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Inverse analysis for the identification of temporal and spatial characteristics of a short super-Gaussian laser pulse interacting with a solid plate

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ABSTRACT

In this paper, the results of numerical experiments verifying a novel setup for laser beam profiling are presented. The experimental setup is based on infrared thermography and includes laser beam illuminating a thin metal plate. The method allows to determine four parameters of the short high-power laser pulse, namely the Super-Gaussian profile coefficient, laser power, pulse start time and duration. The unknown parameters are retrieved based on temporal and spatial temperature distributions at the rear side of the illuminated plate. The applied inverse method is based on Levenberg-Marquardt technique and is implemented in the GNU Octave environment. Solutions of the forward problem are obtained numerically, with the aid of three-dimensional transient heat transfer model implemented in the commercial software ANSYS Fluent. The paper presents the results of the sensitivity analysis as well as calibration and verification of the developed inverse algorithm through application of numerically-generated simulated (artificial) experimental data instead of the physical one. Strengths and weaknesses of the applied approach are widely discussed.

1. Introduction

Laser beams of high-energy are encountered in material processing [1] and characterization [2], electro-optical systems [3] and weapon technology [4] among other engineering applications. Many aspects of such laser beam interactions with matter are well-described in the work of von Allmen [5]. The presented study focuses on the identification of transient and spatial characteristics of a high-power super-Gaussian laser pulse interacting with a solid specimen.

In the case of a high-power beam formed in an optical system, the component elements of this system undergo heating during laser operation and their optical surfaces may deform changing the beam profile from the desired Gaussian one to super-Gaussian or even more complex form. It means that it is required to check the profile of a working laser beam. In the industry today, typical laser beam profilers include scanning aperture profilers using slits, knife-edges, or pinholes that utilize single large area detectors, or camera-based profilers using CCD's or photodiode arrays. The high sensitivity of camera profilers require the laser light to be reduced in intensity by many orders of magnitude using beam sampling or optical attenuation [6]. Recently a new profiling technique that uses Rayleigh scatter from the beam overcomes the power obstacle and allows measurement and monitoring of the beam caustic and determination of M^2 parameters of laser beams with power from 1kW to 100kW [7]. In many applications where the Gaussian profile is desired, M^2 describes the relative characteristics of the beam and is determined by making multiple measurements of the beam width. However, this instrumentation is very expensive and requires great care in its usage during signalizing possible changes of a beam parameters.

Recently the new approach to this problem was proposed by Kujawińska et al. [8] which is very simple and therefore may be easily applied in the industrial or field conditions with a relatively low cost compared to the other methods. This method assumes that the characteristics of the laser pulse may be found based on temperature distributions recorded with high-speed infrared camera at the rear surface of the heated aluminum plate. The rear surface was selected for collecting the data in order to mitigate the risk of damaging the camera sensors by high-power laser beam which might be reflected from the front surface of the sample. Additional refining of estimated parameter values based on maps of displacements acquired with the aid of Digital Image Correlation (DIC) method [9] is also planned. The DIC method allows to track sample deformation resulting from thermal stresses induced by significant sample heating by the laser pulse [8]. Nevertheless, the current paper is focused only on the details of the thermal part of the introduced problem. It means that the measurement of displacements is not included in the considered inverse method at this

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stage and only temperature measurements are taken into account in the estimation of laser pulse parameters. The solution of the extended problem, including the finite element displacement model and its incorporation into the inverse estimation procedure will be discussed in a separate article.

Identifications of the unknown surface heat flux based on measured temperatures were discussed before by various authors. General solution approaches for inverse heat transfer problems (IHTPs) employing analytical and numerical heat transfer models were given by Ozisik and Orlande [10] and Beck et al. [11]. Among other notable publications is the one by Huang and Wang [12], who demonstrated the calculation of an unknown boundary heat flux in three-dimensional (3-D) transient inverse heat conduction problem by applying the conjugate gradient method (CGM) and the general purpose commercial software CFX4.2. They assumed infrared temperature detection on one side of a planar body and transient heat flux boundary condition of unknown functional form on the other side, with all surfaces remaining insulated, except for the heated one. In the next work Yang et al. [13] considered simultaneous estimation of the laser heat flux and melted depth during laser processing in one-dimensional (1-D) geometry. In the research published by Zhou et al. [14] 3-D body subjected to the Gaussian laser beam was considered, with the sinusoidal moderation of the beam intensity. Beam parameters were retrieved based on temperature and heat flux measurements on the back surface with the aid of the CGM. A non-iterative and non-sequential numerical method for solving one- and multi-dimensional transient IHTPs, based on control volume approach, was proposed by Taler and Zima [15]. The method was successfully applied to reconstruct surface heat fluxes in 1-D and 2-D slabs based on temperature measurements. Unfortunately, the proposed approach requires a custom in-house computational model for the solution of thermal problem, which development may be quite cumbersome and time-consuming, especially for heat transfer in the body with complex geometry and a higher number of spatial dimensions. Taler and Taler [16] discussed in detail the intricacies of heat flux and heat transfer coefficient measurement based on temperatures, including design of sensors, their arrangement in various real-life cases, mathematical description of resulting inverse problems and techniques for their solution. In the next work [17] they considered measurements of constant and time-varying heat fluxes or heat transfer coefficients on the surface of a semi-infinite body (1D problems) based on surface temperature measurements. The analysis of uncertainty of the obtained results was performed using the variance propagation rule developed by Gauss. In succession Cebula and Taler [18] developed a space-marching method for determination of transient heat flux distribution on the solid surface based on temperature measurements at selected points located inside the solid. The method was designed for measurements involving surfaces which are inaccessible from the outside, for example the surface of a control rod, and subjected to fast-varying heat fluxes. Similar study by Cebula et al. [19] concerned the measurement of both heat flux and temperature on a cylindrical surface based on the finite element-finite volume method (FEM-FVM) and using thermocouples placed inside the cylinder. Special emphasis was put on the robustness of the method to measurement errors, for example these caused by mispositioned temperature sensors. It is also worthwhile to consider Taler's paper [20] in which a method for determining space-variable heat transfer coefficient using the Levenberg-Marquardt (LM) approach and singular value decomposition (SVD) was presented.

The approach undertaken in the present research is different than the methods discussed above. Firstly, it is aimed at utilization of ready-to-use, well-developed and tested numerical suite for the solution of a direct heat and fluid flow problems (ANSYS Fluent) with its advance functionalities (User Defined Functions, UDF), while many of the published approaches to IHTPs involve analytical models or custom in-house numerical codes. Therefore, presented method is better suited for applied thermal engineering, where bodies of complex geometry are usually encountered. Such geometries can be easily imported to the ANSYS Workbench environment from specialized CAD/CAE programs and then utilized in the numerical simulations. Moreover, application of a solver with multi-physics capabilities allows to easily increase the number of phenomena incorporated in the numerical modeling, which is another advantage of the proposed approach. Secondly, the approach proposed here employs powerful mathematics-oriented free software (GNU Octave) with built-in plotting and visualization tools to develop the proposed overall inverse algorithm. The GNU Octave allows for external solution of the forward problem (ANSYS Fluent), modification of input parameters to the thermal model (modification of input files to the ANSYS Fluent which are read by UDF macros), utilization of the output parameters from the thermal model (reading of output files from ANSYS Fluent which are written by UDF macros), development of the inverse problem solution method by applying build-in libraries, iterative execution of the overall inverse algorithm and analysis of the obtained results. It should be noted that similar approach to the IHTP was demonstrated earlier by Stryczniewicz et al. [21,22] who determined the out-of-plane thermal diffusivity of a thin graphite layer deposited onto a substrate of known thermal properties by means of the flash technique [14,15]. In their case, the forward problem was solved using the commercial multi-physics software COMSOL and the LM algorithm, applied to find unknown parameters, was implemented in the MATLAB environment. Apart from the out-of-plane thermal diffusivity, the problem involved identification of two other parameters, i.e., surface heat flux and heat transfer coefficient. In the case presented in this paper, the functional form of the recreated boundary heat flux is assumed to be known. Due to that, the function-estimation problem is substituted with a parameter-estimation one, with four unknown parameters, i.e., laser power, dimensionless spatial profile coefficient, start time of the pulse and end time of the pulse. Limited number of unknown parameters allowed for graphic representation of the sensitivity analysis. The usability of the applied method was verified applying numerically-generated simulated (artificial) experimental data instead of data from actual physical experiments.

2. Considered inverse problem

The undertaken problem belongs to the class of the IHTPs. In general, they can be viewed as optimization problems in which the sum **S** of squared residuals **r** is minimized [10]. The sum can be written in matrix notation as:

$$\mathbf{S} = \mathbf{r}^T\mathbf{r} \tag{1}$$

where the residual **r** is simply the difference between temperatures predicted by the model of the considered problem $\mathbf{T^m}$ and those obtained experimentally $\mathbf{T^e}$, i.e.,

$$\mathbf{r} = \mathbf{T^m}(\mathbf{q}) - \mathbf{T^e} \tag{2}$$

Here, the objective function **S** depends on some unknown parameters **q**, as the modeled temperatures $\mathbf{T^m}$ depend on them. The goal of the optimization is to find the set of parameters **q** that minimizes **S(q)**.

Beck and Woodbury [23] gave a general overview of the IHTPs and pointed out specific difficulties characteristic for this class of engineering tasks. Inherent in these problems are following unfavorable properties:

a) possibility of solution non-uniqueness (different vectors of input parameters **q** may result in the same vector of measured quantities – here the same temperatures),
b) ill-conditioning (measured quantities depend weakly on the input parameters, which makes the inversion of the problem difficult – here measured temporal and spatial variations of temperature may weakly depend on laser beam parameters),
c) amplification of measurement and numerical errors.

The inconvenience of type (a) is alleviated by choosing a right initial