NEW LASER ULTRASONIC INTERFEROMETER FOR INDUSTRIAL APPLICATIONS

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Abstract: A novel interferometric scheme for detection of ultrasound is presented. The proposed technique is based on the classical Michelson architecture, which is known for its high sensitivity on mirror like surfaces. In order to adapt this inteferometer for industrial applications, quadrature demodulation is implemented. The use of quadrature demodulation eliminates the requirement of path stabilization, leading to a compact and rugged design. Furthermore, high sensitivity is achieved using multi-detector combined with parallel electronic signal processing in order to efficiently process the speckled light reflected from rough surfaces. The performance of this multi-detector interferometer is described and its advantage for measurement in industrial environments is discussed.

Introduction: Remote, non-contact detection and generation of ultrasound by laser present many advantages over conventional piezoelectric transducer methods [1]. Laser-based ultrasonic (LBU) is now becoming a more mature technology, making the transition from research laboratory specialized equipment to industrial on-line measurement system. Successful industrial integration includes inspection of composite aircrafts [2], online seamless tubes [3] and semiconductor thin film metrology [4]. Commercial Laser ultrasonic system used in the semiconductor industry for measurement on thin film/layer will not be discussed here, the measurement conditions being very specific (very high frequency technique on optically smooth surface). Industrial applications of LBU have been limited to specific applications that can justify the higher cost and complexity of LBU systems. In order to become more broadly used as an on-line measurement tool, LBU is still looking for a more rugged, compact and cost effective solution.

In a LBU system, the receiver is the most critical component. Various optical techniques have been developed and extensively reviewed [5], [6]. For industrial application, the receiver must be able to overcome or compensate for dynamic perturbation due to workpiece translation or vibration and it must be capable to process speckled returns from the optically rough workpiece.

In recent years, a number of adaptive or compensated LBU receivers using photorefractive crystals have been developed. In the two most common approaches, the crystal is either used as a real-time hologram via two-wave mixing [7] or as a compensated photodetector via the photo-induced electromotrive force (photo-EMF) effect [8]. The photorefractive crystal acts as an adaptive beamsplitter, which combines the transmitted signal beam with the diffracted reference beam with exact wavefront matching. It also compensates for whole-body vibration of workpieces and environmental vibration if the grating-writing times are appropriate. Adaptive interferometers are mainly used in R&D laboratories. They have not yet been integrated into industrial inspection system, mainly because of their limited response time or, in the case of very fast adaptive systems based on photo-EMF, of their limited sensitivity. To date, LBU industrial inspection systems are mostly based on the confocal Fabry-Pérot interferometer.

To overcome the current LBU receiver limitations, we present here a compact and robust interferometric scheme that exhibits high sensitivity, independently of the environment.

Quadrature Interferometer: Quadrature interferometers are very attractive for industrial applications. Quadrature interferometers are two-beam interferometer that uses two interference signals 90^o out-of-phase [1]. A schematic of the quadrature interferometer is shown in Fig.1. The 90^o phase difference is obtained by placing a quarter-wave plate in the path of channel 1. There are different possibilities for combining the signals from the two channels in order to extract the ultrasonic information [1]. Depending of the demodulation, the output signal can be proportional to the displacement-square, the displacement or the velocity of the surface motion. The schematic for displacement-square and displacement demodulations are shown in Fig.2. After demodulation, the sensitivity to the high-frequency small ultrasonic signals is independent of large amplitude phase variations occurring at low frequencies.

In the case of displacement-square demodulation, the directional information is lost. This is usually not important in most ultrasonic applications where information of interest is deduced from the time of arrival and/or the peak-to-peak amplitudes. Amplitude-square demodulation is generally more robust than the amplitude demodulation. Indeed, with amplitude demodulation, the large amplitude background phase variations and the ultrasonic signal must be well separated in frequency, in order to avoid that significant phase shift be introduced by the filters.

The amplitude demodulation generally exhibits higher dynamic and lower noise. Laser intensity noise can be effectively rejected with the balanced detection scheme in the case of amplitude demodulation. Amplitude-square demodulation does not take advantage of the balanced detection. The noise rejection is achieved when the DC level of the two detectors is balanced. This is only true when the phase difference between the two interfering beams is exactly $\pi/2$. This can be seen on Fig.3 where the high frequency signal and the large amplitude and low frequency signal at the output of the balanced detector are simultaneously recorded. The noise is minimal when the low frequency signal crosses zero: the balanced condition. In the case of amplitude-square demodulation, the two 90^o out-of-phase signals being summed after squaring, the intensity noise of both channels is added. The balancing detection is thus ineffective with this demodulation scheme. On the other hand, with amplitude demodulation, the noise rejection from the balanced detection scheme is effective because the cross multiplication minimizes the high frequency signal when it is unbalanced (high noise level) and maximize the signal when it is balanced (minimum noise).

Depth-of-field: For on-line measurement in industrial environment, the ability for the interferometer to operate satisfactorily even if the sample is not placed at the optimal position is critical. The ability of the interferometer to accept large variation of the sample position without much degradation in sensitivity is characterized by the depth-of-field (DOF). When the sample moves away from the "at-focus" position, the object beam on the detector is no longer a plane wave filling the detector but rapidly diverges or converges, overfilling or underfilling the detector, as it is shown on Fig. 4. If a fast optical system is used in order to increase the collected light and thus increase the sensitivity, then the sensitivity quickly degrades when the object moves out-of-focus. This is due to the focal ratio f_1/f_2 that is needed in order to concentrate the collected light onto the small detector area. In order to have large depth-of-field, the focal ratio f_1/f_2 must be kept to the smallest possible value, requiring either a small aperture or a large area detector. Comparison between calculated DOF for two detector sizes is shown Fig. 4. Because the interferometer sensitivity highly depends on the amount of light collected, reducing the collecting aperture is not recommended. To use a detector with large area is preferred. Unfortunately, large area single photodetector presents some limitations: 1) a large area detector is limited to low frequency application because of its associated capacitance and 2) integration of a too large number of speckles is not highly effective because of the random nature of speckle light. These limitations can be overcome with a multi-channel interferometer using detector arrays.

Multi-channel quadrature interferometer: The optical arrangement of a multi-channel quadrature interferometer is identical to the single detector configuration shown in Fig.1. Each detector is now replaced by a detector array and the reference beam is expended in order to fill the larger detection area. The demodulation is now done in parallel and the demodulated signal of each channel is added to generate a highly stable output signal. Both demodulation configurations described above could be integrated. The amplitude-square demodulation requires less components and can thus lead to a more compact electronic design.

The advantage of a multi-channel interferometer is first demonstraded by simulating a laser ultrasonic time-of-flight experiment. This simulation uses: (1) a "noise-free" (large number of averaging) laser ultrasonic signal corresponding to a pulse-echo experiment, (2) speckles randomly generated by computer, (3) these speckles are made to interfere with a plane wave reference and the resulting modulation coefficient is calculated and applied to the amplitude of the ultrasonic signal, (4) random noise simulating the electronic noise and the shot noise is added to the signal, (5) finally, time-of-flight measurement between the peak of the first echo and the peak of the second echo is calculated. If a deviation from more than 5% of the correct value is calculated, the measurement is then considered false and recorded as an error. For these simulations, we assume that the amount of light collected from the object is small compared to the reference beam intensity and thus the shot noise on the detector is due mainly from the reference beam. Fig.5 shows the comparison among detection using 1) a single-speckle with single-element detector, 2) a single-element detector with 10 speckles, 3) a 4-element detector with 10 speckles per element, 4) a 25-element detector with 10 speckles per element, and 5) a 256-element detector with 10 speckles per element. As expected, increasing the number of detector elements increases the sensitivity of the interferometer allowing to detecting smaller ultrasonic signals.

For demonstration, a 4-channel quadrature interferometer was tested. Both the amplitude-square and the amplitude demodulations were implemented. The 4-channel interferometer and a single-channel interferometer were compared. Fig.6 shows the strength of the corresponding demodulated signals when a scattering target is translated. As expected, the 4-element detection always gives higher signal than the single-element detection, corresponding in average to a 4 times signal increase. We also found that the relative signal fluctuation is also reduced by a factor 2 in average. This smaller variation of the signal indicates that the probability of blackouts is being greatly reduced. In this experiment, blackouts did not occur for the 4-element detection.

As indicated earlier, the use of multi-element detectors allows the interferometer to increase its collection efficiency without reducing its DOF. The depth-of-field of the 4-channel interferometer was measured on a uniformly scattering sample. As shown in Fig.7, we measured a long DOF: typically 30mm for a 100mm focal lens. Similar value of the DOF was measured for the single-element interferometer. In both case, the interferometer was optimized for collecting about 10 speckles when at-focus. For comparison, using an adaptive interferometer based on photorefractive two-wave mixing with a fast collecting optic (F/2) and a single detector (1mm^2 area), we measured a DOF for a 100mm focal length of only 2mm.

An example of laser ultrasonic signals recorded with the 4-channel quadrature interferometer using amplitude and amplitude-square demodulations are shown in Fig.8. The detection of laser generated ultrasonic signal was carried out for both the amplitude-demodulation and the amplitude-square demodulation. In this experiment, ultrasounds were generated in a 6mm thick steel plate by laser ablation resulting from the absorption of a 100mJ, 10nS pulse of a NdYag laser @1.06µm. The detection of the ultrasound was carried out using the a 20mW Diode laser @ 635nm and a detection bandwidth of 20MHz. Figure 19 shows the detected signal corresponding to the through-transmission geometry for both amplitude demodulation and amplitude-square demodulation. The 1st echo amplitude is about 2nm displacement. With the amplitude-square demodulation, the small signal (2nd echo) is more difficult to detect.

Conclusion: By taking advantage of today integration capability of electronics, compact and cost-effective multi-channel interferometers now become a reality. Increasing the number of channels directly increases the light collection efficiency and thus it sensitivity for inspection of optically rough surface, without reducing the DOF of the interferometer. The demodulation being carried out electronically, the requirement on the stability of optical system is minimal, making the system very robust. The high sensitivity, robustness and long DOF of this interferometer make it well suited for on-line industrial measurement.

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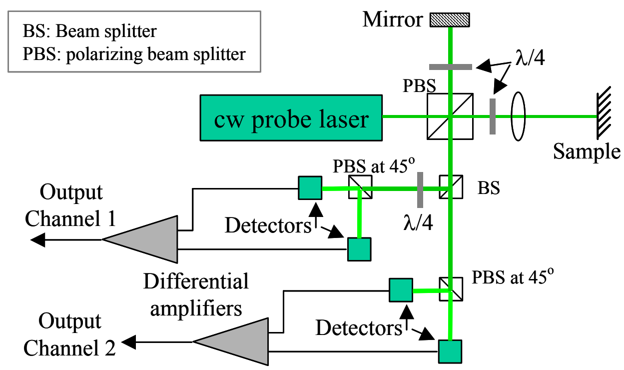

Figure 1: Schematic of quadrature detection.

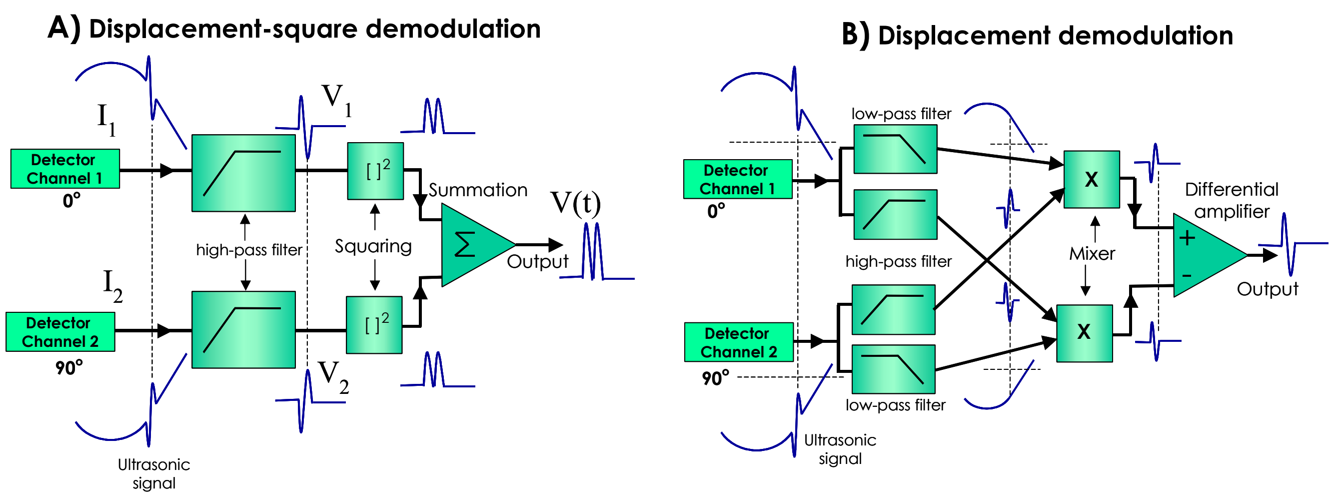

Figure 2: Demodulation of quadrature signals with the output signal proportional to A) square of displacement and B) displacement.

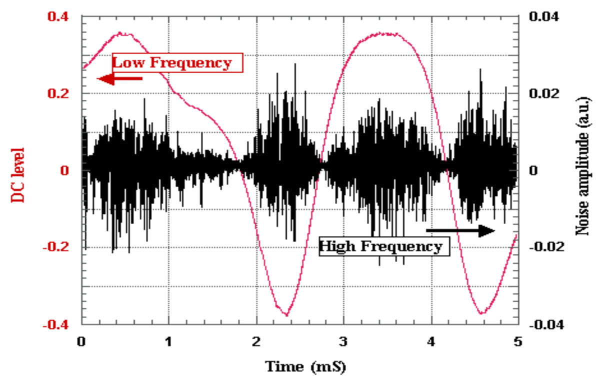

Figure 3: Laser intensity noise rejection.

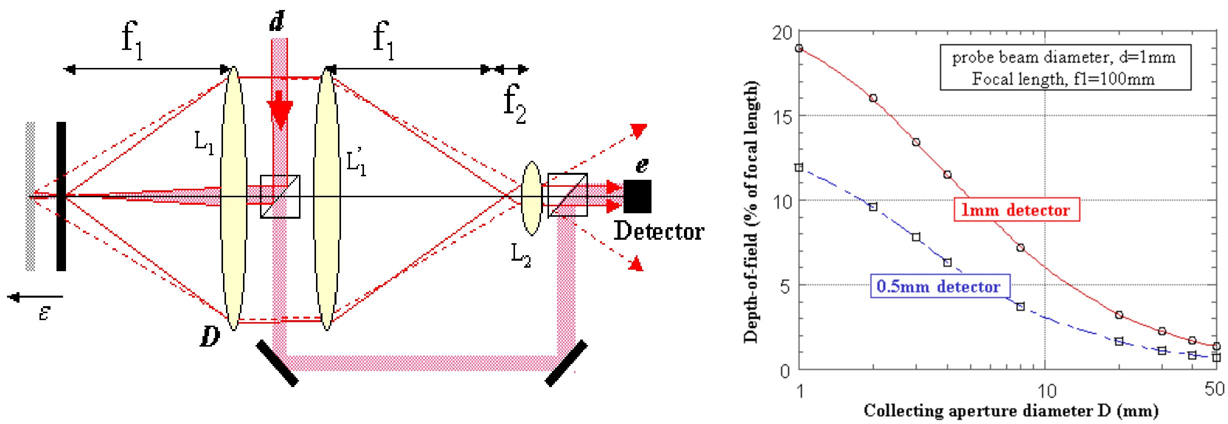

Figure 4: A) Schematic of interferometer used for calculation of depth-of-field. B) Depth-of-field results showing the influence of the detector size.

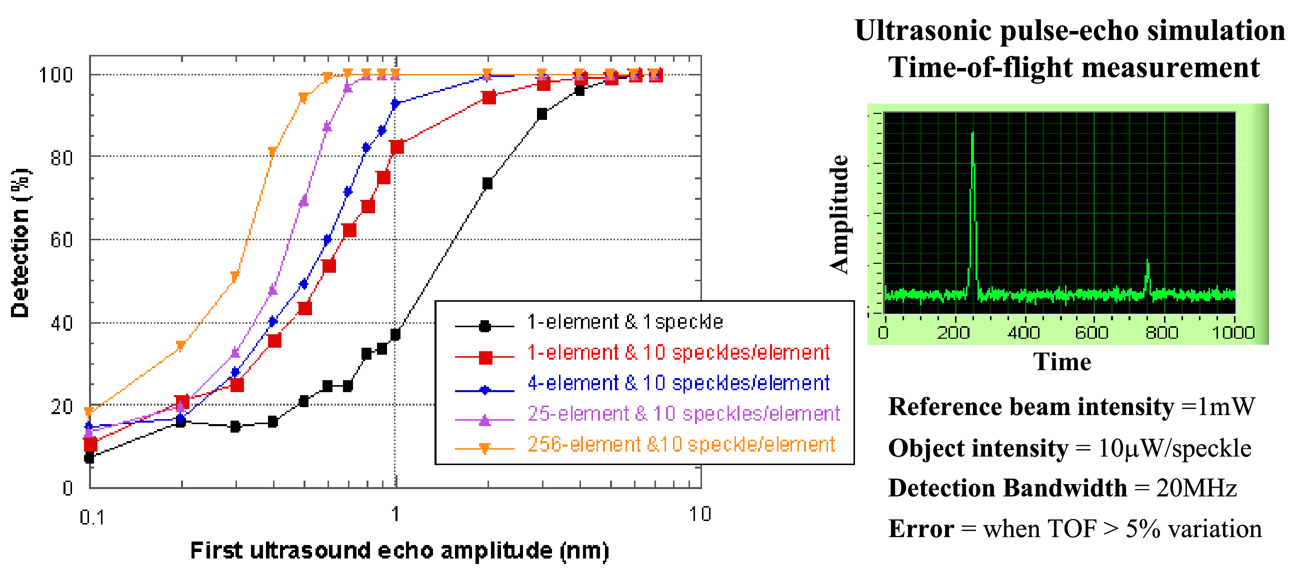

Figure 5: Probability of detection for time-of-flight experiment with different number of speckles and number of detector elements.

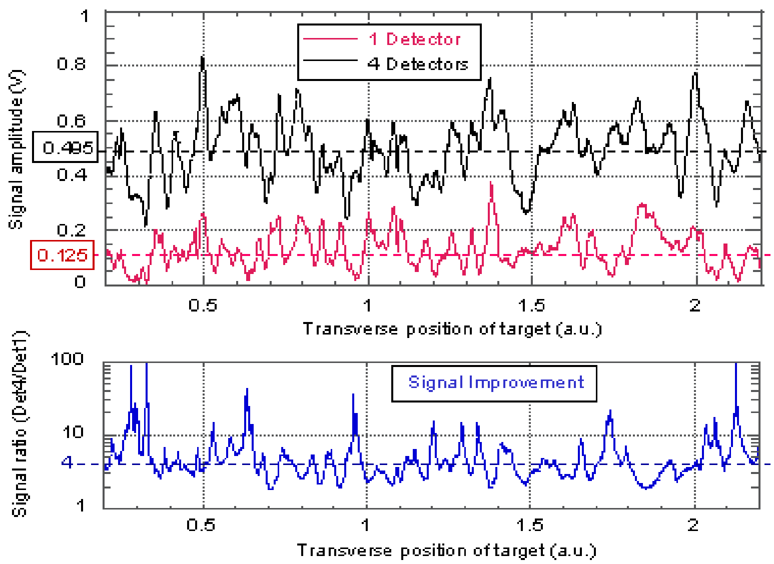

Figure 6: Sensitivity comparison between a single-element and 4-element interferometers.

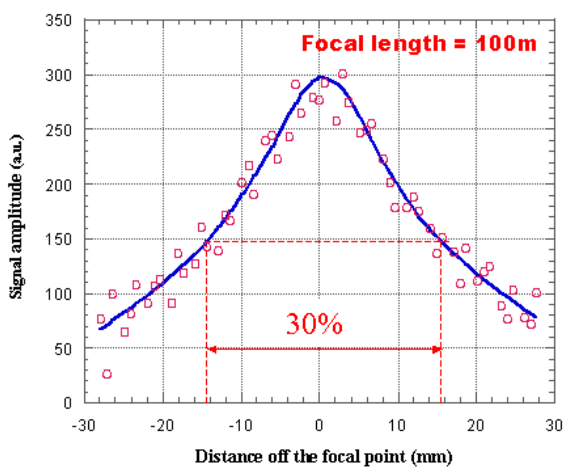

Figure 7: influence of the out-of-focus position of the sample on the interferometer sensitivity.

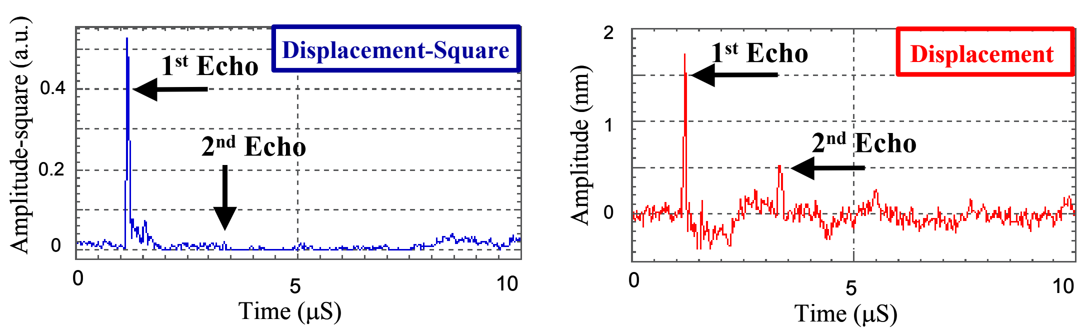

Figure 8: Laser ultrasonic signal with displacement-square and displacement demodulations.