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DIFFERENTIAL CONFOCAL FABRY-PEROT FOR THE OPTICAL DETECTION OF ULTRASOUND

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Abstract. The best detection limit of an optical system for the detection of ultrasound is obtained for a system limited by the shot noise. However, typical laser oscillators are not free of intensity and phase fluctuations, and such laser noise exceeds the shot-noise level above a given laser light power. Moreover, since typical industrial surfaces are optically rough and absorbing, laser amplifiers are frequently used to increase the light power collected back from the surface. Such amplifiers add both intensity and phase fluctuations. While intensity fluctuations can be eliminated by a simple differential scheme when using a confocal Fabry-Perot, no simple solution has been given to reduce the phase noise. In this paper, differential schemes that reduce both laser intensity and phase noises are proposed for the transmission and reflection configurations and experimental results on the noise reduction reached are presented. The advantages of this differential approach to image variable reflectivity surface parts and to relax detection laser requirements are then discussed.

Keywords: Optical detection, Laser-ultrasonics, Laser-ultrasound, Laser-based ultrasound, Optical amplification.
PACS: numbers

INTRODUCTION

Optical systems for the detection of ultrasound based on a confocal Fabry-Perot interferometer are now widely used in laboratories and industries for process control during manufacturing or for nondestructive evaluation of parts in service [1]. As shown in Figure 1a, the basic setup employs a stable single frequency laser to illuminate the material surface in ultrasonic motion on which the light reflected or scattered off this surface acquires phase modulation. Since optical photodetectors are not sensitive to phase modulation, an interferometer such as a confocal Fabry-Perot (CFP) is used [2-4]. The CFP, operated either in the transmission or reflection mode, holds the necessary characteristics to properly probe parts in real industrial conditions, since it is intrinsically insensitive to low frequency ambient vibrations. The CFP frequency response is broad enough to detect ultrasonic motions in a range from about 1 MHz up to a few hundred MHz. Also, the CFP has the large etendue, or light gathering efficiency, requires to probe parts having optically rough and absorbing surface.

Since the ultrasonic motion amplitude is typically of a few nm, a very good detectivity, or minimum detectable ultrasonic displacement, is required. The best detectivity is reached when detection is limited by the shot-noise. In this case, the ultrasonic signal varies as the light power collected back from the surface whereas the shot-noise varies as the square-root of this light power. The signal-to-noise ratio (SNR) then accordingly varies as the square-root of the light power collected from the surface. Higher light power results in a better SNR and a better detectivity. However, typical lasers are not free of intensity and phase fluctuations, also called laser noise. In addition, industrial surfaces being highly scattering and absorbing, laser amplifiers are frequently used to increase the light power collected back from the surface. Such amplifiers add both intensity and phase fluctuations to the laser beam [5]. Above a given laser light power collected back from the surface, the laser noise dominates the shot-noise. Since both the ultrasonic signal and the laser noise depend linearly on the light power, increasing the light power collected back from the part no longer improve the SNR.

Optical detection of ultrasound can also be performed by an adaptive interferometer based on wave mixing in a photorefractive crystal. With this kind of two-wave interferometer, intensity fluctuations can be easily eliminated by a balanced detection scheme and the phase fluctuations are eliminated by keeping the pump and signal beam paths nearly equal [6]. With the CFP, intensity fluctuations can be eliminated or strongly reduced by subtracting the signals at the entrance and at the output of the interferometer, or by other similar schemes [7]. Eliminating phase fluctuations is more problematic since the CFP is a time-delay interferometer, in which the incident beam somehow interferes with itself. Getting rid of both intensity and phase laser noises would allow one to still operate in the shot-noise regime while collecting high light power from the part surface, resulting in a better detectivity. In this paper, differential schemes for the CFP that reduce both the laser intensity and phase noises are proposed in the transmission and reflection configurations. These approaches allow improving the minimum detectable ultrasonic displacement that can be measured by a system based on a CFP interferometer for the optical detection of ultrasound. Experimental results on the noise reduction reached are presented. Also, the advantages of these differential approaches for ultrasonic imaging parts with variable surface reflectivity and relaxing detection laser requirements are discussed.

DIFFERENTIAL CFP IN TRANSMISSION MODE

The CFP is used in the transmission mode where the light power input and output are on opposite sides. Figure 1b shows the theoretical frequency response of a system to a phase modulation, assuming mirror reflectivities $R_1=R_2=0.94$ and a cavity length of 50 cm. Details of the calculation can be found in Ref. [8, 9]. Figure 1b indicates that the interferometer has the best sensitivity to ultrasonic displacement in the frequency range from 1 to 15 MHz. However, the system is also sensitive to laser intensity and phase noises present in the same frequency range.

The basic idea of the proposed differential approach is to pick up a fraction of the main laser beam at the output of the laser oscillator, or of the laser amplifiers if any, to create a reference beam. The reference beam is then sent to the CFP interferometer to get an electrical signal proportional to the laser intensity and phase noises. This electrical signal is then subtracted from the signal generated by the interferometer for the probing beam. Since the probing beam has both contributions from the laser intensity and phase fluctuations and from the ultrasonic surface motion, while the reference beam has only the intensity and phase fluctuations, the results is an electric signal that is cleared from laser noise. While the method can be implemented with two CFP interferometers, one to

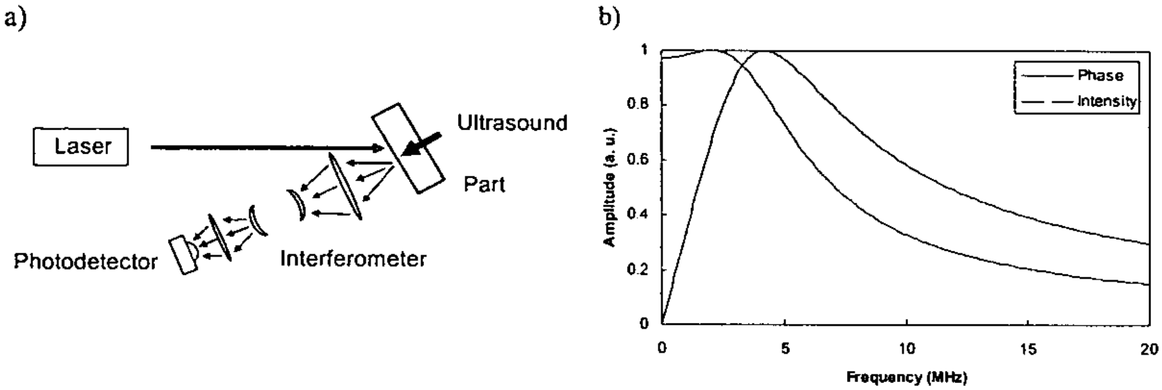

FIGURE 1. a) The basic setup for optical detection of ultrasound and b) example of theoretical frequency response of the CFP interferometer in transmission mode to a phase and an intensity modulation.

measure the reference beam noise and the other to measure the probing beam ultrasonic signal and noise, thermal and electronic drifts of the length of the two CFP will result in a not very reliable system. Using the same CFP to measure both beams appears more stable and practical.

Figure 2 shows a first differential scheme for the CFP used in transmission mode. The CFP optical transmission is dynamically maintained at half maximum using the difference of the stabilization detectors to drive the piezoelectric pusher on one of the CFP mirrors [3, 4]. The probing beam is made from the main laser power collected back from the surface in ultrasonic motion while the reference beam is made from a low light power extracted at the laser output. Both beams are brought to the CFP interferometer by free space propagation or, more practically, using optical fibers. A polarizing beam splitter in front of the CFP allows the selection of one linear polarization from each beam and injection of these two orthogonally polarized beams in the interferometer. If the probing or reference beam is unpolarized, the penalty for selecting one polarization is to inject only half of the beam power in the interferometer. Another polarizing beam splitter at the output of the interferometer is used to physically separate the two beams. Each beam is then sent to a photodetector, the outputs of which are subtracted to get an electrical signal proportional to the ultrasonic surface motion and free of the laser intensity and phase fluctuations.

A better reduction of the noise is obtained when the probing and reference beams are of equal power. A mean to control the light power of the reference beam may be added to the system to compensate for the variable reflectivity and the power collected back from the material surface. In addition, the optical path length of the probing and reference beams could be made nearly equal, by free propagation or using optical fibers, to avoid a time delay in the laser noise carried by the two beams. The variation of the extinction ratio of the noise with the optical path length difference depends on the spectral frequency of the noise. The extinction ratio, defined as the ratio of the RMS noise with and without the differential scheme, varies as $1/2\sin(\pi fd/c)$, with f the fluctuation frequency, d the optical path length difference and c the speed of light. For example, an extinction ratio of 30 is obtained for fd = 1.6 MHz.m, which means that at 1 MHz an optical path difference of 1.6 m still allow an extinction ratio of 30. A better alternative to the variable reflectivity and time delay problems is to digitize the electric signals from the two photodetectors and adjust the amplitude and the relative delay before subtracting them to get the maximum noise reduction, which is also known as adaptive filtering [10]. This approach is more appropriate when inspecting a material with a highly variable reflectivity or a highly contoured part on which the probing path length changes from one location to the other.

However, the differential scheme of Figure 2 may not work properly when the light power collected back from the surface varies too much over the inspected part. One example would be testing a composite part with both metal and graphite epoxy surfaces. In such cases, the photodetector capturing the signal from the surface saturates on the metal surface and is not sensitive enough on the graphite epoxy surface. Figure 3 shows a second differential scheme that removes these limitations. In this approach, the light power of the probing beam rejected by the polarizing beam splitter in front of the CFP is sent to a photodetector. The electrical signal from this photodetector is then subtracted from the photodetector signal from the probing beam at the output of the CFP interferometer. This differential procedure allows one to remove some of the intensity noise but also to operate on materials with strongly varying surface reflectivity, without any saturation of the detector. The same scheme is also applied to the reference beam. The two resulting electrical difference signals are then digitized and processed. As previously for processing, the relative delay and amplitude of the signals are adjusted before subtracting them to get a maximum noise reduction.

As shown in Figure 1b, the frequency response of the CFP interferometer to intensity and phase fluctuations of an incident laser beam is not flat. The first scheme is not sensitive to this non-flat response since both signals come from an optical beam that goes through the CFP. In the second scheme, the signals to be subtracted come from beams captured in front and at the output of the CFP. The intensity noise is then efficiently subtracted within a finite frequency range only. However, since this occurs for the both the probing and reference beams, subsequent subtraction after proper delay and amplitude corrections, provides complete elimination of both phase noise and residual intensity noise. While more complicated than the first scheme, this second scheme is actually a perfect differential detector. It allows one to work on materials of strongly varying surface reflectivity, while removing both the intensity and phase noises. The limit of this scheme is given by the dynamic range of the differential detectors, which can be made easily large. The large dynamic range feature coupled to this differential scheme makes the proposed approach very useful for integration in a laser-ultrasonic scanning system. All the light power collected back from any point of the material surface can be used while keeping the detection system in the optimum shot-noise regime, without saturation of the photodetectors. While the amount of light varies from one location to another, the amplitude images obtained from the scan are self-normalized by the processing.

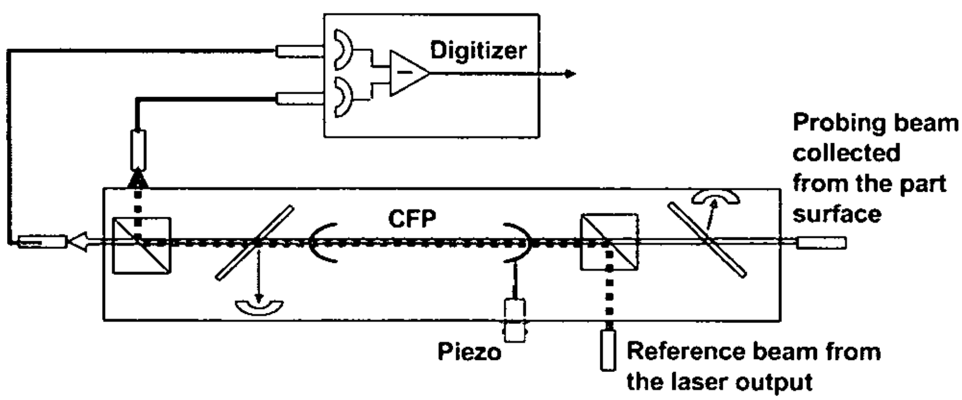

FIGURE 2. A first differential scheme for the CFP in transmission mode.

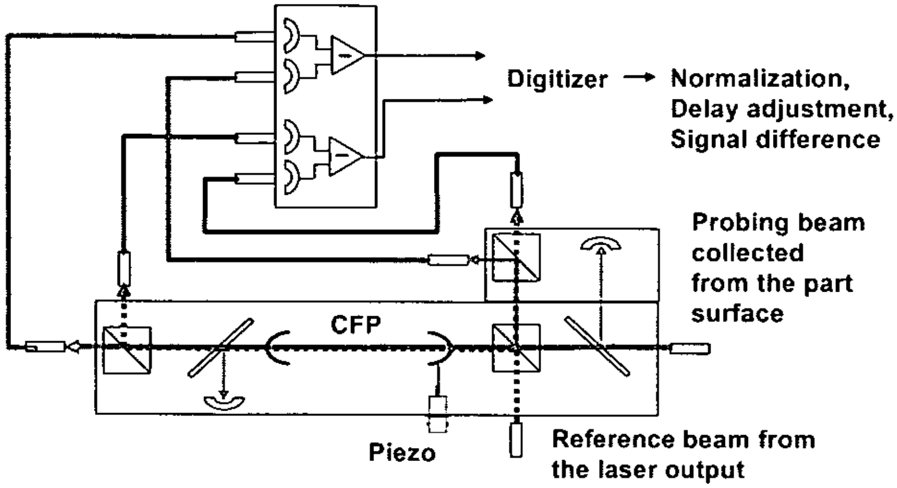

FIGURE 3. The second differential scheme for the CFP in transmission mode.

DIFFERENTIAL CFP IN REFLECTION MODE

The optical detection of ultrasound can also be based on a CFP in the reflection mode where the light power input and output are on the same side. The CFP in reflection mode has a larger ultrasonic frequency bandwidth response than its transmission counterpart and extends from a few MHz to a GHz or more, limited by the photodetector bandwidth. The system is sensitive to laser intensity and phase noises also present in this frequency range, in practice up to about 20 MHz.

Figure 4 shows a differential scheme for the detection of ultrasound based on an asymmetric configuration of the CFP in reflection mode (back mirror close to 100% reflectivity). The basic principle is the same as previously. The reference and probing beams are collected at the output of the CFP and sent to photodetectors. The signals from the two photodetectors are then subtracted to remove the laser intensity and phase noises and improve the SNR of the ultrasonic signal. Again, a better noise rejection is obtained when the reference and probing beam intensities and path lengths are both nearly equal. A mean to control the power of the reference beam and to make the optical path length of the probing and reference beams nearly equal may be added to the setup. A better alternative is to digitize the electric signals from the two photodetectors and adjust the amplitude and the relative delay before subtracting them to get the maximum noise reduction.

Figure 5 shows another differential scheme based on a symmetric configuration of the CFP in reflection mode. In this scheme, the probing and reference beams are fed to the CFP from opposite sides. Two quarter-wave plates, one on each side of the CFP, are tuned to compensate each other. For example, the horizontal polarization of the probing beam transmitted by the polarizing cube is transformed in a circular polarization by the first quarter wave plate and fed in the CFP. The second quarter wave plate at the output of the CFP is tuned to get a horizontally polarized beam on the second polarizing beam splitter. Otherwise, the basic principle of collecting the reference and probing beams at the output of the CFP and subtracting the signals from the two photodetectors to remove the laser noise is similar. This scheme results in probing beam power losses of a factor of 2, compared to a factor of 8 for the asymmetric configuration. However in both cases, the light power losses at the beam splitters can be used to build a setup similar to, and with the same advantages as, the second scheme proposed for the transmission mode, in which the signals of the probing and reference beams at the input and the output of the CFP are subtracted.

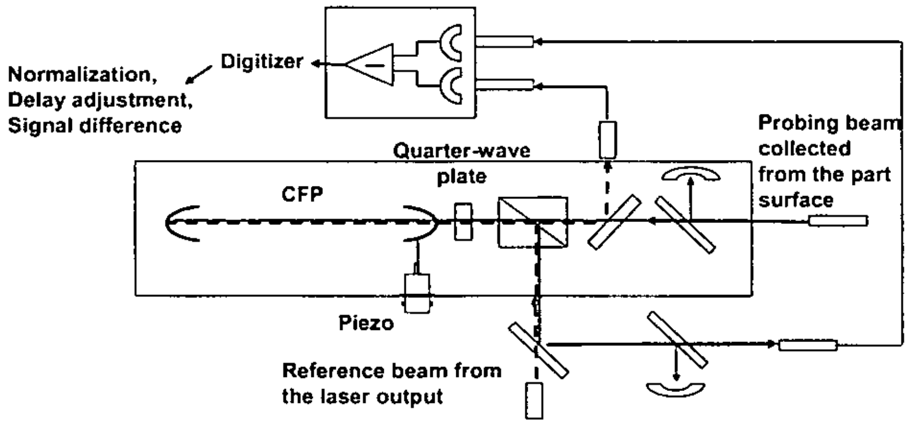

FIGURE 4. A differential scheme for an asymmetric configuration of the CFP in reflection mode.

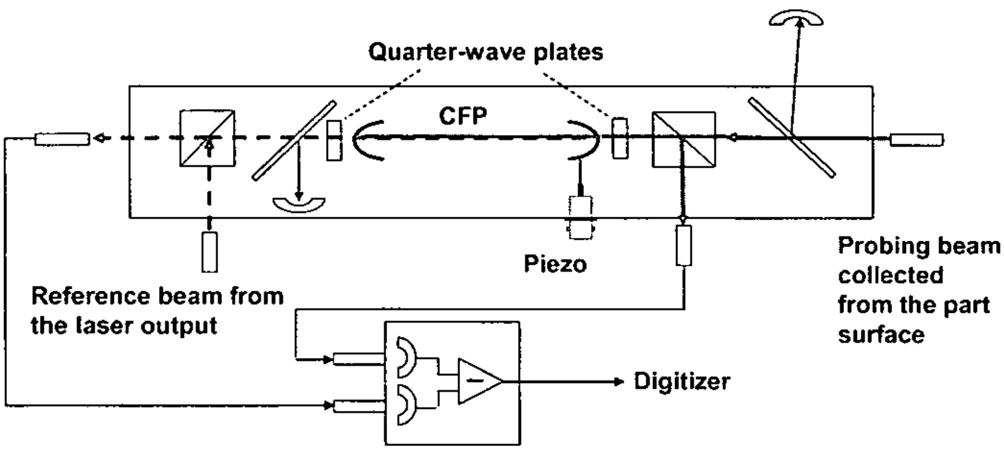

FIGURE 5. A differential scheme for a symmetric configuration of the CFP in reflection mode.

LASER-ULTRASONIC RESULTS

The differential scheme approach described above was used for a difficult application of laser-ultrasonics, in which the thickness of an oil layer on top of water is measured from a flying airplane. The laser-ultrasonic system is located on board the airplane and shots downwards onto the wave agitated surface. For this application a very variable detection beam return is expected, ranging from less 1 mW to several tens of mW. High sensitivity is also required since nearly acoustic matching between oil and water gives a weak interface signal. Those are the conditions which will benefit from the configuration shown in Figure 3 (second differential scheme of the CFP in transmission mode) Figure 6 shows a typical result obtained during such an experiment with and without the differential scheme. It can be seen that the high noise level is strongly reduced by the differential scheme. The noise floor is about the shot-noise, as expected. The ultrasonic echo from the oil-water interface at about 28 μs is barely seen without the differential scheme, but appears clearly with the differential scheme in operation. In figure 6, the noise is reduced by 11 dB to the shot-noise after rejection of the laser noise. Up to 30 to 40 dB noise rejection is however expected from this differential scheme. The CFP length was 50 cm and the mirror reflectivities were 0.94. Ultrasound was generated by a CO_2 high power short pulse. Notice that the huge signal at about 18 μs is caused by the oil surface displacement following the absorption of the generation laser pulse.

CONCLUSION

For the optical detection of ultrasound, differential schemes that reduce both the laser intensity and phase noises have been proposed for the CFP in the transmission and reflection configurations. Removing the laser noise improves the SNR and allows maintaining the ideal conditions in which the signal is limited by the shot noise, even when high light power is collected back from the surface. For variable surface reflectivity, the signals of the probing and reference beams both at the input and the output of the CFP are used. Also for variable working distance, the electric signals from the photodetectors are digitized, and the amplitude and the relative delay are adjusted before subtracting them to get the maximum noise reduction. The approach allows the improvement of the sensitivity of a system based on a CFP interferometer and an illustration of its performance on the noise reduction was demonstrated.

According to its frequency response, the CFP in transmission is preferably used for the detection of ultrasonic frequencies below 15 MHz, while the CFP in reflection is more suitable at higher frequencies. Since both laser intensity and phase noises are typically concentrated at frequency below 20 MHz, the differential scheme appears more relevant for the CFP in transmission. The implication of this differential approach is a reduction of some laser requirements for optical detection of ultrasound. Similar performances can be obtained with a noisier and cheaper detection laser, thus reducing the cost of the overall system.

The proposed schemes can be advantageously integrated to a laser-ultrasonic scanning system. In this case, all the light power collected back from any point of the material surface can be used while keeping the detection system in the optimum shot-noise regime, without saturation of the photodetectors. There is no need of attenuating the detection laser beam to keep the photodetector/preamplifier below saturation when the surface is highly reflecting. Even if the SNR of the detection system varies from one location to another during scanning, the described schemes provide signal normalization, so the amplitude images will not show any effect of variation of surface reflectivity or collected light power.

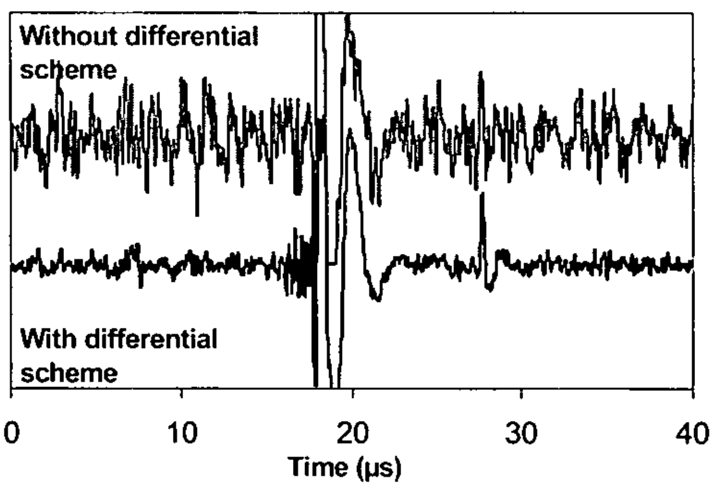

FIGURE 6. Illustration of the performance of the second differential scheme for the CFP in transmission mode.

REFERENCES

1. J.-P. Monchalin, "Laser-ultrasonics: from the laboratory to industry", in *Review of Progress in Quantitative Nondestructive evaluation 23A*, ed. by D.O. Thompson and D.E. Chimenti, AIP Conf. Proc., New York, 2004, pp. 3-31.
2. C.B. Scruby and L.E. Drain, *Laser-Ultrasonics: Techniques and applications*, Adam Hilger, Bristol, UK, 1990.
3. J.-P. Monchalin, IEEE Trans. Ultrason. Ferroelectrics and Freq. Cont. UFFC 33, p. 485 (1986).
4. J.-P. Monchalin, R. Héon, P. Bouchard, C. Padioleau, *Appl. Phys. Lett.* **55**, 1612 (1989).
5. A. Blouin and J.-P. Monchalin, "Optical amplification of the laser-ultrasonic signal", in *Review of Progress in Quantitative Nondestructive evaluation 23A*, ed. by D.O. Thompson and D.E. Chimenti, AIP Conf. Proc., New York, 2004, pp. 270-277.
6. B. Campagne, A. Blouin, L. Pujol, J.-P. Monchalin, , Rev. of Sc. Inst., **72**, 2478, (2001).
7. J.-P. Monchalin and R. Héon, "Laser optical ultrasound detection using two interferometer systems", US patent 5,080,491.
8. J.-P. Monchalin and R. Héon, *Materials Evaluation* **44**, 1231 (1986).
9. Q. Shan, A. S. Bradford and R. J. Dewhurst, *Meas. Sci. Technol.* **9**, 24 (1998).
10. A. S. Thomas, *Adaptive signal processing: theory and applications*, Springer-Verlag, New York, 1986.