filter may be easily implemented using an SLM which only needs to display the filter as a binary mask. If the SLM is not absorbative and separates the light into a positive and negative images then the light from both of these may be collected on separate photodiodes and the signals subtracted to gain an improvement in the signal levels (and reject common mode noise)[5]. For large movements (compared with the illumination spot size) the speckle pattern

changes its spatial distribution and becomes decorrelated with the spatial filter. If this occurs then the filter ceases to function correctly and the detection sensitivity is lost until the spatial filter is reprogrammed.

2.1. Sensitivity of the SCSF detector

The movement of the speckle pattern for small displacements of the sample surface is geometric and determined by the optics in the same way as a KE detector. The size of the speckles is determined by the numerical aperture (NA) of the optical system delivering light to the sample and the focal length of the objective lens (exactly equivalent to the specular beam size in the KE detector). Neglecting the light that is lost due to scattering at high angles, it is easily shown that the sensitivity of the SCSF detector is exactly the same as the KE detector operating on a smooth sample. In the SCSF detector the light is divided between N speckles crossing N knife-edges (instead of one specular reflection crossing one knife-edge). Since the total amount of light and the distance it moves is the same in both cases and the average speckle size is the same as the specular beam size in the KE detector, the resulting sensitivity of the SCSF detector is the same as the equivalent KE detector operating on a smooth sample.

By electronically dithering the position of the spatial filter and measuring the change in light output, a calibration signal can be generated which, with knowledge of the geometry of the optics, can be used to obtain the absolute displacement.

For small movements of the sample the response is linear. This linear region occurs when the angular deflection caused by the ultrasonic wave is small compared with the NA of the illumination optics (as a rule of thumb $\theta_{\text{deflection}} < \text{NA}/10$). As an example, for 50MHz SAWs the linear region extends to $\sim$50nm amplitude– a substantial amplitude at this frequency.

3. Methodology

Figure 1 shows a schematic of the optical configuration used. In this case an inexpensive video projector was used to provide the SLM. This device contained a Texas Instruments digital mirror device with HVGA (480×320) resolution. The projector was stripped of its optics to obtain access to the modulator. These SLMs consist of an array of small mirrors that can be tilted +/-12°. The tilt axis was 45° to the pixel tiling direction, and to keep the optical paths on the horizontal plane the SLM was rotated by 45°. Similarly the camera was also inclined at 45° so that its aperture better matched the SLM aperture. A mapping between the pixels in the SLM and camera was performed using a trapezoidal transform so that the spatial filter could be be accurately mapped to the observed speckle.

3.1. Computing the SCSF

In the normal mode of operation the system needs to determine the SCSF and then display it on the SLM. In order to do this the SLM was first programmed to send a blank image to the camera so that the speckle distribution over the SLM could be determined. Then a SCSF was computed so that each speckle was cut in half by a 'knife-edge' across the expected direction of movement. Once the filter was computed, it was displayed on the SLM. The intensity received by this photodiode is the integral of the product of the spatial filter and the speckle pattern. As the speckle pattern moves (with respect to the spatial filter) the amount of light falling on the photodiode varies. For small movements this variation is proportional to the movement of the sample (see §2.1).

Figure 2 shows the process of the system adapting to a new position on the sample by recomputing the SCSF: (a) an image of the speckle pattern on the SLM was taken with the camera, (b) the spatially correlated spatial filter was computed such that it cuts each speckle in half and (c) spatial filter was displayed on the SLM to filter the speckle pattern. This results
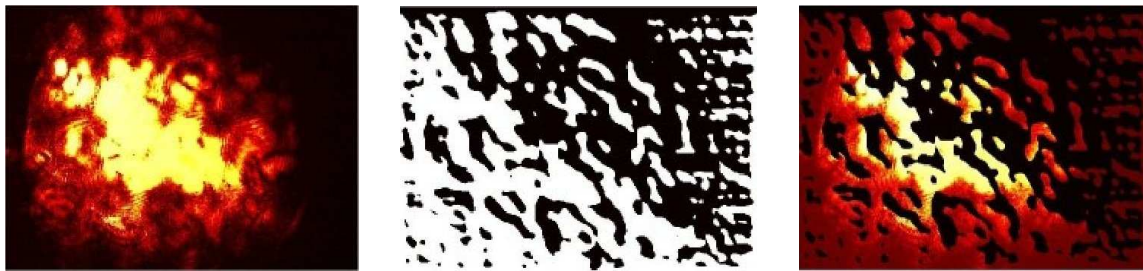
Figure 2. (left) (a) Speckle pattern observed on the SLM, (middle) (b) the SCSF computed from the image of the speckle pattern and (right) (c) the overlay of the filter over the speckle pattern. The filter cuts the speckle across the direction of movement (which is 45° left to right in these image due to the inclination of the SLM see §3)

in half the light from each speckle being collected by the detector lens and focused on the the photodiode.

4. Results, discussion and conclusion

The SCSF detector can be made to operate as a conventional KE detector by displaying a single edge at the geometric centre of the SLM. Figure 3 shows typical signals taken with a 5mW HeNe laser on an optically rough surface. It compares the signal obtained between the conventional knife-edge mode of detection and the adaptive speckle mode of detection. The b-scans were taken by scanning the detector across the sample, recomputing the spatial filter every point. It can be seen that the SCSF detector exhibits much higher sensitivity than the KE detector. For this system the detector can adapt to new positions on the sample at a rate of ∼12Hz determined by the frame rates of the camera and the SLM (25Hz). Frame rates of well over 1kHz can be achieved with more sophisticated SLMs.

This technique provides a simple, low cost method for the optical detection of ultrasound on optically rough surfaces.
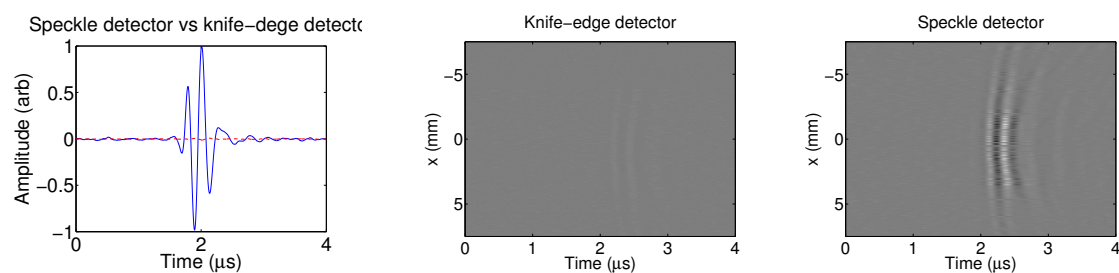
Figure 3. (left) Signal trace of KE detector (red, dashed) and SCSF detector (blue) at same position on sample. The sample was a diffusely reflecting, machined block of aluminium and the SAW was excited by a 5MHz transducer mounted on a perspex wedge. (middle) b-scan of the SAW wave taken with the KE detector and (right) with the SCSF detector (both using the same colourmap scale).

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