

# Weld gap position detection based on eddy current methods with mismatch compensation

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## Abstract

The paper proposes a method for finding the accurate position of narrow gaps, intended for seam tracking applications. Laser beam welding of butt joints, with narrow gap and weld width, demand very accurate positioning to avoid serious and difficult to detect lack of fusion defects. Existing optical and mechanical gap trackers have problems with narrow gaps and surface finish. Eddy current probes can detect narrow gaps, but the accuracy is affected by mismatch in height above the surface on either side of the gap. In this paper a non-contact eddy-current method, suitable for robotic seam tracking, is proposed. The method is based on the resistive and inductive response of two absolute eddy current coils on either side of the gap to calculate a position compensated for height variations. Additionally, the method may be used to estimate the values of height and gap width, which is useful for weld parameter optimization. To investigate the response to variations in height, the method is tested on non-magnetic metals by scanning one commercially available eddy current probe across an adjustable gap and calculating the expected response for a two-probe configuration. Results for gap position are promising, while mismatch and gap width results need further investigation.

## Introduction

The narrow beam focus and resulting melt zone in laser welding puts high demand on precision in weld robots and joint preparation. To automate the welding process, the gap needs to be reliably measured in a range of different conditions. Limited information on gap alignment may lead to serious defects such as lack of fusion, where the two parts are not properly joined together.

There are many different methods available for gap detection and tracking, e.g. tactile probes, acoustical, optical and inductive [1]. Each method has advantages and drawbacks, and must be selected to suit the particular application. Tactile probes e.g. are simple and useful for wide gaps with suitable geometry, but subject to wear. Acoustic methods can be used for wide gaps. Optical methods, because of their high accuracy and non-intrusive operation, have become very popular with increasing availability of cameras and processing power. Different variants have been developed for different joints, geometries, surface properties etc. [2-4].

Eddy current seam trackers also come in various configurations, often as a combination of two [5, 6] or more [7, 8] sensor coils connected to produce a difference signal from both sides of the gap.

These systems can be very sensitive and detect very narrow gaps. Visual appearance of the surfaces does not influence measurement, and sensors can be robust and suitable for industrial applications. One common weakness among them is sensitivity to changes in distance between sensor and surface. If the surfaces on either side of the gap are at different heights, this height sensitivity can influence precision. Even if the surfaces are at the same height, varying distance to the surface can still introduce a change in unbalance unless the sensor is centred over the gap by a servo mechanism. Readings can also be influenced by the geometry close to the sensor. In this paper we propose a method to make an eddy current based sensor less sensitive to height and difference in height, but still sensitive to narrow gaps, so that it can be used even for demanding laser welding applications. The behaviour of the method is tested by comparing three different cases of gap alignment and the resulting errors.

### **Proposed method**

Inductive methods make use of eddy currents induced in electrically conducting materials by time-varying magnetic fields [9], and have been used for inspection of various cracks and defects for decades. A coil probe can be used to generate the magnetic field which induces eddy currents in the material. The induced currents in turn produce a magnetic field which interacts with the primary field, resulting in a change in coil impedance. The eddy currents are interrupted by gaps in the conducting material, which then can be detected as change in impedance. However, the field is also altered if the probe height over the metal is changed, and the sensitivity to a gap is reduced.

The behaviour of a probe to a specific disturbance can in some cases be predicted analytically, though it often requires much work. Instead, the general appearance of some responses can be sketched from experiments by plotting the inductive and resistive part on the impedance plane, see Figure 1. Two points can be found, the air point which is the response of the probe far away from the metal, and the material point, where the probe is in contact with the material, and thus influenced by induced currents in the metal acting to counter the alternating magnetic field of the probe. The response will depend on the frequency and the magnetic field generated by the probe, and on the magnetic permeability and resistivity of the material. If the probe is lifted from the surface, the field in the metal is weakened and eddy currents reduced. The response will follow the so called liftoff curve until it reaches the air point. If the probe, while in contact with the metal, is approached to the edge of a plate, there will no longer be enough room for the eddy currents. This will trace out an edge curve [10]. Passing the edge, eventually there will be no metal under the probe, again reading the air point. Between these two curves, constant liftoff values and constant distance to the edge both produce separate families of curves. Finally, complementing the edge with a second plate to produce a narrow gap instead of an edge should produce a similar set of curves, but without reaching the air point.

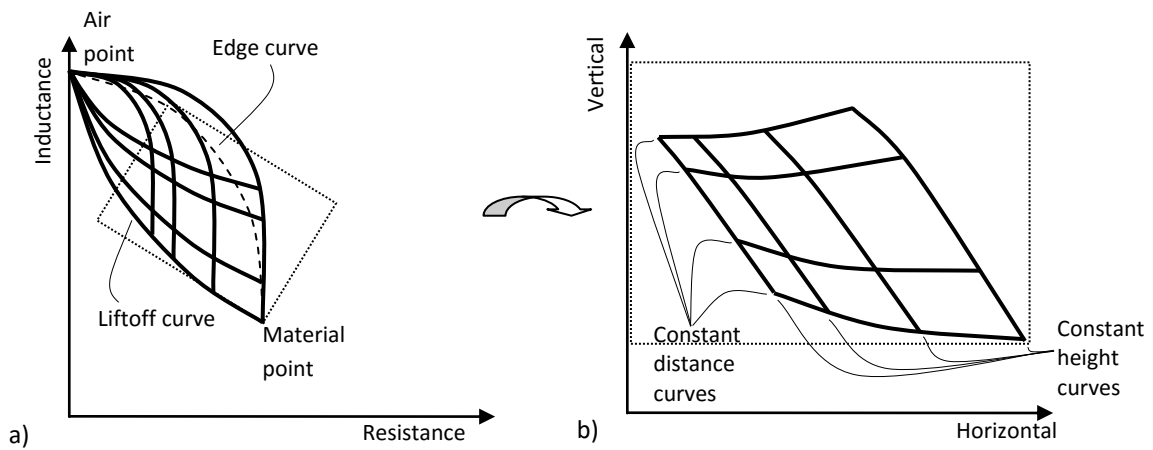


Figure 1 a) Principle of eddy current response in impedance plane and b) transformed instrument output in horizontal and vertical display axes.

In eddy current inspection it is common to rotate this impedance plane display to separate interesting responses into horizontal and vertical direction. Following this practice, the signal from a coil adjacent to a gap can largely be separated into a vertical part representing distance to the gap, and a horizontal part representing height above the surface. The separation can be further improved by constructing a calibration set of typical response to a known gap.

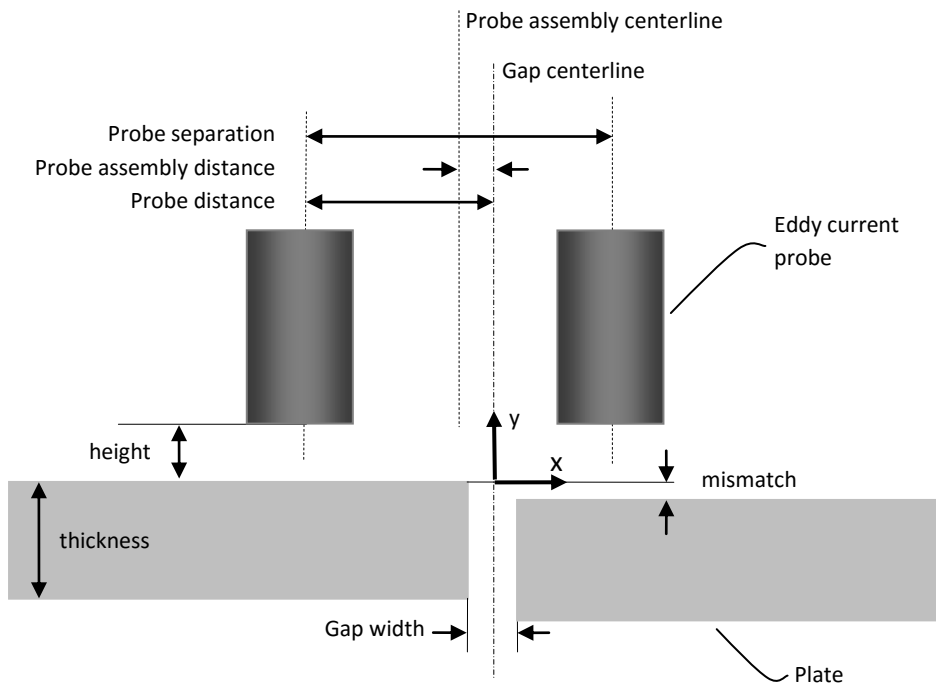


Figure 2 Definitions. Left side is negative x-position, right side is positive.

It is proposed to use these calibrated responses from two probes, one on each side of the gap, to produce improved values of both gap position and probe height. Further, readings can be combined to represent mismatch, i.e. difference in height across the gap, and gap width, both useful values for weld parameter optimization. The principles are illustrated in Figure 3.

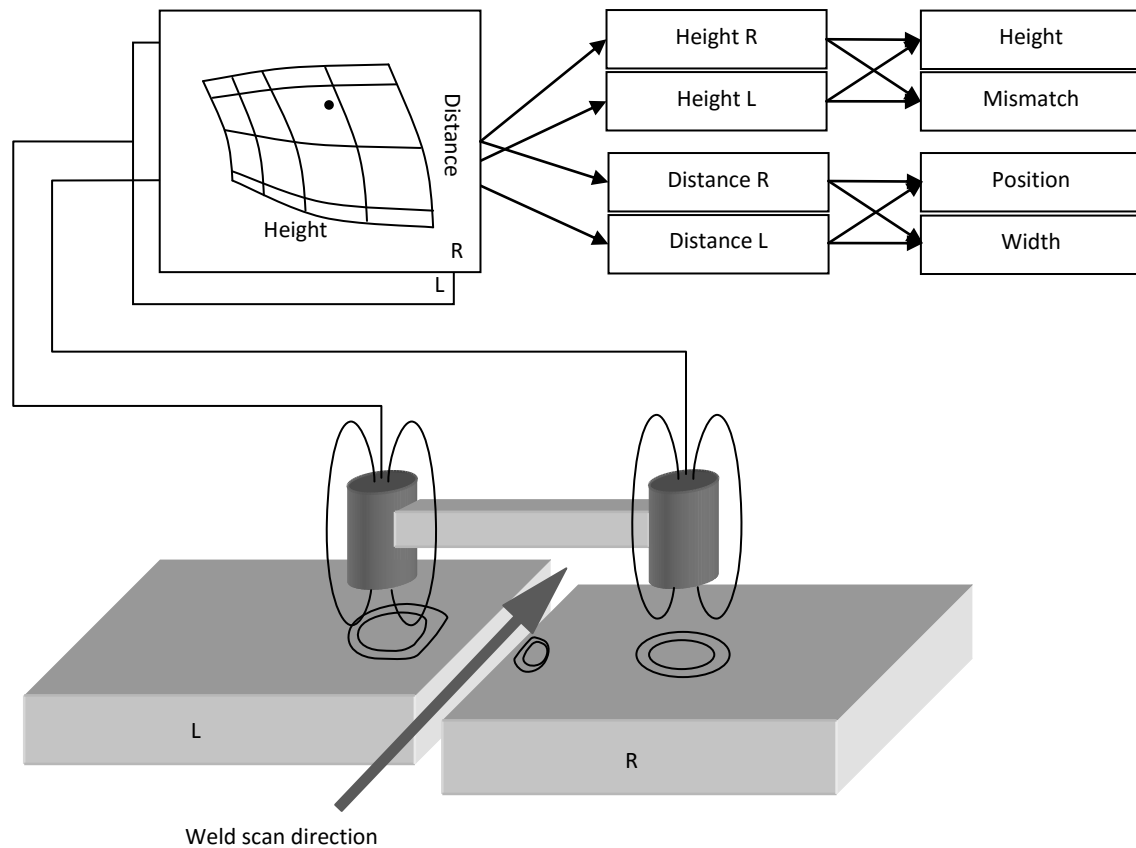


Figure 3 principles of proposed method, showing signals compensated by calibration data and combined to represent gap alignment.

### Experimental setup

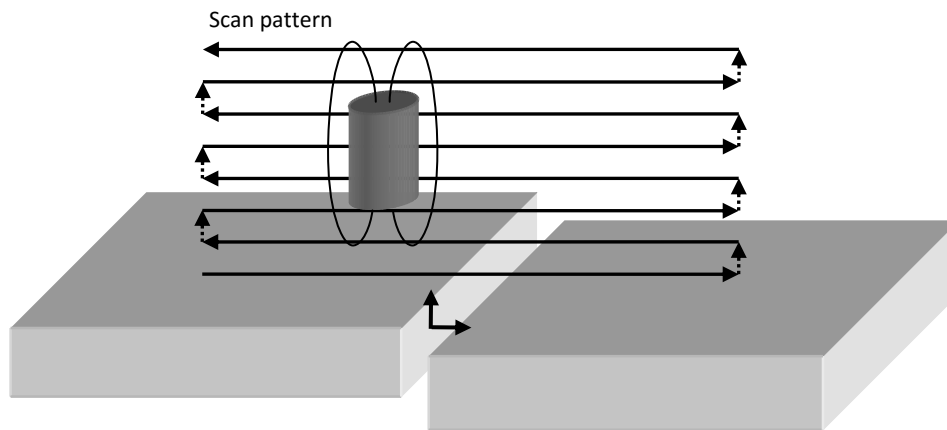
To investigate the properties of the proposed method, two plates of 3.4 mm thick Inconel 718, which is a non-magnetic material, were mounted next to each other creating a narrow gap in the same way as for a butt-joint weld. With the left plate fixed and the right plate on a 2-axis micrometer mount, the gap width and mismatch could be manually adjusted, see Figure 2 for definitions.

A two-axis stepper motor traverse system, controlled by a LabView program [11] was used to scan the eddy current probe across the gap. For each scan line, the height was increased. Every other line was scanned in the opposite direction to save traversing time.

For measurements, a Rohmann Elotest B1 eddy current inspection instrument was used with one Rohmann KA 2-1 probe of the absolute unshielded type. A frequency of 320 kHz was used, which gives a standard penetration depth of 1 mm. The instrument was used to adjust gain, and to rotate the impedance response so that the liftoff trajectory registers close to negative x-axis, as is common for eddy current inspection. Before each run, the instrument was zeroed with the probe placed on

the metal at the start of the scan-line. This is far enough away from the gap to correspond to the material point. The signal was not scaled to physical quantities, but the horizontal and vertical display channels were recorded as voltages.

In the finished system, two probes would be assembled together to scan in the direction of the gap. In this experiment though, the one probe was used to scan across both sides of the gap at different heights and distances, see Figure 4. This way, the behaviour of the method can be investigated and results can be combined to simulate a two-probe assembly at a chosen separation distance.



**Figure 4** Experimental setup with probe scan pattern

The scan area is about  $\pm 8$  mm distance on each side of gap along the x-axis, and 0-1.5 mm height in steps of 0.1 mm along the y-axis. Three data sets were recorded, one set with the plates in level contact i.e. zero gap and zero mismatch, one set adjusted to 0.5 mm gap width, and one with the right plate lowered to 0.5 mm mismatch.

The data set with plates in level contact was chosen as reference and used to determine gap centre position for subsequent data sets from absolute maximum of the response. It was also used to determine where the probe response is most sensitive in order to decide a suitable separation for a two-probe assembly. Figure 5 shows recorded signals for scans across the reference gap in steps of 0.5 mm increase in height, and it can be seen that the slope for all lines is reasonably large for distances between 1 and 3 mm from the gap. Consequently, the nominal working position for each probe was set at 2 mm distance, and the assembly can be expected to perform best at distances of  $\pm 1$  mm from gap centre.

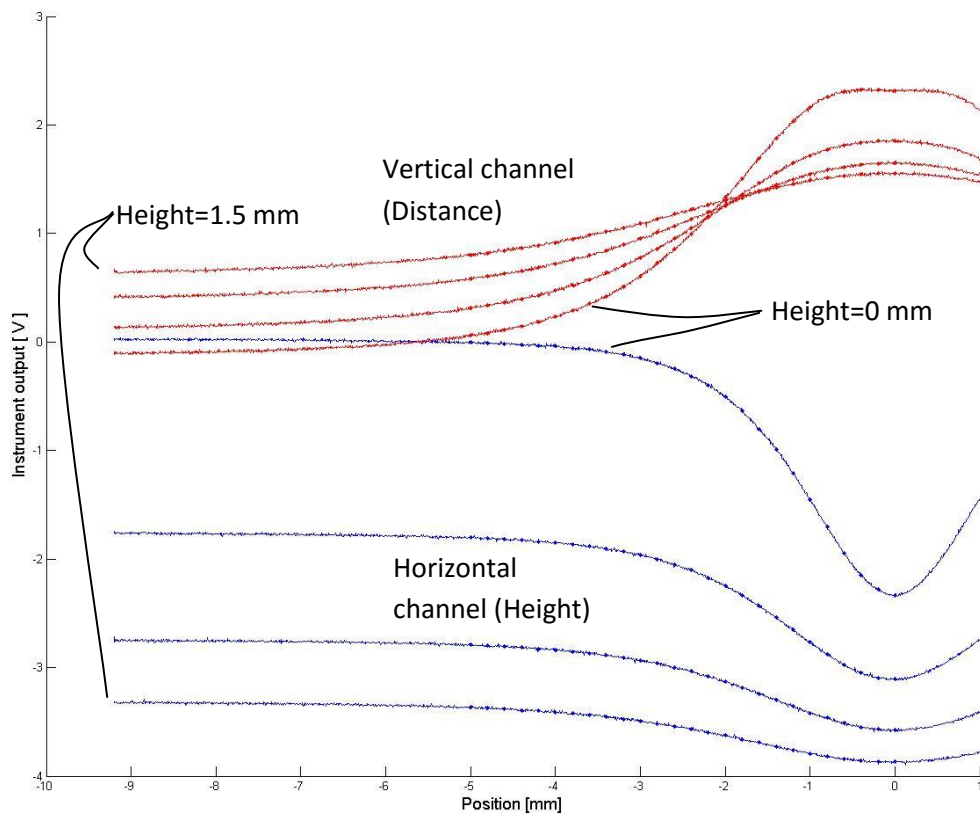


Figure 5 Probe response to nominal zero-gap. With increasing height, the sensitivity in both channels is reduced. Calibration set is marked with dots.

The reference set was also used to construct a calibration set, i.e. a reduced data set formed from the points indicated by dots in Figure 5. These points are averaged over 10 samples, corresponding to about 0.04 mm, to reduce noise. From the calibration set, the distance and height corresponding to a measurement can be interpolated.

Figure 6 shows a more useful representation of the reference data from Figure 5, a grid plot in the rotated impedance plane (as described in Figure 1). Here, increasing height is generally in decreasing horizontal direction and increasing distance in decreasing vertical direction. The varying sensitivity can be seen in the size of the grids in the pattern; small grids mean reduced sensitivity. The grid covers a larger area than the expected working area to avoid extrapolation at the extremes.

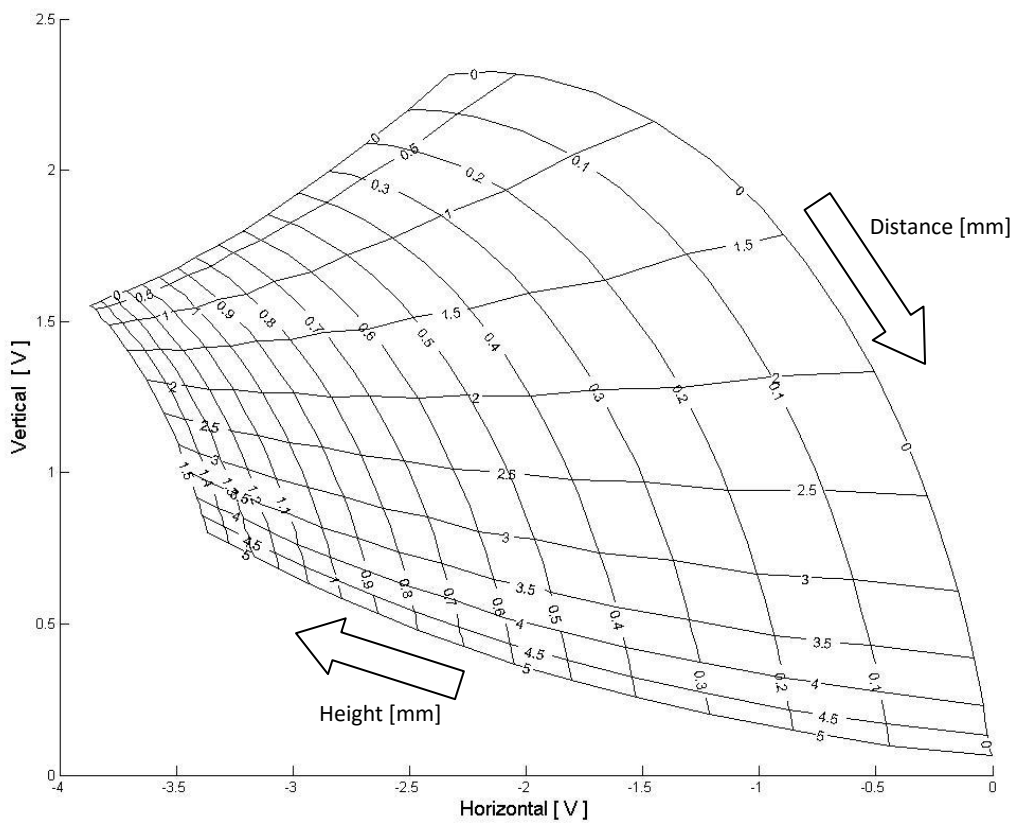


Figure 6 Calibration grid from nominal zero-gap set.

## Results

The gap width set and the mismatch set were used together with the calibration to verify the behaviour of the simulated two probe assembly, and the resulting grid plots can be seen overlaid on the reference grid in Figure 7. Comparing these results to the reference grid, both sets generally overestimate distance to the gap. Height is overestimated for the gap width set. For the mismatch set, readings are different on the right and the left side since the height of the probe is different. On the left side, which is closest to the probe, the height is overestimated. On the right side, which is further away, the height is underestimated.

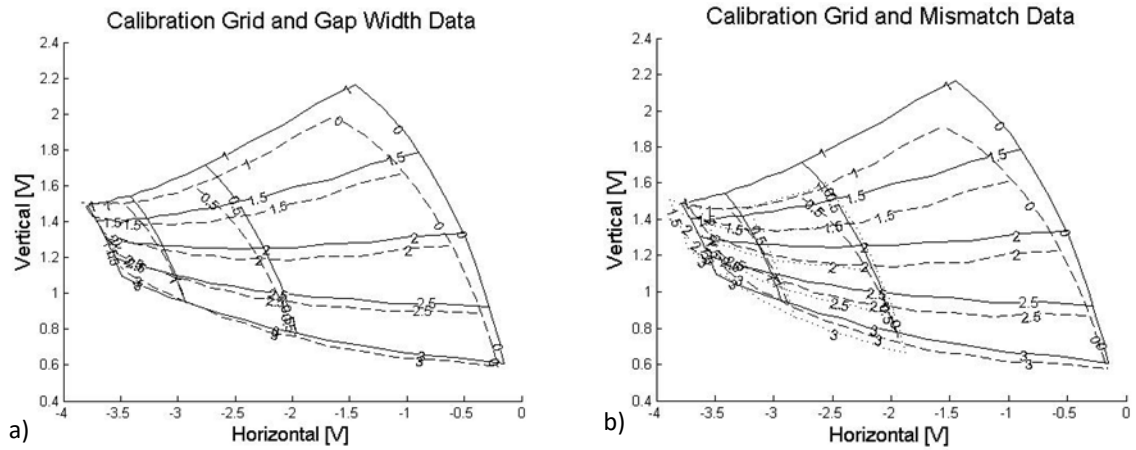


Figure 7 Single probe response in working area. Calibration grid is in full lines. a) shows gap width set, b) shows mismatch set with nominal plate data in dashed lines, lowered plate data in dotted lines.

Combining the results from probe positions 2+2 mm apart to represent a probe assembly, maps of expected results for position, gap width and mismatch can be constructed. In Figure 8, contour plots constructed from the scan lines show the error at recorded traverse positions and for the two different gap alignments.

To summarize, position errors are smaller than 0.1 mm up to a height of 1 mm if the probe is positioned above the actual gap. Error is still smaller than 0.1 mm about 0.8 mm to the sides, but for the set with mismatch the response is skewed so that the height is limited to about 0.7 mm. Gap width errors are about 0.4 mm. Mismatch errors are below 0.2 mm, and similarly skewed for the mismatch set.



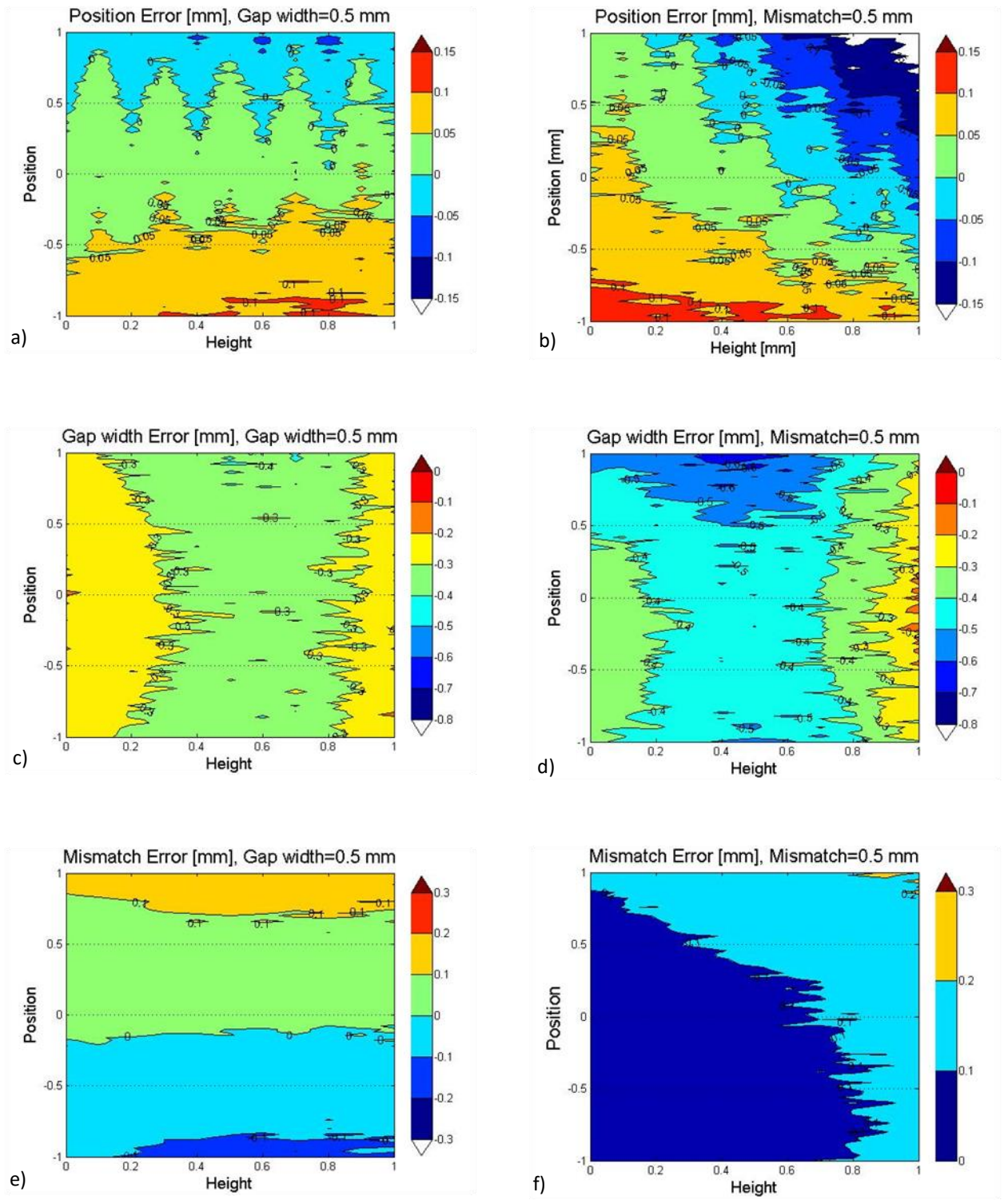


Figure 8 Two probe assembly response. The error comparing known traverse and gap alignment to measured values is plotted a,b) for position, c,d) for gap width and e,f) for mismatch. a,c,e) are from the gap width set, b,d,f) are from the mismatch set.

## Discussion

Error in position is not so much affected by errors in each probe since they are largely cancelled as long as the response is symmetrical, producing acceptable results in quite a wide area around the gap. The large errors in gap width results from the systematic overestimation in distance to gap being added from both probes. Errors in mismatch determination are influenced especially from probe response on the lower plate side.

Looking at the comparison of calibration and data grids in Figure 7, it can be noted that both data sets are different to the calibration set in similar ways. It is therefore likely that an optimized calibration set or compensation method could be constructed if more data was available to evaluate the effects. Further, the choice of probes could be optimized for certain demands on working area and performance. Depending on material and choice of frequency, finding the position of gaps partially bridged by tack welds would be an interesting challenge.

During the experiment and processing, some factors that influence the result were noted. First, differences in repeated positions, especially the lift off line, indicate that some instrument drift may have influenced the recordings. Second, some hysteresis in the data remains despite traverse alignment, and could also be introduced by the meeting edges of the plates that were not completely straight and smooth. Since the edges of the plates were not carefully machined, the actual gap width when the plates were mounted as close as possible was not determined. Third, the striped appearance of the position error plot indicates some play in the traverse system between forward and return scan, on the order of 0.05 mm.

Some disadvantages of the method are increased complexity, requiring use of a computer for signal processing, and additional electronics to amplify the two separate channels. The two probes will likely need individual calibration, possibly specific for material and test frequency. The method will also be influenced by different geometry similar to other eddy current gap finders.

The measurements show that it is possible to compensate for gap misalignment using the complex impedance response from two probes. More carefully designed experiments are needed to find the best performance, and to determine the effects of disturbing influences such as e.g. curved gaps and plates, joint geometry, tilted probes and varying plate thickness.

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