KALMAN FILTERING OF ACOUSTIC EMISSION SIGNAL GENERATED BY LASER-MATERIAL INTERACTIONS

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1. INTRODUCTION

Laser material removal process (LMRP) requires a proper selection and optimization of a large number of interdependent process parameters related to laser, optics, workpiece material, and the motion system. All of these parameters significantly influence accuracy, precision and surface quality of the laser machined parts. Therefore, on-line process monitoring and control is required based on effective signal processing algorithms and reliable, physically observed information on actual process parameters and the state of the laser–material interactions.

This work was conducted to study an applicability of the Kalman filtering for on-line monitoring of the laser material removal process. The study is based on an experimental investigation of the informational properties of the acoustic emission (AE) signal generated by the surface acoustic waves in the laser-material interaction zone, selection of the signature that reliably characterizes the LMRP, and comparative analysis of the state variables affected by a working distance, which is one of the most critical process parameters.

2. EXPERIMENTAL SET-UP AND PROCEDURE

Figure 1 shows the schematic of the experimental set-up and procedure. The laser-material removal experiments were carried out on a brass foil with a thickness of 152 μm using Q-switched diode pumped solid state Nd:YVO_4 laser system with a pulse width of 20 ns and wavelength of 1064 nm. During the experiments, working distance (WD) was varied from 14.710 mm to 15.385 mm. Several trenches were machined by moving a sample with a feed rate of 2 mm/s and by applying laser pulses with a frequency of the 10 kHz and pulse energy of 0.055 μJ. The surface acoustic waves were measured during LMRP experiments using a high-fidelity acoustic emission transducer with a frequency bandwidth of up to 500 kHz, which was directly placed in contact with the top surface of the laser ablated sample 30 mm away from the LMRP zone. The AE signals were recorded by an oscilloscope for a total duration of 130 ms with a sampling period of 1 μs.

3. LMRP'S DYNAMIC CHARACTERISTIC

During the preliminary signal analysis, it was observed that each measured AE signal corresponding to an unchanged working distance had a noticeable periodic structure with a period of applied laser pulses. In addition, all the periodic structures had consistent signal signatures with small variations for the LMRP with unchanged process parameters. This signature was selected for further analysis as an LMRP's dynamic characteristic, which characterizes an LMRP's state through the AE response on applied laser pulse. Figure 2 shows an LMRP's dynamic characteristic, $y(t)$, experimentally obtained for a working distance of 15.01 mm as an averaged signature of 1000 synchronized periodic structures with a duration of 100 μs between applied 10 kHz laser pulses.

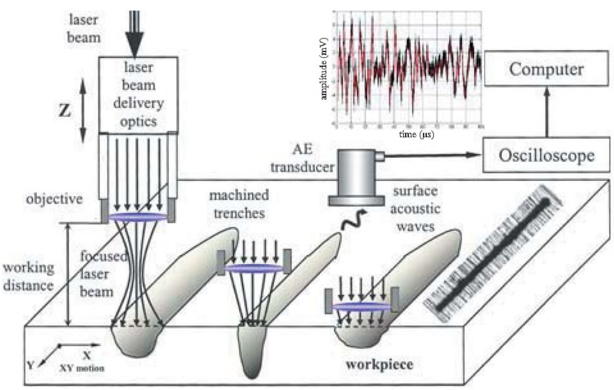

Figure 1. Schematic of the experimental set-up and procedure.

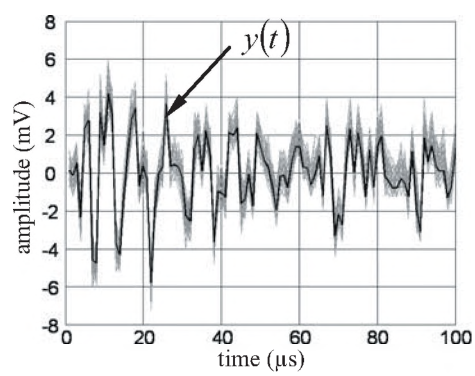

Figure 2. Experimentally obtained LMRP's dynamic characteristic.

The LMRP was described in the general form of a linear, discrete time, time-invariant state space model:

$$\begin{aligned} \hat{\mathbf{x}}(n+1) &= \mathbf{A}\hat{\mathbf{x}}(n) + \mathbf{B}u(n) + \mathbf{D}w(n) \\ y(n) &= \mathbf{C}\hat{\mathbf{x}}(n) + v(n) \end{aligned}, \tag{1}$$

where $\hat{\mathbf{x}}(n)$ is the LMRP's state vector, $u(n)$ is the control input vector associated with an applied laser pulse; $y(n)$ is the measured output vector, which is an LMRP's dynamic characteristic; $w(n)$ and $v(n)$ are the process and measurement noises, respectively; $\mathbf{A}$, $\mathbf{B}$, $\mathbf{C}$, $\mathbf{D}$ are the system state, input, measurement and noise matrices, respectively. Eq. (1) was considered as an informational model of LMRP in the form of a transfer function between applied laser pulse and measured AE signal and it was used to calculate $\hat{y}(t)$ as an estimation of $y(t)$. The optimal system order of 14 and elements of $\mathbf{A}_{14x14}$, $\mathbf{B}_{14x1}$, $\mathbf{C}_{1x14}$, $\mathbf{D}_{14x1}$, matrices were identified using the deterministic-stochastic realizations algorithm [2] applied to the experimentally obtained LMRP's dynamic characteristic. The measurement noise was estimated based on the measured AE signal before the actual laser-material interactions. The process noise was estimated using the deviations between the measured AE signal and $y(t)$.

4. KALMAN FILTERING

The matrices, $\mathbf{A}$, $\mathbf{B}$, and $\mathbf{C}$, were used in the standard Kalman filtering algorithm [1] for linear time-invariant stochastic systems:

$$\begin{aligned} \tilde{\mathbf{x}}(n+1) &= \mathbf{A}\tilde{\mathbf{x}}(n) + \mathbf{B}u(n) + \mathbf{H}r(n) \\ r(n) &= y(n) - \tilde{y}(n) \\ \tilde{y}(n) &= \mathbf{C}\mathbf{x}(n) \end{aligned} \quad , \qquad (2)$$

where $\mathbf{H}$ is the Kalman Filter gain matrix, and $r(n)$ is the residual vector which represents the quality of the Kalman filtering as a difference between measured and predicted LMRP's dynamic characteristics.

Figure 3 shows a comparison between the measured, estimated, and predicted LMRP's dynamic characteristics obtained for a working distance of 15.01 mm. The quality of the identification and simulation was estimated from the correlation coefficient and the mean-square error with respect to $y(t)$. The results are shown in Table 1.

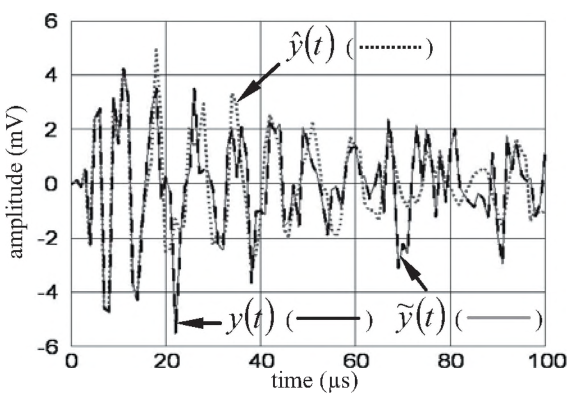

Figure 3. Comparison of measured, estimated and predicted LMRP's dynamic characteristics.

The LMRP's dynamic characteristics were obtained experimentally and estimated using Eq. (1), the Kalman filters were determined and the corresponding state vectors were studied in details for three different working distances, {14.76, 15.01, 15.26} mm. One of the 14 state variables considered was found to be affected considerably more than others by the working distance. Figure 4 shows the comparison of these vector signatures, which had variances of {3.82, 1.64, 4.72} mV^2 respectively.

Table 1. Quality of identification and simulation

	$\hat{y}(t)$	$\tilde{y}(t)$
correlation coefficient, dimensionless	0.714	0.998
mean-square error, mV	2.006	0.099

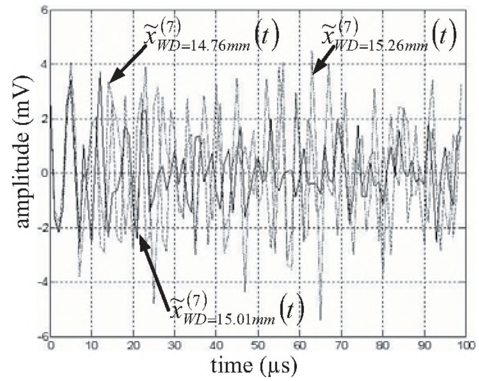

Figure 4. Comparison of the state vectors.

5. SUMMARY AND CONCLUSIONS

This paper presents a study of applicability of the Kalman filtering methodology for on-line monitoring of the laser-material removal processes. Based on the experimental observations, a periodic signature with a period of applied laser pulses was selected for characterization of the LMRP's dynamic characteristic. An informational model of LMRP was proposed as a transfer function between applied laser pulse and measured AE signal. The system matrices of the state space representation of this model were identified that allowed calculation of the Kalman filters and evaluation of the measured, estimated, and predicted LMRP's dynamic characteristics obtained for working distances of {14.76, 15.01, 15.26} mm. The effect of the working distance on the state variables was studied. The following conclusions can be drawn from this study:

1. The proposed dynamic characteristic reliably characterizes LMRP.
2. The Kalman filtering methodology allows extraction of reliable information about the actual state of LMRP.
3. The state variables are significantly affected by the process parameters and therefore they can be used for on-line monitoring, diagnostic and control of LMRP.

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