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Model based compensation of systematic errors in an inductive gap measurement method

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ABSTRACT

A model-based correction of systematic errors to improve the measurement of gap dimensions in a recently presented method is described. Using one inductive coil on each side of the gap to measure distance and liftoff, the method detects zero width gaps and shows position error less than 0.1 mm. The correction model relies on observations of experimental data, and is calibrated to a small set of measurements. From the initial measurement of gap dimensions, the model estimates errors in each coil to calculate new values for gap width, alignment and height. The errors in the compensated results are within 0.1 mm except for gap width, which still suffers from the effect of combined gap width and misalignment. The method is intended for gap measurement in laser keyhole welding, where the laser beam and the resulting weld seam are very narrow, requiring high precision in alignment and gap preparation.

1. Introduction

Laser beam welding has found use in industries such as automotive, aerospace and shipbuilding due to deep penetration, low distortion and high productivity [1]. Because of the narrow width of the beam, and of the resulting narrow weld seam, successful laser beam welding relies on careful preparation of the weld gap and high precision in tracking the weld gap position, especially in a butt joint configuration. Changes in position, gap width and misalignment in height between the plates can all affect the quality of a weld. To secure the quality, efforts have been made to automate the welding process, including methods for weld gap tracking, see for example [2,3]. Today there are many different gap tracking methods available based on different techniques, some are reported in [4–9]. Vision sensors are common and can be used to measure position, width and misalignment of the gap [10], but with very precisely aligned plates, they may fail [11]. A relatively novel method for detecting narrow gaps based on magneto-optical imaging has been presented by Gao et al. [12–14]. The method has so far only been reported to be able to measure the position of the gap.

Inductive methods are commonly used in non-destructive testing to find narrow cracks and flaws in conducting materials [15]. An inductive method for gap measurement has previously been presented [16], and is improved in this paper. The method has the potential to measure both position, gap width, misalignment and height variation also in very narrow gaps [11]. The method uses the complex response of two inductive coils, and measures the gap position with less than 0.1 mm of error in nearly the whole defined working range. For gap width, alignment and height, the method shows results better than 0.1 mm only in a limited part of the working range. The main reason for the lacking performance is that systematic errors are introduced when gap dimensions change from calibration conditions. In this paper, a model of the systematic errors is proposed in order to improve the performance of the method.

An ideal sensor should have a linear response to the phenomena that is measured, and not react to anything else. Unfortunately such sensors are rare, and it is common to linearize the response, e.g. for resistance temperature sensors in the international temperature scale [17], to compensate for unwanted influence, such as for temperature in strain measurement [18], or to compensate for linear cross sensitivity from other directions in a load cell [19]. If the response is not linear, it may still be possible to use a model to calculate a compensation, such as in an example of a capacitive displacement sensor [20]. Brignell et al. [21,22] reported on smart

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sensors that use a combination of sensors and microcomputers to compensate for nonlinearities and cross sensitivities.

The approach of this paper is to model the systematic errors reported in [16] and make use of a compensation to realize increased accuracy. The error model is adjusted from a small number of extra measurements, and is then used to compensate the results from the individual coils, using uncompensated estimates of gap dimensions. That is, information from both coils can be used to estimate the dimensions, and the error model estimates the influence of those dimensions to correct the results for each coil. Then, the compensated results from both coils are combined to calculate a new result.

2. Inductive gap measurement method

In the complex inductive gap measurement method previously reported in [16], two high frequency coils are used, one on each side of the gap at a separation, *S*. From calibration on a zero width, zero misalignment gap, the inductive and resistive response can be interpreted as distance to the gap, *d*, and liftoff above the plate, *l*, for each coil. Combining these individual coil readings into one probe as shown in Fig. 1, the position of the probe, *p*, and height above the closest plate, *h*, as well as width, *w*, and alignment, *a*, of the gap can be estimated. Upper case letters designate true values derived from a traverse system, while lower case letters designate estimated results from the coil calibration. The left side plate, with index 1, is fixed in the experiments, while the right side plate, with index 2, is adjusted to change the gap dimensions.

The relationships used for calculating probe results from individual coil readings are given by

$$\begin{aligned} &p = 1/2(d_2 - d_1) \\ &w = S - (d_1 + d_2) \\ &-a = a_1 = l_1 - l_2 \\ &a_2 = -a_1 = l_2 - l_1 \\ &h = \min(l_1, l_2), \end{aligned} \tag{1}$$

For alignment, variables a_1 and a_2 are used to account for the sign, representing the difference in alignment as seen by coils on the fixed and adjusted sides of the gap. With the experimental setup used here, the method has a working range of probe position of 1 mm to each side of the centre of the gap, and height above the closest plate up to 1 mm. With a coil separation of 4 mm, this means that each coil will be within 1 and 3 mm from the gap. The error in each estimation is defined as the difference between the estimated value and the value from the traverse system and plate adjustment.

The data collected for the development of the complex response method in [16] is used in this investigation to model the error. All data was recorded from one inductive coil, traversed across the gap, and recalculated to represent a virtual two-coil probe. A commercial eddy current inspection instrument, Rohmann Elotest B1, was used, indicating the complex result as Instrument-X and Instrument-Y. The coil, a Rohmann KA-1, was used with a frequency of 3.2 MHz, which gives a negligible influence (1% of the current density at the surface) beyond 1.5 mm depth. The plates used were two 6.8-mm-thick Alloy 718 with milled edges, ensuring a narrow gap. The position of the traverse system and of the micrometer mount for the adjusted plate can both be accurately set. The reference for the traverse parameters where established from the calibration set, with the centre of the gap determined from the extreme values of the probe response while traversing

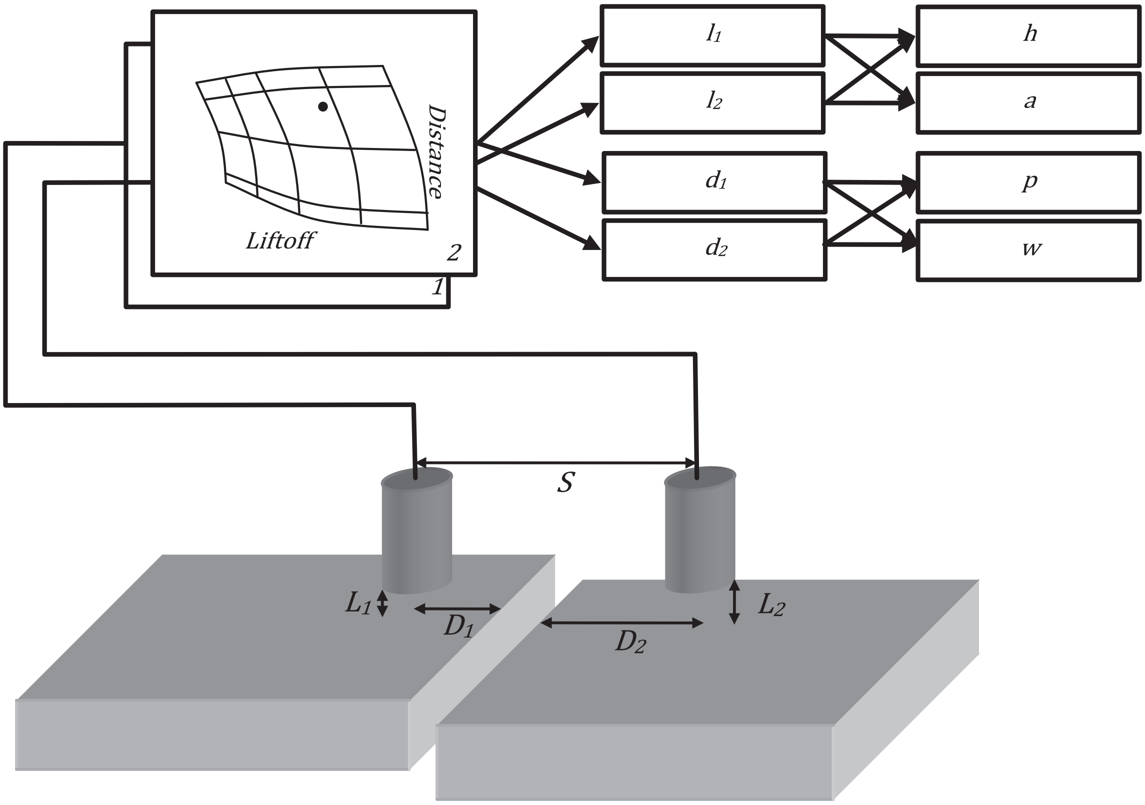

Fig. 1. Principle of complex inductive gap measurement method. The left side plate, 1, is fixed in experiments, while the right side plate, 2, is adjusted both horizontally and vertically to change the gap dimensions.