APPLICATION OF HIGH-AMPLITUDE ULTRASOUND FOR NON-DESTRUCTIVE EVALUATION

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ABSTRACT

High-amplitude ultrasound \( (u_0 > 100 \text{ nm}) \) generated by pulsed laser material processing carries important information about the mechanisms of light-material interaction and the propagation of the wave within the work-piece. In addition, it can also be applied for the purpose of non-destructive evaluation of the sample.

The propagation of high-amplitude ultrasonic waves inside a plate is measured with an improved interferometric method and compared with standard PID-controlled stabilized interferometer. The improved method is based on the quadrature detection of two orthogonally polarized laser beams. It has a constant sensitivity which enables measurement of high-amplitude ultrasonic waves as well as monitoring of ultrasonic waves superimposed on the translatory movement of the object.

An application of high-amplitude ultrasound for non-destructive evaluation is demonstrated. A comparison between non-destructive evaluations based on low- and high-amplitude laser generated ultrasound is also performed using both interferometric methods. Advantages of the improved detection method of high-amplitude ultrasound are additionally discussed.

Key words: Optodynamics, High-amplitude laser-generated ultrasound, Non-destructive testing, Interferometric detection methods.

1. Introduction

The ultrasound can be generated by lasers and remotely detected by measuring the material’s surface displacement with laser interferometers [1-4]. Laser-generated ultrasound is one of the many optodynamic phenomena [5-7], which include all kinds of macroscopic motion that can be caused by high-intensity laser light. High-amplitude ultrasound, i.e., ultrasound causing surface displacements greater than 100 nm is generated during the laser material processing and carries important information about the mechanisms of the light-material interaction, the propagation of the wave within the work-piece, the elasto-mechanical properties of this piece, and also about the position of the processing-laser beam. Therefore it can be applied for the purpose of non-destructive evaluation of the sample as well as for the non-destructive control of the applied laser processing.
Various techniques were used for the detection of ultrasonic waves, such as: piezoelectric probes, capacitive and inductive sensors, and optical probes [8]. Interferometric methods are the main representative of the last group [9]. In general, displacement-measuring interferometers [10] can be divided into three main categories according to the measurement range and resolution. Displacements which are several orders of magnitude longer than the wavelength of the interferometric laser are usually determined by counting interference fringes which is a low resolution technique [1] appropriate for measuring unidirectional motion. On the other hand, displacements which are small compared to the wavelength are usually measured around the most sensitive point of the detected signal. A typical representative of this category is a Proportional-integral-derivative controlled Michelson interferometer (PID-MI) [5,8] with a common resolution of about 0.1 nm and maximum displacement of 100 nm, thus covering the dynamic range of $10^3$.

However, only low-amplitude ultrasonic waves ($< 100$ nm) can be measured with this type of interferometers. Interferometers in the third category can be represented by a homodyne quadrature laser interferometer (HQLI) [11,12], which combines both, the long measurement range and high resolution. It is an interferometer with a constant sensitivity which enables measurements of high-amplitude ultrasonic waves ($> 100$ nm) as well as monitoring of ultrasonic waves superimposed on the translatory moving objects.

In our experiments we simultaneously employed the two interferometric methods: the standard PID-controlled stabilized interferometer (PID-MI) and an improved interferometric method based on the HQLI. The main aim of our work was a comparison between the methods for non-destructive evaluations of low- and high-amplitude laser generated ultrasound.

2. Experimental setup

The experimental setup is shown in Fig. 1. The laser generated ultrasound was induced by the Q-switched Nd:YAG operating at 1064 nm capable of producing 10-ns-long pulses with the maximum energy of 300 mJ. The excitation laser pulse was focused to a 1-mm-diameter spot on the front surface of an 8-mm-thick aluminum plate. The intensity of the pulse on the aluminum surface was high enough to surpass the ablation threshold, thus producing strong longitudinal ultrasonic wave propagating predominantly in the normal direction.

Laser induced ultrasound as well as its reflections of the front and the rear surfaces of the plate were simultaneously measured with the two interferometric methods: the PID-MI and the HQLI. As an interferometric laser we applied a continuous He-Ne with an output power of 10 mW at 632.8 nm. It was reflected from the rear surface of the aluminum plate. The beams of the interferometric and the excitation laser were aligned, thus forming the epicentral position.

The PID-MI (the pink outline in Fig. 1) has the reference arm compensated for the low-frequency ($< 1$ kHz) environmental mechanical noise by a feedback loop. It uses only one (PDx) photodiode. The feedback loop of the PID-MI locks the interferometer at its most sensitive point in the middle between the signal’s maximum and minimum, thus enabling displacement measurement of about $\pm \lambda/16$ with respect from the locked position without considerable loss in linearity and sensitivity. The detailed description of the PID-MI can be found elsewhere [5,8]. On the other hand, the improved interferometric method, based on the HQLI, uses two orthogonally polarized signals with a 90° phase shift. The quadrature of both signals is achieved by a retardation plate (OWP) in combination with the linearly polarized laser output and the polarization beam splitter (PBS). Its principle of operation is described in Ref. [12].

The signals from both photodiodes (PDx and PDy) were acquired and processed with specially developed software in order to obtain the desired displacement. In the contrast with the PID-MI, which loses the linearity and sensitivity when the measured displacement exceeds $\lambda/8$, the HQLI has a constant sensitivity, resolution below 1 nm, and a high dynamic range, greater than $10^5$.  

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Furthermore, the HQLI works well even when the displacement frequencies exceed the bandwidth of the photo-detector. The signals were equidistantly sampled by a 500-MHz oscilloscope with a sampling capacity of 2 MS per channel. The sampling is limited either by the oscilloscope’s sampling rate or by the frequency response of the 200-MHz photodiodes. We measured the displacement in the first 100 µs after the laser pulse hit the surface.

3. Results and discussion

Fig. 1: Schematic top view of the improved laser interferometer combining the two detection methods: the HQLI and the PID-MI. The exiting light from the 10-mW interferometric He-Ne laser source (λ = 632.8 nm) is linearly polarized at 45°. The excitation laser is an Nd-YAG laser (λ = 1064 nm) with maximum energy of 300 mJ per 10-ns pulse. NBS: non-polarizing beam splitter, PBS: polarizing beam splitter, BPF: optically narrow band-pass filter, OWP: octadic wave plate, PDx and PDy: photodiodes, PZT: piezoelectric transducer, PID: proportional-integral-derivative controller, OSC: digital acquisition oscilloscope, PC: personal computer, u(t): normal displacement.

Measurements of the high- and low-amplitude laser-induced ultrasound performed with a single 300 mJ pulse and detected by an interferometric laser beam in the epicentral position are shown in Fig. 2. The low-amplitude (30 nm; the red line in Fig. 2) ultrasound was generated by a direct ablation and measured with the PID-MI, while the high-amplitude (330 nm; the black line in Fig. 2) ultrasound was generated in the constrained surface regime using a transparent coating to enhance the ultrasonic amplitudes [3]. The low-amplitude ultrasonic displacements were measured with both detection methods, giving highly comparable measurements. The high-amplitude ultrasound can
only be measured by the HQLI, since the PID-MI gives an inappropriate displacement as it is presented in Fig. 3.

When material is ablated from the front surface of the aluminum sample, an ultrasonic wave is generated at the interaction site. After \( t_L = 1.265 \mu s \), i.e., the time-of-flight of the longitudinal wave in an 8-mm-thick Al plate, the rear surface experiences a sudden forward motion due to the first arrival of the compressional ultrasonic wave. This surface motion is detected as the first peak, labeled L1 in Fig. 2. In the case of the epicentral position, the other reflections L3, L5, \ldots, L25 are detected with the time period of 2\( t_L \). In our time-of-flight analysis, we considered only longitudinal waves, which can be recognized from their sharp rise-time corresponding to high velocities of the surface displacements. The other reflections of the shear waves and the waves resulting from various mode conversions were not taken into account.

The time-of-flight analysis of the high-amplitude ultrasound enables accurate calculations of the speed of the longitudinal wave, since the longitudinal arrivals up to L25 can be easily recognized. On the other hand, when the low-amplitude ultrasound is applied, only the first few (up to L9) reflections can be distinguished from the background. Another interesting application based on the high-amplitude ultrasound is the detection of the epicentral position. If the excitation and the interferometric laser beams are not in the epicentral position, the arrivals are no longer periodic. In this case, the time between the two consecutive arrivals \( t_{L(n+1)} - t_{Ln} \) approaches 2\( t_L \) as \( n \) rises. From such a time-of-flight analysis, the epicentral position can be easily recognized.

The displacement caused by the high-amplitude ultrasound designated by the shaded region in Fig. 2 is presented in Fig. 3a in greater detail. The raw signal from a single photodiode (PID-MI method) is
shown in Fig. 3b. The displacement is obtained using both photodiodes with the quadrature detection method. The first arrival of the longitudinal wave (L1) is detected as a 330 nm sharp peak at 1.265 µs. The amplitude of this peak cannot be determined using a single photodetector as in PID-MI, because such an interferometer is insensitive to displacements near $V_{\text{max}}$ and $V_{\text{min}}$. As seen in Fig. 3b, it cannot be distinguished whether the first arrival is indeed a single peak or rather composed of multiple peaks, since the direction of the displacement is indiscernible near the maximum and minimum of the detected signal.

The PID-MI was stabilized to 0.38 V. The stabilization technique as well enables the determination of the initial direction of motion. Knowing that the initial drop of the voltage corresponds to the forward motion of the measuring surface, and taking into account that it is also known how the shape of displacement looks, one can mark which portions of the signal correspond to the same half-fringe ($\lambda/4$). The half-fringe is the distance that the measuring surface needs to travel so that the intensity on the photodiode changes from its maximum to its minimum value – when the interference changes from constructive to destructive. The dashed lines in Fig. 3a separate the graph into $\lambda/4$-displacement intervals, where the slopes of the displacement are either equal (the black colored curve) or opposite (the blue and green colored curves) to the slopes of the raw signal. The corresponding half-fringe lines lay at 0.13 V and 0.93 V on the graph in Fig. 3b.

![Graph showing displacement and voltage](image)

Fig. 3: The same epicentral displacement measured with both detection methods: (a) with the HQLI and (b) with the PID-MI. Displacements greater than $\pm\lambda/16$ with respect to the most sensitive point cannot be determined with PID-MI, while they can be obtained with HQLI. (a) The displacement as a function of time as it is designated by the shadowed region in Fig. 2. This displacement is obtained by proper processing of the signals from both photodiodes PDx and PDy. (b) The voltage from the PDx photodiode as a function of time from which the displacement can be obtained with the PID-MI. Half-fringe lines separated by $\lambda/4$ are drawn in (a) which corresponds to the $V_{\text{max}} - V_{\text{min}}$ in (b). The ultrasonic displacement in each half-fringe band in (a) is drawn with different color in order to distinguish how the displacement is encoded in (b).

The measured surface experiences a sudden forward motion due to the first arrival of the compressional high-amplitude ultrasonic wave and reaches the velocity which exceeds the
frequency range of photodiodes. Displacements with frequencies higher than 200 MHz are detected as if their amplitudes were lower. The encircled numbers in Fig. 3b clearly demonstrate this effect – the raw signal does not touch the lines at $V_{\text{max}}$ and $V_{\text{min}}$. Surprisingly, the quadrature detection method used in HQLI is also capable of detecting ultrafast motion as long as the amplitudes can be distinguished from the noise and as long as both photodiodes have the same gain and frequency response characteristics.

4. Conclusion

We have measured the laser generated high-amplitude ultrasound propagating inside an aluminum plate. For this purpose we used an improved interferometric method based on the HQLI. These results were compared with the measurements obtained by the standard PID-controlled stabilized interferometer. The comparison between both techniques has shown that the HQLI enabled measurements of high-amplitude ultrasound, while the PID-MI gave inappropriate results, if the distance exceeded 100 nm. The high-amplitude ultrasound is useful for non-destructive evaluations, where multiple reflections of the ultrasonic wave improve the accuracy of non-destructive analysis. It can be applied at the laser marking for the monitoring of the laser beam position based on the time-of-flight analysis of multiple reflections.

5. References