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Abstract. We present an improved optodynamic (OD) method which enables measurement of the distance between the OD source on the ablated surface and a piezoelectric sensor above it, with a relative error of about 1%. The method is based on the point explosion model and allows determination of the distance to the OD source and the released energy for each detected OD signal. We estimate the distance and released energy on the basis of two measured OD signal characteristics: the time of flight and the duration of the compressive phase. We show that the finite aperture of the sensor needs to be taken into account to improve measurement accuracy. We present experimental validation of the method using an Er:YAG laser and water as a tissue phantom. We observe an excellent agreement between the measured and theoretical OD signals and between the measured and estimated distances. The method opens the way to practicable implementations of on-line OD monitoring of laser ablation in surgery and medicine. © *2013 Society of Photo-Optical Instrumentation Engineers (SPIE)* [DOI: 10.1117/1.JBO.18.10.100505]

Characterization of air propagating shock waves, resulting from the microexplosions generated during infrared laser ablation of biological tissues, is an optodynamic (OD) technique that has the potential to be used for on-line monitoring of ablative medical and surgical laser treatments.[1] Compact and affordable broadband piezoelectric (PE) acoustic transducers that could be integrated into current medical laser systems have the potential to make OD ablation process monitoring practicable. The PE detection could be used for on-line tissue topography measurement by means of ablation source localization, which in combination with modern Er:YAG laser guiding systems, could enable the creation of defined geometries[2] that would open a way to new laser-assisted treatments, i.e., in bone surgery. In contrast to alternative techniques, such as optical coherence tomography[3] or laser triangulation,[4] no additional excitation or optical elements are needed by this method.

Strgar and Možina[5] have shown that measured times of flights of air propagating shock waves have nonlinear dependence on the depths of laser-drilled holes. They fitted an exponential function over the measured data which gave significantly better results than the linear, however, such empirical definition of shock trajectory has limited applicability in practice. Perhavec and Diaci[6] used a spatially resolved shock detection technique in the case of Er:YAG laser ablation where a Sedov–Taylor point explosion model proved to be suitable in describing shock-wave propagation. Nonlinear trajectory is a function of released energy which can be estimated from the characteristics of pressure waveforms using the point explosion model: Stauter et al.[7] used shock time of flight, however, Diaci and Možina[8] noticed that time of positive pressure phase gives better results in comparison with time of flight, which has greater sensitivity to released shock energy and only slight sensitivity to the distance from the source. The known OD methods of energy estimation use the source-to-sensor distance as a parameter and thus they cannot be used to improve source localization.

In this letter, we present a method that enables simultaneous estimation of the released shock energy and the distance between the OD source on the ablated surface and a PE detector from a single detected OD signal. The method takes into account a nonlinear propagation of the released OD waves as well as finite aperture and oblique orientation of the PE detector. We demonstrate that the method significantly improves the accuracy of estimating the distance between an OD source and the PE detector.

The experimental system used for this experiment is shown on Fig. 1. A free running Er:YAG laser (Fidelis Plus III, Fotona, Slovenia, European Union) beam is focused onto a water surface (focal diameter 0.9 mm) that serves as a tissue phantom. The water surface forms a quasi-ideal half-space which facilitates comparison with the theoretical model. A pulse generator (PG) triggers the laser system that uses VSP[9] flashlamp pumping and also sets the pumping pulse duration (45 μs). The resulting laser pulses are short (≈ 2 μs), which allows repeatable generation of a single shock wave per laser pulse, rather than several consecutive shock waves that are typical for longer pulses. Laser pulse energy is 3.14 ± 0.16 mJ (measured by Nova II, Ophir). A PE sensor (CA-1135, Dynasen, Goleta, California) with a PZT-5A crystal disc and diameter of 1 mm is used to detect the OD wave in air above the irradiated water surface. The sensor is mounted on a linear micrometer stage that allows setting of the vertical distance h_0 relative to the ablation spot with 10 μm resolution. The horizontal distance ($s_0 = 10.25$ mm) between the center of the sensor and the ablation spot is determined by the radius of a CNC machined sensor bracket that is centered to the optical path. The aperture of the sensor is aligned parallel to the water surface for the purpose of easier experimental validation.

OD signals are measured at six different vertical distances h_0 ($10, 12, 14, \ldots, 20$ mm) with six repetitions carried out in each position. The digital oscilloscope (DSO6034A, Agilent, Santa Clara, California) used for signal acquisition (12-bit digitization, 10-ns sampling time) is triggered by the signal of an InAs photodiode (J12, Teledyne, Montgomeryville, Pennsylvania) which is mounted behind the back laser mirror. Measurements are collected on a personal computer (PC) where signal characteristics t_s and t_n, as shown in Fig. 2, are extracted from each measured signal waveform. They are defined in a way that allows reliable measurement: t_s, representing the time of flight and t_n

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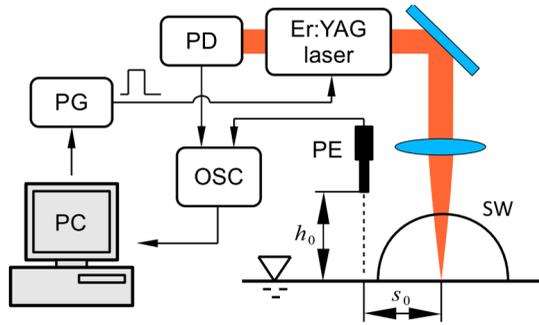
Fig. 1 Experimental set-up: shock wave (SW), piezoelectric sensor (PE), personal computer (PC), pulse generator (PG), photodiode (PD), oscilloscope (OSC).

Fig. 3 Relative errors of estimated vertical distances h_0: acoustic wave propagation model, point detector model ($\Delta h_{0a}/h_0$); spherical blast wave propagation model, point detector ($\Delta h_{0s}/h_0$); spherical blast wave propagation model, finite size detector model ($\Delta h_{0p}/h_0$).

representing the duration of the compressive phase. Room temperature and pressure are measured using standard meteorological equipment: $T_0 = 298$ K, $p_0 = 996$ mbar.

Horizontal distance s_0 is considered as a known parameter in this experiment and vertical distance h_0 as the estimated one. Using the acoustic wave approximation and assuming an idealized point sensor, we estimate h_0 from $h_{0a} = \sqrt{(c_0 t_s)^2 - s_0^2}$, where c_0 represents the speed of sound that is calculated from T_0 using the ideal gas approximation. We define the relative estimation error

$$\frac{\Delta h_{0a}}{h_0} = \frac{h_{0a}}{h_0} - 1,$$

where h_0 represents the reference vertical distance determined by using the micrometer stage. Figure 3 shows the relative estimation error of this approximation at six measured reference distances h_0. It is evident from Fig. 3 that the estimated distance is systematically smaller than the reference one, which is clear evidence that the OD wavefront propagates with supersonic speed.

In order to improve distance estimation, we employ the Sedov–Taylor point explosion model, which describes spherical blast wave propagation and allows calculation of the pressure waveform (and thus its characteristics) at some distance $l_0 = \sqrt{s_0^2 + h_0^2}$ from the source, given the conditions of the undisturbed surrounding medium (defined by pressure p_0 and temperature T_0) and one parameter, the released energy E_h: $\Delta p(t) = \Delta p(t; l_0, E_h)$. It is important to note that we assume

Fig. 2 Two selected signal features t_s and t_n defined on 10% of the normalized amplitude, used for the estimation of the vertical distance h_0 and released shock energy E_h.

that the released energy E_h of the hemispherical OD wave is half of the released energy E of an equivalent spherical blast wave. Figure 2 shows an example of a pressure waveform calculated using the model. To obtain the pressure waveforms, the model is formulated in the Euler form and solved numerically using the second order WAF finite volume explicit method with an approximate HLLC Riemann solver.[10] Assuming an idealized point sensor, we take that the measured signals are proportional to the calculated pressure waveforms:

$$V(t) \propto \Delta p(t; s_0, h_0, E_h).$$

Pressure waveforms are then used to determine two functions that describe the dependence of the characteristics t_s and t_n on the height h_0 and shock energy E_h. The waveform characteristics t_s and t_n are determined using the definition given above with the measured signals. The two functions determined in a discrete form are numerically inverted to obtain the dependence of the height h_0 and shock energy E_h on the pressure waveform characteristics t_s and t_n:

$$h_0 = f_1(t_s, t_n) \quad E_h = f_2(t_s, t_n).$$

We use the above functions to estimate the parameters h_{0s} and E_{hs} from the characteristics t_s and t_n, obtained by the analysis of the detected OD signals. The relative estimation error of this approximation, defined in a similar way as in the case of acoustic approximation, is shown in Fig. 3. We notice that this approximation significantly improves estimation accuracy by taking into account the nonlinear wavefront propagation, however, there are still some systematic errors present: h_{0s} estimates are systematically larger than the reference values h_0.

Another manifestation of the systematic errors present in this approximation is evident in Fig. 4, where we show the estimated released energy E_{hs} versus the reference distance h_0. We observe that this approximation predicts a systematic decrease of the estimated released energies E_{hs} versus the reference distance h_0 which is in clear contradiction to what we expect in this particular experimental situation. Since we have reasonably constant excitation laser pulse energy, stable experimental conditions, and stable irradiated matter (water), it is reasonable to expect that the released OD wave energy is relatively stable.
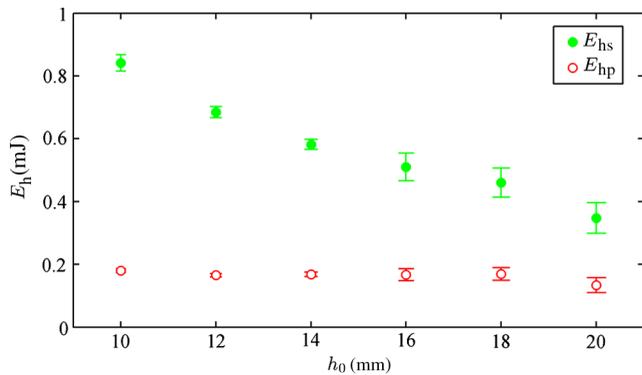
Fig. 4 Estimated released shock energy E_h versus vertical distance h_0: point detector model (E_{hs}) and finite size detector model (E_{hp}).

It might exhibit some statistical fluctuations but no systematic dependency on the distance h_0.

The observed systematic errors in this approximation can be explained by taking into account the finite aperture of the employed PE sensor. It takes some time for the shock wavefront to pass the complete sensor aperture and this accounts for some averaging effect in the response of a real sensor to shock-wave excitation. For this reason, the effect of a finite sensor aperture, and consequently the errors, is larger at lower vertical sensor positions h_0.

To further improve the distance estimation, we use a model of a PE sensor of finite aperture in conjunction with the point explosion model. We describe the employed sensor model in detail elsewhere.[11] Here we present just a short outline. We treat the sensor as a one-dimensional element where current generating deformations occur only in its axial direction. With the assumption of pure elastic deformations, a transfer function for a force sensing element is obtained[12] and validated by measuring electrical impedance on an impedance analyzer. Based on the analysis of the acquired waveforms and the transfer function for the given resistive load of the recording device (1 MΩ) and the total capacitance, the measured voltage is considered as proportional to the force of axial excitation. Neglecting the effects of changed acoustic impedance (weak incident shocks), we assume that the sensor response is proportional to the pressure distribution over the sensor aperture:

$$V(t) \propto \int_{dA_s} \Delta p(t; l_0, E_h) \mathrm{d}A_s.$$

Employing linear spherical wave propagation theory, we express the above integral as a convolution of the pressure transient $\Delta p(t; l_0, E_h)$ at a point in the center of the aperture with the impulse response $h(t; r_0)$ of the finite sensor aperture in a way described by Jensen.[13] As in the case of an idealized point sensor, we then extract characteristics t_s and t_n from the normalized waveforms, determine the corresponding functions f_1 and f_2 for this particular approximation, and use them to estimate the parameters h_{0p} and E_{hp} from the measured signal characteristics t_s and t_n.

Results on Fig. 3 show that the systematic part of the relative estimation error is thus significantly reduced in comparison with the point sensor model. The estimated released energy E_{hp} exhibits no systematic dependency on the distance h_0 (Fig. 4). A good agreement is observed by comparing the theoretical and measured waveforms. An example is shown in Fig. 2.

In conclusion, the presented method employs PE detection and allows determination of the distance to the OD source and the released energy from each detected OD signal. The results demonstrate that the presented method allows single-shot measurements of the distance between an OD source and the PE detector with relative error of about 1%. This opens the possibility for on-line monitoring of Er:YAG laser ablation of tissue in quasi half-space for the purpose of creating defined geometries in a way similar to the approaches reported using other lasers and materials[5,7] but with an improved accuracy and a measurement set-up which is more suitable to practical implementation. The released energy, on the other hand, can be a valuable process characteristic that does not depend on the position and the characteristics of the employed detection system in contrast to, e.g., the OD signal amplitude, which has been employed so far[1,14] in characterization of laser ablation processes.

Acknowledgments

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