Optical detection of ultrasound from optically rough surfaces using a custom CMOS sensor

S O Achamfuo-Yeboah, R A Light and S D Sharples
Applied Optics Group, University of Nottingham, Nottingham, United Kingdom, NG7 2RD
E-mail: samuel.achamfuo-yeboah@nottingham.ac.uk

Abstract. The optical detection of ultrasound from optically rough surfaces is severely limited when using a conventional interferometric or optical beam deflection (OBD) setup because the detected light is speckled. This means that complicated and expensive setups are required to detect ultrasound optically on rough surfaces. We present a CMOS integrated circuit that can detect laser ultrasound in the presence of speckle. The detector circuit is based on the simple knife edge detector. It is self-adapting and is fast, inexpensive, compact and robust.

The CMOS circuit is implemented as a widefield array of 32×32 pixels. At each pixel the received light is compared with an adjacent pixel in order to determine the local light gradient. The result of this comparison is stored and used to connect each pixel to the positive or negative gradient output as appropriate (similar to a balanced knife edge detector). The perturbation of the surface due to ultrasound preserves the speckle distribution whilst deflecting it. The spatial disturbance of the speckle pattern due to the ultrasound is detected by considering each pair of pixels as a knife edge detector. The sensor can adapt itself to match the received optical speckle pattern in less than 0.1 µs, and then detect the ultrasound within 0.5 µs of adaptation. This makes it possible to repeatedly detect ultrasound from optically rough surfaces very quickly. The detector is capable of independent operation controlled by a local microcontroller, or it may be connected to a computer for more sophisticated configuration and control.

We present the theory of its operation and discuss results validating the concept and operation of the device. We also present preliminary results from an improved design which grants a higher bandwidth, allowing for optical detection of higher frequency ultrasound.

1. Introduction
Laser ultrasonics presents an excellent methodology for inspection of industrial components and characterisation of materials because it is non-contact, fast and may be used in hostile environments. The typical setup for all-optical inspection is to use a high energy light pulse to generate an acoustic wave. This acoustic wave propagates as an ultrasound wave, and may be detected using a coherent laser beam. The main parameters of interest for optical detection of ultrasound are achievable bandwidth, sensitivity, dynamic range, linearity of response, spatial resolution, mechanical stability and the surface finish required. A critical parameter of sensitivity is the minimum detectable surface displacement called the noise equivalent surface displacement (NESD). It is possible to achieve sensitivities of the order of $10^{-6}$Å(W/Hz)$^{-1/2}$ [1].

Optical detection of ultrasound may be categorised into interferometric or non-interferometric methods [2]. The non-interferometric methods include the optical beam deflection (OBD) technique [3], surface grating technique [4] and reflectivity [5]. Interferometric methods include the use of optical heterodyning, differential interferometry or velocity interferometry [2].
confocal Fabry-Perot interferometer (CFPi) \[6, 7\] and adaptive interferometers provide high sensitivity even in the presence of speckle \[8, 9\].

Recent work in the development of optical detectors has focused primarily on interferometric techniques in particular for multi-point detection, high adaption rate and industrial applications\[10\]. The use of two-wave mixing (TWM) in photorefractive crystals (PRC) is well researched\[11\]. The PRC requires about 2 ms to adapt to the speckle pattern received, making the detectors quite slow, but this technique is able to work effectively with rough surfaces and can work at reasonably high acoustic frequencies (in the region of 1 GHz). The use of photodetector arrays with multiplexed laser interferometers\[12, 13\] and based on random quadrature demodulation for multi-speckle processing has also been investigated\[14\]. The interferometric techniques are usually quite vulnerable to low frequency vibrations, expensive, bulky and tend to be quite difficult to set up and keep aligned. Both OBD and interferometric systems work very well when the surface finish is smooth (mirror-like), and offer similar sensitivities. However the OBD technique fails when the surface of the specimen under test is rough\[15\].

The knife-edge detector (KED) is the simplest form of the OBD detector. It is attractive because it satisfies most of the parameters of interest - particularly achievable bandwidth, linearity of response, mechanical stability, low-cost, small size, and small number of optical components. The KED is most simply implemented with a knife-edge to obscure half of a reflected laser beam that is collected on a photodiode. Use of a balanced or split photodiode provides a differential signal and recent work includes the use of split fibre optic bundles for light collection\[16\].

To overcome the requirement for a smooth surface for OBD detection, Clark\[17\] uses a spatial light modulator (SLM) to implement a reconfigurable KED. The probe beam is reflected off the specimen under test onto the SLM. An image of the speckle pattern received on the SLM is captured by a camera, and this image is used to compute a speckle correlated spatial filter - ‘an ensemble of knife-edges’. This filter is implemented as a binary mask on the SLM. The mask spatially filters the speckled probe beam and reflects it onto a photodiode for detection of the surface displacement. This system is limited by the frame rate of the camera and SLM to approximately 12 Hz.

In operation, the KED detects the deflection of the probe beam caused by the surface perturbation. The knife edge acts as a boundary or spatial filter, and the detector measures the change in light energy as the beam is deflected across it. It is most commonly implemented as a split photodiode (effectively two photodiodes in very close proximity to one another), and by connecting each of the outputs (labelled L and R) to one input of a difference amplifier, a balanced signal sensitive only to the deflection is obtained. This is shown in figure 1.

2. Optical detection on rough surfaces

Since light is used for detection (the probe beam), the use of lasers for detecting ultrasound is however usually restricted by the surface finish of the material or component under inspection. All surfaces are rough at the atomic level, but of interest to inspection are surfaces which have a roughness of the order of the wavelength of the probe beam used in inspection. The Rayleigh criterion is often used as a criterion for the degree of roughness of a surface\[18\]. The criterion may be summed up as follows: if $\Delta h < \lambda/8$ the surface is smooth, otherwise it is rough, where $\Delta h$ is a measure of surface height fluctuation, and $\lambda$ is the wavelength of the light. Optical smoothness or roughness is dependent on light wavelength and angle of illumination: both factors affect how smooth the surface appears to be.

Thus the optically rough surface presents three problems: firstly, if the surface roughness is comparable with the wavelength of the acoustic signal, then the Rayleigh wave is usually highly attenuated. Secondly, the reflected light is diffusely reflected. Matching the étendue (or
Figure 1. A schematic of a system that uses a knife edge detector (KED) to detect optical beam deflection due to a surface acoustic wave.

throughput - the product of the effective entrance aperture area by the solid angle limited by the rays of maximum inclination) of the detection system to that of the surface space quickly becomes difficult to achieve experimentally [2]. This means that the change in light caused by the surface displacement is usually very difficult to detect because insufficient light is collected.

The third problem that manifests when working with optically rough surfaces is that the variations in the surface under the probe beam reflect the light back with a random phase profile. When this reflected light is captured on a screen or detector, it causes an interference pattern: a speckle pattern. The speckle pattern is a function of the sample surface and the optics. This interferogram causes problems for the KED because the deflection in the reflected probe beam due to the acoustic wave is such that dark and bright parts of the speckle move synchronously, i.e. at the point being inspected, the whole speckle image received is translated in tandem with the acoustic wave. Moving to a different position on the sample results in a new speckle image.

A model illustrates the problem. Figure 2 shows the different scenarios possible. Figure 2(a) shows the light received at the detector when a probe beam with a Gaussian intensity profile has been reflected by a smooth sample surface. The signal sent to each output is shown in a different colour: red is L, and green is R, using the labels in Figure 1. As an acoustic wave passes under the spot illuminated by the probe beam, the wave is deflected, leading to the result shown on the right in Figure 2(b). If a rough surface is inspected, a speckle pattern is received at the detector. Figure 2(c) shows a speckle pattern incident on a KED after reflection off a rough surface. The perturbation due to an acoustic signal results in the acoustic signal shown in Figure 2(d). The signal has a much smaller amplitude compared to Figure 2(b) because both bright and dark parts of the speckle have synchronously crossed the knife edge, resulting in a smaller energy transfer across the knife edge boundary.

Consider a device able to treat each speckle as a separate beam, and thence dynamically able to create a number of knife edge detectors in response to any received speckle pattern. The outputs of these KEDs would be tied together: all Ls together, all Rs together. We call this configuration of linked multiple knife edge detectors the configuration state, as depicted in Figure 2(e). Figure 2(f) shows that the amplitude of the received signal is greatly improved as compared to the KED.

The ideal reconfigurable KED would therefore be a very welcome device, allowing non-contact inspection of samples without the need for extra processing to enable the sample surface to satisfy the Rayleigh criterion. Conceptually, the detector would analyse the gradient of the received light and create splits at the points of maximum intensity. It could do this in both vertical or horizontal axes—corresponding to the orientation of a regular KED. The configurations shown
in figure 2 are for a horizontal axis.

![Image 127x607 to 252x700](a) Light from smooth surface received on KED

![Image 356x611 to 469x696](b) Detected signal

![Image 127x490 to 252x584](c) Light from rough surface received on KED

![Image 356x495 to 469x480](d) Detected signal

![Image 127x374 to 252x467](e) Light from rough surface received on configurable KED

![Image 356x378 to 469x463](f) Detected signal

**Figure 2.** Light received at a KED and detected signal for configurations of surface roughness. (a) shows light from smooth sample inspected with a KED and the result obtained (b), (c) is for a rough sample inspected with a KED and result obtained (d), and (e) is shows speckle from a rough sample inspected with a reconfigurable KED, and the result obtained (f). The total light energy is the same for each of the 3 situations.

3. **The SKED - Speckle Knife Edge Detector**

The Speckle Knife Edge Detector (SKED) reported here is a detector that implements the automatic self configuration process outlined above. It is implemented as an integrated circuit and is fabricated in a 0.35 µm standard CMOS process. It is laid out as an array of 32×32 smart pixels. Each pixel is 59 µm×59 µm, 43% of which is photosensitive. Each pixel contains an N-well photodiode (the light-sensitive region), signal conditioning, a comparator, and 1 bit memory (for storing configuration states). It also contains 3 switches implemented as transmission gates. This amounts to 78 transistors per pixel. A simplified schematic of the pixel is shown in figure 3.

The SKED has two modes of operation. In configure mode, each pixel of the SKED compares the light received to the light received by the pixel adjacent to it. The adjacent pixel to it is defined by the axis of comparison (vertical or horizontal), which is selectable by the user. The comparator output is used to determine which of the L or R outputs (equivalent to red or green in figure 2) that the photodiode for this pixel should be connected to. This result is stored in
the memory at this pixel. It is possible to send a signal to each pixel to explicitly define which output the photodiode should be connected to. The L outputs from all the pixels, and R outputs from all the pixels are tied together and presented as two outputs outside the chip. This gives the sum of all positive gradients in L, and sum of all negative gradients in R, equivalent to a normal KED. In the measurement mode of operation, the comparator is disconnected, and the photocurrent is switched through to the appropriate output at each pixel.

Figure 4 shows the printed circuit board laid on an optical table. The SKED chip is outlined in red. Figure 5 shows an outline of the decision making process. It shows 7 pixels, each receiving different light intensities. Since there are two peaks in the light intensity distribution, each of those peaks will act as a split point for a knife edge. The decisions taken by the SKED are shown in the same figure.

The SKED is small, very fast, rugged and easy to swap into existing systems which use a KED. It is relatively inexpensive, with 9500 Euro providing 30 fabricated devices. It is hosted on a credit-card sized printed circuit board with microcontroller providing control and USB connectivity. It is possible to read the configuration state of each pixel (i.e. which output the pixel is connected to - L or R), or to write arbitrary patterns to the SKED, such as a KED with a diagonal axis.

In normal operation, at the start of the scan the SKED configures itself to the received speckle
pattern, then goes into measurement mode where it is ready to measure the acoustic signal. The sample may then be moved, at which point the speckle pattern changes completely, and it becomes necessary to reconfigure to this pattern before the next acoustic signal is measured. A raster scan may then be performed, alternating between configure and measurement modes at each point.

4. Results
This section presents some preliminary results obtained with the SKED. A commercially available detector from Bossa Nova, the Tempo [19], was used as a reference device to calibrate the SKED.

4.1. Adaption Speed
The SKED can configure itself to the received speckle in as little as 0.1 µs, and be ready to measure ultrasound within 0.5 µs of configuration. This means that it is possible to take as many as 1,000,000 measurements per second. This makes it extremely fast compared to existing technology such as the Tempo. The Tempo needs approximately 2 ms to reconfigure to speckle.

4.2. Sensitivity
The sensitivity of the SKED is affected by how each pixel correctly configures to the light received, connecting the photodiode to the appropriate output (L/R). It has been determined that the SKED does this correctly approximately 90% of the time, under typical light power conditions, and will correctly choose which output when there is as little as 18 nW difference in light intensity between two adjacent pixels.

4.3. Bandwidth
The bandwidth of the device is limited by the capacitance of the photodiode and the parasitic impedances from the switches and tracks. It was determined that when balanced, i.e. with 512 pixels connected to each output (L/R), the -3 dB bandwidth is approximately 16 MHz. We have successfully measured signals at 82 MHz, but observed attenuation due to the bandwidth.

4.4. Comparison with a KED
Since it is possible to write configuration patterns to the device, it is possible to configure it to operate as a regular KED. This allows the performance of the SKED to be compared with a KED without other factors affecting the results (such as total photosensitive area). Figure 6 shows the improvement that can be achieved when the SKED operates in the self-configured mode. An 82 MHz surface acoustic wave was generated on an aluminium sample with a machined finish. A 1 mm line scan was performed across the surface, and at each point the signal was measured both with the SKED configuring itself to the received speckle pattern, and programmed as a KED. The mean signal and amplitude show a clear improvement over the KED operation.

4.5. Improved design - SKED2
Following from the lessons of the prototype device, an improved second device was designed and fabricated. It was fabricated in the same 0.35 µm CMOS process. Each pixel is 62 µm × 62 µm, with a photosensitive area 27% of the pixel area. It also has 32×32 pixels. The main improvements are as follows:

(i) Simplified comparator: the comparator accounted for a significant area of the prototype device. It was simplified from 12 to 4 transistors. This improved both the space utilisation and improved the adaption speed.

(ii) Reduced parasitics: the parasitic impedance in the prototype device were quite high, and by simplifying the switches and reducing the track width this was reduced.
Figure 6. On the left, the SKED device automatically configures itself as a line scan is performed on machined aluminium; on the right, the SKED device is manually configured to behave as a conventional KED. The upper traces are the ultrasonic signals at the last point in the line scan. The centre traces show the mean signal level, normalised to the maximum of all recorded signals. The images at the bottom represent the configuration state for the last point in the line scan.

(iii) Improved bandwidth: a more radical change was the introduction of a second 4-transistor comparator in each pixel. This comparator is used to compare the photocurrent with a reference current supplied from the printed circuit board. The reference can be changed to match the experiment. In configure mode, this comparator is used to determine whether the light intensity at the pixel exceeds the reference value. The output of the comparator determines whether this pixel is connected or disconnected to the outputs in measurement mode. This is useful because if a photodiode does not receive much light (i.e. dark speckle), it does not contribute signal, but the capacitance of the photodiode reduces the bandwidth of the device. By disconnecting pixels in this way, the bandwidth of the device can be improved without sacrificing signal.

Figure 7 shows an experimental result that demonstrates the value of being able to disconnect dark pixels from the chip outputs. The reference current applied to the chip is varied whilst measuring a single sample point, hence a constant speckle pattern. The black region indicates pixels which receive low light and have been disconnected from the outputs. At both 10 MHz and 20 MHz, as more and more pixels are disconnected by increasing the reference current (the SKED chooses which pixels to switch off), the received signal amplitude increases, until the reference level is high enough to start disconnecting pixels that have significantly high illumination levels and not enough light is detected. At this point the amplitude begins to fall.

This new design is also more sensitive to differences in the received light between adjacent pixels, with correct configuration when there is as little as 6 nW difference in light power.

5. Conclusion
We have presented a CMOS integrated circuit capable of optical detection of ultrasound from optically rough surfaces. It is robust, cheap and adapts very quickly. Preliminary results
Figure 7. Improvement in detected signal by switching off pixels.

demonstrate the improvement in detection capability as compared with conventional detection techniques based on optical beam deflection. Initial experiments indicate a noise equivalent surface displacement of $12 \times 10^{-6} \text{Å}(W/\text{Hz})^{1/2}$ for the SKED compared with $2 \times 10^{-6} \text{Å}(W/\text{Hz})^{1/2}$ for the Tempo. Full specifications will be published soon.

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