Inductive measurement of narrow gaps for high precision welding of square butt joints

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Acknowledgements

I am grateful to my supervisors for their patience, for their suggestions and for rewarding discussions. At University West, Anna-Karin Christiansson and Anna Runnemalm, and at GKN Per Henrikson.

I also gratefully acknowledge the financial support from the research school SiCoMaP, funded by the Knowledge Foundation, and GKN Aerospace Engine Systems.

Edvard Svenman

31st of October 2016
Populärvetenskaplig Sammanfattning

Nyckelord: Automation, Virvelström; Spaltföljning; Mätteknik; Lasersvetsning

Lasersvetsning kräver smala spalter mellan de plåtar som skall fogas. Det kan lätt hända att spalten blir så smal att den inte syns, och då fungerar inte de optiska givare som ofta används. Riktas laserstrålen fel svetsas inte plåtarna ihop på rätt sätt, och fogen håller inte lika bra. Med en induktiv sensor, som känner av spalten med hjälp av magnetfält och virvelströmmar inne i metallplåten, kan spalten upptäckas även om den inte syns.


Metoden har kontrollerats genom experiment med en sensor, som mätt på en sida i taget, var efter mätningarna kombinerats. Spalter upp till 0.40 mm bredd har detekterats med goda resultat, liksom höjdskillnader upp till 0.40 mm.
Abstract

Title: Inductive measurement of narrow gaps for high precision welding of square butt joints

Keywords: Eddy current; Seam tracking; Measurement; Laser beam welding

ISBN: 978-91-87531-45-3 (print)
       978-91-87531-44-6 (electronic)

A recent method in aero engine production is to fabricate components from smaller pieces, rather than machining them from large castings. This has made laser beam welding popular, offering high precision with low heat input and distortion, but also high productivity. At the same time, the demand for automation of production has increased, to ensure high quality and consistent results. In turn, the need for sensors to monitor and control the laser welding process is increasing.

In laser beam welding without filler material, the gap between the parts to be joined must be narrow. Optical sensors are often used to measure the gap, but with precise machining, it may become so narrow that it is difficult to detect, with the risk of welding in the wrong position. This kind of problems can cause severe welding defects, where the parts are only partially joined without any visible indication. This thesis proposes the use of an inductive sensor with coils on either side of the gap. Inducing currents into the metal, such a sensor can detect even gaps that are not visible. The new feature of the proposal is based on using the complex response of each coil separately to measure the distance and height on both sides of the gap, rather than an imbalance from the absolute voltage of each coil related to gap position. This extra information allows measurement of gap width and misalignment as well as position, and decreases the influence from gap misalignment to the position measurement. The sensor needs to be calibrated with a certain gap width and height alignment. In real use, these will vary, causing the sensor to be less accurate. Using initial estimates of the gap parameters from the basic sensor, a model of the response can be used to estimate the measurement error of each coil, which in turn can be used for compensation to improve the measurement of the gap properties.

The properties of the new method have been examined experimentally, using a precise traverse mechanism to record single coil responses in a working range around a variable dimension gap, and then using these responses to simulate a
two coil probe. In most cases errors in the measurement of weld gap position and dimensions are within 0.1 mm.

The probe is designed to be mounted close to the parts to be welded, and will work in a range of about 1 mm to each side and height above the plates. This is an improvement over previous inductive sensors, that needed to be guided to the mid of the gap by a servo mechanism.
Appended Publications

**Paper A.** A complex response inductive method for improved gap measurement in laser welding

Published in “International journal of advanced manufacturing”, available online 2016-04-24 – Authors: E. Svenman, A. Runnemalm

**Paper B.** Evaluation of non-contact methods for joint tracking in a laser beam welding application

Presented at the Swedish Production Symposium, SPS, in Lund, Sweden, October 2016 – Authors: F. Sikström, A. Runnemalm, P. Broberg, M. Nilsen, E. Svenman

**Paper C.** Model based compensation of systematic errors in an inductive gap measurement method

To be submitted for publication – Authors: Edvard Svenman, Anna Runnemalm
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Appended Publications

**Paper A.**  A complex response inductive method for improved gap measurement in laser welding

**Paper B.**  Evaluation of non-contact methods for joint tracking in a laser beam welding application

**Paper C.**  Model based compensation of systematic errors in an inductive gap measurement method
1 Introduction

Automation of production is at the heart of the – continuing – industrial revolutions. The benefits gained in productivity and quality motivates development of new automation methods, applied to existing manufacturing processes and enabling new processes and products.

Welding is a production method with ancient roots, which is still developing and demanding more efficient automation. Welding allows complicated products to be built of simpler parts, where each can be tailored to have suitable properties. A thinner plate can be used in part of a component, or a more durable material, or a cheaper design, to give the product the desired properties. This is used for example in production of tailored blanks in automotive industry, and in fabrication of aero engine components. The thesis is directed towards measuring narrow gaps in keyhole laser beam welding of aero engine parts.

1.1 Laser keyhole welding

In laser keyhole welding, the laser beam is focused so that the radiation intensity is high enough to melt, and partly vaporize, the material. The pressure of the vapour displaces the molten metal, forming a deep and narrow hole into the material [1]. Welding in the keyhole mode delivers energy deep into the material, where it is needed to melt metal and form a joint, without excessive spreading that would affect the properties of the material or cause deformation. This also gives high welding speed and productivity. Because of its low heat input and small heat affected zone, laser keyhole welding is well suited to production with high demands on precision and material properties [2].

On the other hand, laser keyhole welding is also a demanding application, where it can be difficult to find good welding parameters. Small disturbances can cause defects that lower productivity, ruin the product, or worse go unnoticed to cause an in service failure or an accident. Some defects that can affect static strength, fatigue life, or cosmetic appearance of a weld are illustrated in Figure 1. The effect of a particular weld flaw will depend on the circumstances of the application, but in general any defect that reduces the solid cross section of a weld may affect static strength, while small cracks or stress concentration from unfavourable weld geometry may decrease fatigue life. Spatter can affect corrosion properties [3, 4], and weld appearance may sometimes render a product commercially unacceptable. Lack of fusion defects, caused by welding to the
side of the gap, can be especially difficult to find when the weld bead is wider on
the top and root side than it is inside the metal. In these cases, there may be a
weaker part of the weld that cannot be found by visual inspection, and is so
narrow that it is also difficult to detect in x-ray inspection.

![Figure 1 Examples of welding defects and errors](image)

**1.2 Automation of welding**

Modern production increasingly demands predictable and consistent quality, and
at the same time increasing productivity. These demands are carried forward to
the automation of the welding process. Some processes are very predictable, and
can be automated by repeating a predefined procedure, while others need some
feedback from sensors that measure the performance and can detect events that
influence the result. High precision and robustness in processes like laser wel-
ding call for accurate and reliable sensors and control [5, 6].

When a component has been laser welded, an inspection for defects determines
if it can be approved. Figure 2 illustrates the consequences to production of
three different concepts for finding defects at different stages. If defects are
found in the final inspection, the component must be repaired, losing time and
money. If defects can be found in the welding cell instead of the final inspe-
cion, so that it can be repaired early, unnecessary inspection can be avoided.
Better still, if the process can be controlled well enough so that no defects are
produced, both unnecessary inspection and repair can be avoided. These tasks
of control of pre-existing conditions, of inspection, and of monitoring, require different sensors and measurement methods.

Figure 2 Three different inspection strategies, with different impact on productivity. Finding defects in final inspection (top), in fixture (middle) or avoiding to produce them (bottom).

1.3 Measurement in laser welding

Since laser keyhole welding is a complex process with extreme conditions, it can only partially be determined and modelled [1, 7]. Properties of the finished weld are determined by heat and mass flow, around and in the molten metal pool, where it is difficult to have direct access with sensors.

For practical reasons, non-contact sensors are preferred over sensors that need to secure mechanical contact with the work pieces while the sensor moves along with the welding process. Some acoustic sensors, for example, need special gels or fluids that could interfere with the process, for other sensors wear may be a problem. If the measurement can be made from a distance, fixture mounted sensors can sometimes be accepted. For on-line measurement during welding, real-time response is necessary, demanding short response time, simple algorithms or efficient signal processing.
As mentioned in Section 1.2, measurement for welding can be done before, during or after the process [8]. The results, and the sensors that can be used, are different in each case. Pre-existing conditions that influence the result can be for example the position and dimensions of the welding gap [9, 10], or the thickness of the material. These can affect welding parameters such as, power, welding speed and beam focus, as well as position and direction of the laser beam [11]. Better measurement and control could make it possible to perform the weld with a wider tolerance to conditions, or to determine in advance that adjustments are needed [12].

During the welding process, some phenomena that can be observed and give information about the result are reported in [8, 10, 13-15], such as emitted, absorbed, or reflected electromagnetic radiation, or mechanical waves. Useful sensors can be e.g. photodiodes or cameras of different wavelength, for reflected laser light related to absorption in the keyhole [16], for melt radiation from melt pool and surroundings indicating e.g. temperature [17], or for plume radiation related to keyhole stability [18]. Spectrometers can be used to indicate changes in plasma content related to keyhole conditions [19-21]. Combination of several sensors can be used to combine the information [22]. Optical and vision sensors dominate the literature, reflecting the versatility of these methods. With microphones, recording airborne pressure changes, levels of disturbing noise in industrial environments is described as a problem in [13, 14]. Still, there are investigations using them to detect partial penetration [23]. Accelerometers can be used to record structure borne vibration [14], but these methods traditionally rely on contact sensors, which are impractical in industrial applications. Laser based, non-contact sensing has the potential to change this [24]. Sensors that monitor the welding process may, again, give the feedback necessary to adjust the welding parameters or to abort a process that would result in a bad weld.

For post process investigation, a wide array of non destructive testing methods are available, see for example Shull, [25]. Unfortunately, many of these are not so easily applied to on-line automated inspection. Penetrant inspection is well known, but is based on dye that enters superficial cracks and defects, and coatings to give a visual indication. This would interfere with processing. Magnetic particle inspection, relying on changes in magnetic flux as indication of defects, also uses fluids or particles. It cannot be used for non-magnetic materials. Radiographic methods are common in off-line inspection, and image processing methods may support automation [26], but they demand access from both sides, and requirements for radiation protection can make them difficult to introduce in industrial environments. Thermographic methods, using the emissive properties of surfaces and defects, can be useful to identify surface, [27, 28], and subsurface [29] defects. Inductive methods like eddy current testing, or acoustic
methods like ultrasonic testing, can be used to find both superficial and sub-
surface flaws, but both usually rely on skilled operators and manual probe han-
dling. They are also easier to use on smooth surfaces, and the surface of the 
weld can cause problems. Traditional ultrasonic methods further require con-
tacting sensors to scan along the area of the weld joint with fluid or gel used to 
improve the coupling between sensors and work piece. Some investigations of 
other methods to induce and sense mechanical vibrations in metal suggest elec-
tromagnetically coupled acoustical sensors [30, 31] (known as EMATs), laser 
induced [32-34], or air coupled ultrasonic sensors [35, 36].

Broberg et al. [37] compare a number of methods with potential for automation, 
finding that phased array ultrasound showed best results for defects inside the 
plate, while the thermographic method performed the best for surface cracks. 
Narrow cracks were difficult to detect using radiographic methods. 

The most readily applied method is probably optical determination of the di-
mensions of the joint, [38, 39]. The sensor could be e.g. a laser line scanner, 
recording parameters such as reinforcement, weld toe angle, or undercut.

1.4 Objectives and research question

To improve the production and the resulting quality of laser welding in aer-
pace, new and improved sensors and measurement methods for various phe-
nomena are needed. The overall objective addressed in this thesis is to find 
measurement methods and sensors that can increase productivity and quality in 
laser beam welding.

Considerable research efforts have already been directed to both post-process, 
in process monitoring, and measurement of gap position. Still, with high preci-
sion machined components used in aero engine fabrication, seam tracking of 
narrow gaps for square butt welds is a relevant problem. From industrial experi-
ence, these gaps can be difficult to detect and, using optical sensors, there is a 
risk of confusion from scratches.

Welding in the right place is the first requisite of a good result. Knowing the gap 
dimensions can help decide if welding can be performed, or if the fixture or 
welding parameters need to be adjusted. Better accuracy in measurement of gap 
position means less risk of lack of fusion defects and a more predictable result. 
Therefore, this thesis is concerned with better methods of sensing the position 
and properties of the gap to be welded, suitable for future automation of the 
welding process.
The problem addressed will be directed to the needs of fabrication of aero engines. The goal is to find a method to measure very narrow or zero width gaps in order to allow automation of high precision laser keyhole welding. The materials considered are titanium and nickel based alloys, and the joints are square butt joints, typically used in aerospace components. To be practically useful, the method needs to work not only for very narrow gaps, but also for wider gaps, and for gaps that are less well aligned. The integration and use of the sensor in a system, for example on a robot, will not be considered, except that the method should be suitable for such industrial use. Only 2D-applications, that is plane plates are studied. The research question then is:

“How to detect and measure position and dimensions of even a very narrow and well aligned gap in laser beam square butt welding of titanium and nickel based alloys in order to weld correctly and in the right place?”
2 Background

Seam finding means to find the position of the weld gap before the welding process begins. This allows the nominal weld path to be adjusted to take account of any differences in dimensions, or fixturing, of a component compared to the nominal dimensions. Seam tracking means that a robot or manipulator has the ability to detect and follow the weld gap automatically during welding, rather than following a pre-programmed path were the gap is expected to be. This makes production more flexible and further reduces the risk of producing defects, because the process can adapt also to problems like variation from heat input distortion, and still produce good welds.

From the welding point of view, accurate knowledge of the position of the gap is arguably the most important, because lack of fusion can be so difficult to find in inspection and is a serious defect. Gap width is also important, because in autogenous welding (without filler material) wide gaps cannot be tolerated, though sometimes changing weld parameters or addition of filler material may help. Poor alignment in height of the work pieces can also cause problems that can be avoided with parameter control. Measurement of height and alignment of the plates is useful for example to allow control of laser focus. While capable of measuring zero-width gaps then, the method also needs to be able to measure gaps that are wider, and less well aligned, to be of practical use.

The exact requirements on gap measurement vary between applications, with work piece thickness, with beam parameters (spot size, focus distance and depth of focus) and other conditions. No strict limit on accuracy can be decided, but results presented here are compared to a 0.1 mm guideline that is believed to be useful for measurement of position and gap width as well as misalignment.

2.1 Seam tracking

Robot control and seam tracking is of interest to robotic welding for several reasons, for example to achieve flexible and autonomous production [40]. Especially in laser welding, the requirement for high accuracy movement control at high speed has been recognized [41-44]. Seam measurement sensors provide the feedback necessary for accurate positioning.
Several factors can affect the ability to determine the position of the welding gap [41]. Variation in production of parts, or of fixturing, could cause the weld gap to deviate from the nominal path. During welding, thermal distortion could change the path. Inconsistencies in the robot movements could cause differences in measurement that cannot be accounted for correctly. How well these problems are handled depends on how the seam tracking system is implemented.

Depending on the level of robot control available, different setups are used. With only high level control, the robot is often required to follow a pre-programmed nominal path, while the laser weld head and the gap sensor are mounted on a separate tracking actuator on the end of the robot [41]. In this case changes in gap position are detected, but the tracking can be affected by unknown changes in robot speed along the path, or in lateral position. An innovative solution is the use of image correlation techniques to determine the actual position of the welding laser relative the work piece, rather than relying only on nominal path values and gap sensor readings [41].

With a low level robot interfaces, more information about, and control over, the robot movement is available. This allows the weld laser and sensor to be mounted directly to the robot without a separate actuator [42]. This also allows control strategies that position the sensor over the weld gap to follow path curvature.

Since measurement can be affected by environmental conditions, such as surface properties, reflections or scratches [41, 45, 46], measures to avoid costly mistakes and potentially dangerous situations are in order. For example, there could be a requirement not to weld too far from the nominal path, or if the nominal path is out of range of the tracking sensor [41].

In industrial practice, combinations of teaching and real time seam tracking may be more practical than fully autonomous methods [43].

2.2 Some existing gap measurement sensors

Many different methods of seam tracking have been developed that are suitable for conventional arc welding, where the demands on precise joint preparation are usually less strict than in laser welding, a concise account is given by Nomura [47]. Tactile mechanical sensors follow the edge of a plate, or the groove between two plates, with a probe. They are simple and often used e.g. for fillet welds, or for V-grooves used in arc welding, but they are not useful for precision square butt welds where the gap is too small for the probe. In arc welding, the voltage between the electrode and the work piece surface is related to dis-
tance, offering a convenient method for seam tracking [47]. This is often used in a weaving pattern to fill a groove or a fillet in a corner weld. With laser welding of course, this is not an option. Ultrasonic transmitters and receivers can be used to detect the reflection from a gap through air, and have been demonstrated for narrow V-groves [48], but with uncertainties that are not sufficient for precise laser welding.

One investigation reported in [49] describes a method using ultrasonic waves within the work piece, reflecting on the gap to allow a distance to be measured from each side. Using EMAT transducers, this is a non-contact method that detects position and gap width, also with potential zero-gap capability.

Optical methods have seen much attention from researchers [50]. These sensors use the visual appearance of the gap, and of the plates, to find the position of the weld gap. Triangulating laser stripe sensors [51, 52] are often used for less well aligned or wider gaps. They are well established and can measure position as well as gap width and alignment. The principle is based on projecting a line of laser light onto the work pieces. Usually, the line is projected from a direction normal to the surface, and the diffuse reflection from the surfaces is then registered by a 2D-camera. At the gap, the reflection of the line will be missing, indicating the position and the gap width. The height of each work piece can be calculated from position of the reflection on the camera sensor. With shiny surfaces, diffuse reflections can be difficult to detect, and direct reflections can disturb the measurement. Recent investigations [53] use computer vision methods with uniform illumination and image processing to detect gaps as narrow as 0.2 mm, in combination with crossed laser lines to estimate surface orientation. Using a shallow focus length and image processing, detection of narrow gaps as well as surface orientation has been described [54]. With differences in surface properties or illumination on either side of the gap [55], even zero width gaps can be detected from grey scale images. Considering also imperfect surfaces, an image processing method with stereo reconstruction is tolerant to rust, mill scales and scratches [46]. Other vision methods use grey scale images with structured illumination [51, 56, 57]. From observation of the melt pool, the influence of the gap on the temperature distribution can be used to find the position with a camera sensitive to infra-red radiation [58, 59]. Most often, vision based methods do not measure plate alignment and orientation without addition of triangulation methods.

In laser welding, there is a possibility to use cameras and optical sensors through the same optics that is used to focus the welding laser beam. This way, measurements can be added with no physical intrusion. For example [60] describes how a camera can be used to both measure the shape of the melt pool, and to
find the position of the gap using vision methods based on grey scale image values.

A magneto-optic method, [61], has also been proposed. Here, a sensor reacts to the vertical component of the magnetic flux leakage from the gap, to create a contrast transition over the width of the gap. The position is then found using image processing. This investigation does not consider height or alignment of the plates.

Inductive seam tracking has not received the same interest from researchers. Some cases, like a fillet weld in the corner between two plates for example, can use inductive proximity sensors, but square butt joints are more complicated. There are patents though [62, 63], and some reports in literature about development. You et al. present an inductive system [64] using one single coil to both generate an alternating field and sense the response measures the gap position by weaving across the gap, recording the AC-voltage magnitude. This investigation mentions the possibility to measure height, but does not discuss gap width or alignment. Kim et al. report an inductive system [65] where one coil is used to generate the alternating field, while two more coils are used for sensing. The probe is placed across the weld gap so that each of the sensing coils reacts to the distance to the gap with a change in AC-voltage magnitude. The difference in voltage between the two coils is then zero if the probe is centred over the gap, and changes proportionally to the offset if the probe is moved to either side. The sensitivity is affected by the height of the probe above the plates but, the signal remains zero as long as the probe is centred. Plate dimensions and gap width are not reported, but increasing height is said to affect the result adversely because of reduced sensitivity, while a misalignment in height is said to have no effect for this set-up.

In another investigation by Bae et al. [66], three sensing coils are used, one on each side of the gap, and one more centred on the gap. The difference in AC-voltage magnitude between the two sensing coils is used to centre the probe above the gap, and the relation of the voltage between the centre coil and one of the sensing coils is used to calculate also the height of the probe above the plates, and the width of the gap. A tendency to overestimate the gap width is reported. Misalignment in height is not considered.

Yet another investigation by Henry [67] considers a tracking system intended for electron beam welding, where high precision is required. Here, again, a centre coil is used to induce the alternating magnetic field, while two sensing coils each react to the distance to the gap. In this case however the sensing coils are electrically connected, in opposing sense. A phase sensitive amplifier is then used to create a signal where the magnitude is proportional to the probe offset in rela-
tion to the gap, and the sign is related to the direction of the offset depending on the phase of the combined sensing coils in relation to the driving coil. This means that the sensing coil complex responses are added with respect to both resistive and inductive components. The signal is then rectified with respect to the reference signal, which is different from the previously described investigations. The sensitivity to misalignment in height between plates is investigated and found to be considerable in this application, but results are somewhat improved by increasing the height of the probe above the plate surfaces. Gap width, height or alignment is not measured.
3 Proposed gap measurement system

With the objective of measuring gaps that are not visible with current methods, there are two options. Either the current methods could be improved, or some other method must be found. Much research has been directed at improving optical methods that are arguably the most popular today. Here, instead the less common inductive method is revisited. Inductive sensors have an advantage in that they actually sense inside the material to be welded, rather than just on the surface. This means that they can be sensitive also to very narrow gaps. Indeed, sensors of this type are used to detect thin cracks in non-destructive testing. They should also be less sensitive to shallow surface defects, like scratches, that may confuse optical sensors.

3.1 Principle of complex inductive gap measurement

With inductive sensing as a promising candidate for zero-gap sensing, retrieving more information from the sensors should allow for better measurements, and measurement of more gap parameters. Paper A describes a proposed method to use this information.

Inductive sensing works by applying a high frequency alternating magnetic field into a conductive material [68]. According to Lenz’ law, currents will be set up in the material to generate an opposing field. This change in the field can be measured, conveniently by comparing the response in current and voltage on the same coil generating the field. A weld gap between two plates would interrupt the induced current in the material, and therefore change the response. A high frequency will induce currents only in the surface of the material, while lower frequencies can penetrate deeper, depending on the resistivity. Magnetic and non-magnetic materials have different responses, but both the titanium and the nickel based alloys considered here are non-magnetic materials. Commercial instruments used for inspection of material defects are designed to measure both the phase and the amplitude, using for example a phase sensitive amplifier. This measurement, at a certain frequency, is also less sensitive to noise and disturbing signals [69].
The concept of the improved gap measurement method borrows from non destructive testing with eddy current methods, where the complex response is used to better understand flaw signatures [25]. That is, not only the amplitude of the probe signal is used, but the resistive and inductive components of the response are separated. When measuring the weld gap, these components would be used to measure both the height of the coil above the plate, and the distance to the edge of the plate. Doing this with one probe on each side of the gap, the measurements can be combined for both position of the gap and gap width, for both height above the plates and the difference in height, or alignment, see Figure 3. Previous methods, by Henry where the coils were connected [67], or where only the amplitude was used [65], did not have enough information to measure all parameters; only the balance was used to determine position. Using one extra coil, Bae [66] estimated also width and height. Further, there was no way of telling the difference between a change in alignment and position, which is a problem for high accuracy measurement. Henry reported that an increase in height above 2 mm reduced sensitivity to misalignment in position measurement, while Kim et al. [65], measuring at 3 mm height did not find a sensitivity to misalignment. The previous investigations also used a separate feeding coil to generate the alternating field, while the method proposed here uses two separate coils, each generating its own magnetic field.

Figure 3 Principle of a probe from combination of coils. Linearization functions and the combination of coil measurements into probe results are indicated.
Looking to non destructive eddy current testing using commercial instruments, the complex result is conveniently presented on a chart with resistive response on the horizontal axis, and inductive response on the vertical axis, as in Figure 4. Placing a single coil on the plate, far from the gap at the “material point”, and lifting it to an “air point” will draw a trace on screen called the liftoff curve. Instead approaching the gap will draw another curve [68, 70]. Repeating the measurements at different height and distance to the gap, these non-linear responses will form a calibration and linearization function that captures the behaviour of the individual coil, at a certain frequency and with a certain plate material and thickness. Usually, the instrument is used to rotate the response for convenient reading, like in the right hand part of Figure 4. The output of the instrument will then be displayed as Instrument-X and Instrument-Y.

![Figure 4 Calibration grid formed by traversing coil, on the complex plane (left) and as presented on the instrument (right).](image)

### 3.2 Method of investigation

To understand the behaviour of a combined probe, the behaviour of individual coils in response to the gap, that is the resistive and inductive response to distance to gap and height above plate, must be investigated. Further, not only the response to a zero gap width, but to different dimensions should be investigated to learn how different working conditions affect the method. The working range, that is the extent of the probe distance and height to the gap, must also be investigated to understand what changes in measurement performance that can be expected. This could be done in several ways. One idea would be to use an analytical description of the physical phenomena. Unfortunately, this is not straight forward. Often the forward problem of finding the response to a certain
geometry, and the inverse problem of describing the geometry matching a measured response are treated separately [68, 71]. Some analytical solutions exist for simplified geometry such as infinite plates [72], and even for semi-infinite plates [73]. These solutions do not come in closed form equations though, and not for combinations of plates in different alignments. Instead numerical methods, for example finite element calculations, are often used to analyze this kind of problems [71]. It would be possible to set up the corresponding geometry and simulate the response to an ideal coil. Eventually though, these solutions would have to be compared to, and calibrated by, real world measurements. Therefore, the simulation step was bypassed in favor of an experimental investigation using recordings of the actual response from a real coil and plates. These recordings can then be used as calibrations to interpolate the gap geometry corresponding to a coil reading.

3.3 Experimental setup

Two square cut plates were mounted end to end so that one was fixed, and one adjustable by two micrometer screws. This allowed the gap between the plates to be adjusted from close contact at the same level, to a gap width, $W$, and alignment, $A$, of up to 0.8 mm, using micrometer screws for accurate adjustment. An eddy current coil was mounted in front of the plates on a traverse system, so that it could be adjusted in height above the plates, $H$, and in position relative the gap, $P$, see Figure 5. The coil used was a ferrite core absolute probe intended for nondestructive inspection, with a nominal sensing area of 1.5 mm diameter. The instrument used with the coil was a commercial eddy current inspection instrument, with voltage output for the resistive and inductive response respectively. These outputs are presented as a transformed response as explained in Section 3.1.

In Paper A, two plates of 6.8 mm Alloy718 (a nickel based alloy) were used, and the frequency selected, 3.2 MHz, gives a penetration depth of 1.5 mm, which is much smaller than the thickness of the plates. At this depth, the current density is less than 1% of the density at the surface, while at 0.3 mm, which is the standard depth of penetration, the influence is 37%.

In Paper B, plates of 4 mm Hastelloy-X were used instead. This is also a non-magnetic nickel based alloy, but with different resistivity. The frequency was adjusted to 2.9 MHz to give the same penetration depth. The same traverse and recording system was used for both Paper A and B.
The coil was traversed several times across the gap at different heights to collect sets of data from a reasonable working range. Each set was recorded with different settings of the plates to investigate the influence of different combinations of gap width and alignment, while one set with zero gap and no misalignment was intended for linearization. A computer was used to synchronize the recordings of both instrument signals and probe position and height. Further details on instrumentation and procedure can be found in Paper A.

With the reference data recorded for the case of a zero width, zero misalignment gap, each adjustment of liftoff and distance now gives a certain value of Instrument-X and Instrument-Y, i.e. each combination of the two instrument values can be uniquely associated with a liftoff value, and with a distance value. These data can then be organized as two tables where instrument outputs can be used to find distance and liftoff from simple interpolation.

Since the data is recorded in a traverse pattern, it can easily be organized in a regular grid, suitable for interpolation see Figure 6. Each corner of a triangle, defined by values of Instrument-X and Instrument-Y, has corresponding values for distance, $D$, and liftoff, $L$. The sizes of the triangles are adapted to the sensitivity in distance, from 0.1 mm steps close to the gap, to 1 mm furthest from the gap.
Figure 6 Pattern for the interpolation grid for distances from 8.0 to 0.2 mm, and liftoff from 0 to 1.5 mm. Only the area corresponding to the traverse pattern is ordered (solid), triangles outside the traverse area (dashed) produce poor results that are not used.

The principle of how the results from each coil can be combined into a gap measurement probe can be seen in Figure 3, where index 1 refers to the fixed side and index 2 to the adjusted side.

The position, \( P \), of the combined probe is found from the average difference in distance between the coils and the plate edges. This can be seen from Figure 7, where the measurements add up on both sides of the gap centre so that

\[
\begin{align*}
P &= -\frac{W}{2} - D_1 + \frac{S}{2} \\
\Rightarrow 2P &= D_2 - D_1
\end{align*}
\]
Figure 7 Illustration of the dimensions of the probe and work piece for determining position and gap width.

The width, $W$, of the gap is found from the separation distance, $S$, between the coils, and from the measured distance, $D$, from each coil to the plate edge. The alignment, $A$, with index to indicate side, is found from the difference in liftoff, $L$, between the probes.

The formulae are then given by,

$$
\begin{align*}
P &= \frac{1}{2} (D_2 - D_1) \\
W &= S - (D_1 + D_2) \\
-A &= A_1 = L_1 - L_2 \\
A &= A_2 = L_2 - L_1 \\
H &= \min (L_1, L_2)
\end{align*}
$$

\(2\)

3.4 Results and analysis

The result of the proposed method is presented in Paper A, and then compared to a number of different methods, both previously known and experimental, in Paper B.
3.4.1 Single coil response

Having recorded the single coil response to the zero width, zero misalignment gap as a nominal calibration, the measurement principle of the combined virtual probe can be better understood. In Figure 8, the calibration grid is drawn for the working area. Starting with the virtual probe in a nominal position, centered above the gap at a height of 0.5 mm, two crosses can be drawn on the grid for the left side and the right side, see Figure 8. Moving the probe to the left, the left coil indication will move down along the lines reflecting a larger distance to the gap, while the right coil indication will move up reflecting a smaller distance, see Figure 8 (left). Instead lifting the probe from the nominal position, both coil indications will move to the left along the lines of the grid, indicating a larger distance to the plates, see Figure 8 (right).

![Figure 8](image_url)

Figure 8  Response grid from zero-width, zero misalignment gap, showing changes in coil readings for a change of 0.40 mm in probe position toward the adjusted side (left), and an increase of 0.40 mm in height (right). Crosses indicate the reading from a nominal probe position, centred at 0.5 mm height, rings indicate the reading after the change for the coil over the fixed (blue), and the adjustable (red) side. Note that some symbols are overlapping. The inset picture shows the nominal (solid) and changed (dotted) position of each coil.

If instead the gap dimensions are changed, the response is indicated in Figure 9. For an increase in gap width, both coils indicate a smaller distance, see Figure 9 (left), while misalignment moves the indication of the lowered plate to the left, see Figure 9 (right). It can be seen that the response deviates a little from the ideal, which will affect the measurement.
Figure 9  Response grid from zero-width, zero misalignment gap, showing changes in coil readings for a change of 0.40 mm in gap width (left), and in alignment (right). Crosses indicate the response from a zero-width, zero misalignment gap, rings indicate the reading after the change for the coil over the fixed (blue), and the adjusted (red) side. The inset picture shows the changed position of the adjusted plate.

3.4.2 Dual coil method

When the experimental results are combined to represent a combined two coil probe according to (2), the behaviour of the proposed method, as described in Figure 3 with separate measurements from the two coils, can be investigated. The maps in Figure 10 cover the working area and show the error in each measurement, for the worst case gap dimension. The errors are calculated as the difference between the linearized response from the coils and the true value, which is known from the traverse system and the gap adjustment. It can be seen that measurement of position is better than 0.1 mm in the whole working area, while measurement of alignment and height are not as good. Measurement of gap width is the worst and is only within the error limits for a small part of the working area. The responses are asymmetric because there is a misalignment; the adjusted plate is further away from the probe. These errors will be further investigated in Paper C.
Figure 10 Error maps [mm] for position (top left), width (top right), alignment (bottom left) and height (bottom right) measured with the dual complex response method, for a gap width of 0.40 mm, and gap alignment of 0.40 mm.

### 3.4.3 Comparison to hardwired probe

Having the measurement from each single coil, it is interesting to combine them as if they had been wired together in series and compare the result to the new method. This is done in a way similar to the previous method by Henry [67], but with the added opportunity of careful adjustment of the phase sensitive detection. Again, Figure 11 shows worst case results, but this time only for position, since this is the only measurement available from the hardwired probe. The smaller working area of the previous method can be clearly seen, in Figure 11 (right) as well as the asymmetry caused by the misalignment of plates. This type of probe would normally be servo operated to measure only directly above the gap. The probe is calibrated for a nominal working height of 0.5 mm, and Figure 11 (right) shows that errors increase if the probe is lowered, but is not much affected if the probe is lifted higher. At higher liftoff, the influence from the gap
is smaller, but the sensitivity also becomes smaller. Under these conditions, it can be seen that position results for the hardwired probe can be quite accurate, but that the probe is more difficult to operate.

![Error maps for position measurement](image)

**Figure 11** Error maps for position measurement with the dual complex response method (left) compared to a hardwired probe method (right) for a gap width of 0.40 mm, and gap alignment of 0.40 mm.

### 3.4.4 Comparison with other methods

To understand more about the alternative ways of gap measurement, a comparison between four different methods under the same conditions was performed in Paper B. In addition to the inductive method, a laser line sensor, a vision based method and a novel thermographic method were examined with a set of Hastelloy-X plates, which are also non-magnetic and nickel based. The edges of the plates were machined to allow a narrow gap.

All methods were used for different combinations of gap width and alignment to understand their capability. All methods should be able to measure gap width and position, but the thermographic and the vision method use just a single camera and cannot be expected to measure height information or alignment.

In Figure 12, the first five samples show the gap width measurement of a zero gap with misalignment increasing from zero to 0.2 mm in step of 0.05 mm, the next five samples show 0.05 mm gap width with increasing misalignment, and so on. The inductive and thermographic method measures the zero gap, while the vision and laser line methods need a gap of at least 0.05 mm. In Figure 13, both the inductive and the laser line methods show ability to measure alignment from 0 mm. So, the line scanner can measure everything but narrow gaps. Vi-
sion does not handle narrow gaps or height, and width can be difficult. The thermographic method detects narrow gaps, but measuring width is difficult and alignment or height is not measured. The inductive method measures all parameters starting at zero gaps, but again the systematic errors can be seen.

Figure 12  Gap width measurement results from four different methods, compared to the true value. The alignment is changed with each sample number according to Figure 13.
Figure 13  Alignment measurement results, compared to the true value. The gap width is changed with each sample number according to Figure 12.
4 Improved gap measurement method

To further improve on the complex inductive gap measurement method proposed in Section 3, a model based compensation of systematic errors is the subject of Paper C.

4.1 Systematic errors

Figure 14 shows how the response grids are deformed with change in gap width, and in alignment. The deformation of the calibration grid shows systematic errors in response to variation in gap dimension; ideally, the grid shape should stay the same even when the gap dimensions change. The deformation of the grid from a change in gap width is symmetric with respect to the centre of the gap, while the deformation from a change in alignment tends to tilt the grid in different ways. A change in alignment also displaces the adjusted side grid to higher liftoff values as can be expected. It can be seen that most of the identified measurement problems are systematic. That means that they are repeatable, and if they are understood, they can be solved or compensated.

Systematic errors will contribute in different ways depending on how each result is calculated. For position, according to equation (2), the result is effectively half the difference of two values. Therefore, if the errors in the measurement are about the same size and same sign, as in Figure 14 (top left) and (top right), they will tend to cancel. For gap width, on the other hand, errors of the same sign will add up. For height, the error will be the same as that of the closest coil, (bottom left) in Figure 14 (usually, unless the differences are small or for some gap dimensions with larger errors). For alignment, errors of the same sign will tend to cancel, compare Figure 14 (bottom left) and (bottom right) where errors tend to different signs.
Figure 14  Result of a change in gap width for coils over either side (top left and right), and of misalignment from a coil over the fixed side (bottom left), and from the coil over the adjusted side (bottom right). The inset pictures show the plate and coil arrangement.

It is clear that the inductive principle does not produce a linear response to either distance or liftoff. The calibration handles that, but only for the same zero gap conditions. Looking at the results after applying the calibration, the errors introduced by changes in gap dimensions are not necessarily linear. Further, there is a cross influence, where a change in distance will influence the error in alignment, and the other way around.

To improve the results, these systematic errors need to be compensated. That means that a way to estimate the size of the error must be found, for various conditions. Several different approaches could be attempted to do that. To describe the error, a model is needed. For example, the non-linear full calibrations could be taken for different gap dimensions, or otherwise the error could be described by a set of equations, to be derived empirically or analytically. To then find the actual size of the error, the ideal way would be to measure the distur-
bance and compensate for it using the model. Unfortunately, that is not possible here, since the sensors available for measuring disturbances are the same that are to be compensated. What would be needed then is a way to solve for the best compensation, analytically or numerically, using the model and available sensor output.

For a transducer that is close enough to having linear and independent responses, such as a well designed load cell, this is a straightforward operation of constructing the response matrix of cross sensitivities from calibration, and then inverse it for individual contributions. But for an inductive transducer, in a setup that is not expected to be linear nor independent, it is not necessarily straightforward. Another option would be to train a neural network with data from several different dimensions.

Analytical and numerical based compensations are ruled out for the same reason as they could not be used for the original method, namely that there are no such solutions for these geometries in closed form. Neural networks could be useful, but requires training data from more gap dimensions. If other parameters were changed, such as plate thickness or probe frequency, it would need complete re-training. It can also be difficult to guarantee the behaviour of a neural networks according to [74].

### 4.2 Model based compensation

For an industrial solution, a simple method is preferred, with low demands on calibration effort and simple calculations that can be implemented in a real-time instrument. Therefore a model based compensation is proposed, where a set of simple equations are determined from a systematic investigation of the combined probe. These equations are then adjusted with actual values from a small number of calibration measurements.

A pragmatic approach to modelling is taken, where model equations are sketched from empirical data, and then fitted to specific values for a few points in the working range and a few sample gap dimensions. The equations used are not necessarily based in physical behaviour, nor are they the best possible description of the error. Rather, the ambition is to find a description that is good enough to reduce errors to a reasonable level.

The model is constructed to describe errors as a function of the recorded values, which is what will be available when the system is in use. The true values, as found from the traverse system in calibration, are of course not available.
A number of data sets with systematic variation of gap dimensions, covering the working range, were recorded. The corresponding error is plotted as surfaces in Figure 15.

They show that the behaviour in distance error is somewhat complicated, with random error components making identification more difficult. Though there is some curvature in the surfaces, linear planes are considered to be good enough as a modelling function. For error in liftoff, surfaces are smoother and less disturbed by noise, and a behaviour that matches a smooth transition between the two plates can be seen. This behaviour is modelled as a Gauss function for gap width variation, which is symmetrical in distance to gap, and as a logistic sigmoid function for alignment error, which is expected to change sign across the gap mid. See Figure 16 and Figure 17 for the resemblance between the recorded
response and the model functions. The measured curves in Figure 16 have no data in the middle part since the calibration is not valid there.

![Figure 16 Individual coil liftoff response to 0.40 mm gap width (left) and 0.40 mm alignment (right).](image)

These model functions are then adapted to a few calibration points, selected at nominal values, to give a good representation across the working range. Two points are taken in the mid of the liftoff working range but at the ends of the position working range, and two more points are taken in the middle of the position working range but at different liftoff values. These calibration values are measured both for a width only gap, and for an alignment only gap.
The principle for the complete signal processing, with the compensation of systematic error in place, can be seen in Figure 18. The values from the original linearization function are used to calculate first estimates of gap dimensions, $w$ and $a$. These are then used in the error model to calculate a compensation in liftoff and distance, $\varepsilon_l$ and $\varepsilon_d$, that, when applied to the original coil values $l$ and $d$, allows a more precise estimate of the gap dimensions $h$, $p$, $w$ and $a$.

![Diagram of signal processing scheme for error compensation](image)

**Figure 18** Signal processing scheme for the error compensation. Coil measurements are linearized and combined into first estimates of gap dimensions. The model is then used to estimate a compensation to the coil measurements, which are combined into the final probe results.

### 4.3 Compensated results

Results from the compensated method can be compared to the original in Figure 19 for three cases with different dimensions; error for the gap width result, which is the most difficult measurement, is shown. In Table 1 and Table 2, the results for all cases can be compared. The working field coverage figure corresponds to the coloured area in the error maps.
Figure 19 Error maps for gap width, for uncorrected results (left), and model corrected results (right). The gap dimensions shown are only gap width 0.40 mm (top), gap width 0.40 mm and alignment 0.40 mm (middle), and only alignment 0.40 mm (bottom).
Table 1 Working field coverage, $C$, of error within 0.1 mm, for uncorrected and corrected results.

<table>
<thead>
<tr>
<th>Gap [mm]</th>
<th>No correction</th>
<th>Model correction</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$C_P$ [%]</td>
<td>$C_W$ [%]</td>
</tr>
<tr>
<td>W=0.40 A=0.00</td>
<td>100</td>
<td>56</td>
</tr>
<tr>
<td>W=0.40 A=0.40</td>
<td>100</td>
<td>37</td>
</tr>
<tr>
<td>W=0.00 A=0.40</td>
<td>99</td>
<td>23</td>
</tr>
</tbody>
</table>

Table 2 Maximum absolute error, $\varepsilon$, within working range, for uncorrected and corrected results.

<table>
<thead>
<tr>
<th>Gap [mm]</th>
<th>No correction</th>
<th>Model correction</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\varepsilon_P$ [mm]</td>
<td>$\varepsilon_W$ [mm]</td>
</tr>
<tr>
<td>W=0.40 A=0.00</td>
<td>0.04</td>
<td>0.21</td>
</tr>
<tr>
<td>W=0.40 A=0.40</td>
<td>0.09</td>
<td>0.23</td>
</tr>
<tr>
<td>W=0.00 A=0.40</td>
<td>0.10</td>
<td>0.26</td>
</tr>
</tbody>
</table>

It can be seen that the compensated results are improved to within the 0.1 mm limit for both height and alignment, for the whole working range. For gap width, results are improved to within the limit for nearly the whole working range, but only for cases with just gap width, or just misalignment. For the mixed case, that is the case with both gap width and misalignment, the working range is not improved, and the maximum error is actually worse. The results for position are also worse for the mixed case, and are not substantially improved for the other cases.
5 Discussion

To fulfil the objectives set out for a practical method capable of accurate zero gap measurement, a number of factors must be considered.

5.1 Practical issues

As discussed in Paper A, using the method for gap position requires one complete set of calibration data for the specific material, plate thickness and probe used. This set is recorded at nominal zero gap with no misalignment. Paper C discusses how to improve results for gap width, alignment and height, with four additional calibration positions needed for each of two different gap adjustments. This calibration effort is reasonable, but not negligible, as it must be repeated for new plate materials and different thicknesses. The computational demand of the method is moderate, since it is interpolation based, while the model for compensation of systematic errors uses simple formulas.

While the inductive method performs well within the working range of 2 mm, it should be noted that the field of view of laser stripe sensors are usually considerably larger, often 10 mm or more. While the larger working range of laser stripe sensors is associated with lower resolution and ability to detect narrow gaps, it does afford more flexibility in a robotic application. This is an advantage when tracking curved gaps, especially for in process applications. With another choice of coil dimensions and working frequency, the probe could be adapted to have a larger working range, but that would also affect the influence of path radius. More advanced robot control strategies could also reduce the need for a large working range.

One of the benefits of laser line sensors is that the standoff distance, that is the height between the work piece and the sensor, is comfortably large. This means that it is reasonably easy to integrate on a welding head as it does not need to compete for space close to the gap. Still, an integrated sensor and laser line generator can be an obstacle to manoeuvring the weld head in confined spaces. Using a camera mounted co-axially and using the same optics as the welding laser beam can save on the demand for space. In comparison, an inductive sensor needs to be mounted very close to surface of the work piece, but can be quite small. The integration with other equipment, especially metallic conductive parts, needs to be investigated.
5.2 Performance

Gap width results show improvement from the model compensation presented in Paper C, and are nearly within limits unless there is both gap width and misalignment at the same time. Results related to liftoff are good for all cases when compensation is applied. Results for position did not improve from error compensation, but since these were within the limit of 0.1 mm already with the method presented in Paper A, no compensation is really necessary. Overall then, the method has been shown to have useful results within the working range, and should prove useful for its intended application.

The poor accuracy with mixed dimension gaps still needs addressing. There is room for improvement in the model used to describe influence of dimensions and, in particular, handling of covariance between gap width and alignment.

The comparison of different methods done in Paper B also show that visual methods, particularly triangulating line scan, works as well or better as long as there is a visible gap, but gaps that are both narrow and well aligned go undetected. The thermographic method could be used to measure the position of zero width gaps, but cannot measure the other parameters as well.

To get the best of both worlds, a combination of methods could prove useful. Indeed, this is a common strategy with visual detection methods. Although this is a more complicated solution that needs more equipment on the robot, calibration, and data processing, it does allow complementing methods to cover a wider range of working conditions, as well as to offer increased redundancy. Of the alternatives studied here, one option then could be to go for laser line scan, which is a proven method for non-zero gaps, combined with an inductive probe for zero gaps. The thermographic method also handles zero gap, and could be an option for further development.
6 Conclusions and contributions

Automation of laser welding benefits from sensors providing feedback on process results. Accurate gap measurement, for finding the gap before welding or as part of a seam tracking system used during welding, improves efficiency and quality.

In Paper A, an inductive method with capability to measure the position of both zero and non-zero gaps with or without misalignment is presented. A working range of 1 mm to each side and 1 mm in height is an improvement over existing methods with zero width capability that depend on servo control to be centred above the gap.

In paper B, the capability is compared to a selection of different gap measurement methods, highlighting the capability of each. The inductive method is found to have zero gap capability, as do the thermographic method, but the thermographic method does not measure height or alignment. The laser line sensor performs best, but does not have zero-gap capability as the inductive method has.

In Paper C, systematic errors are modelled to provide improved measurement of gap width and alignment, with some limitation to the width measurement capability in cases of combined gap width and misalignment. In cases with only gap width or only alignment, remaining errors are smaller than 0.1 mm for nearly the full working range, and remaining errors for height and alignment measurement are within 0.1 mm for the full working range.

Returning again to the research question in Section 1.4:

“How to detect and measure position and dimensions of even a very narrow and well aligned gap in laser beam square butt welding of titanium and nickel based alloys in order to weld correctly and in the right place?”

The investigation shows that the proposed concept of dual inductive coils with phase sensitive detection and a calibrated compensation model can be useful in applications with high demands on gap measurement for both narrow and ordi-
nary gaps. The method has capability to measure gap dimensions that allows to
direct the laser beam correctly, to adapt welding parameters to gap width and
alignment, and to adjust laser focus, with an accuracy that is believed sufficient
for many practical laser welding applications. To summarise; the contributions
of the work are some steps towards a solution for automation of laser beam
welding
7 Future work

All investigations so far have been performed with a single coil, combining readings into a virtual, probe to understand the properties. Though these results are based on actual measurements, it is still important to verify the method with an actual two coil probe to find any unwanted interactions between coils. For example, it may be necessary to use two different frequencies, or to measure at alternating time intervals to avoid cross influence.

The calibration procedures, while not unreasonably complicated, could preferably be simplified. Ideally, the method would have only one calibration grid derived for a reference setup with nominal plate material, thickness and coil response. Then, separate calibration for individual coils, along with compensations for resistivity and dimensions, would replace the case specific calibration necessary in the proposed method. It is not yet clear how much simpler the calibration could become.

When investigating the principle of the method, the conditions were controlled and the properties of plates and of the environment were well known. It is important, however, to also investigate the influence of disturbances and other conditions that can be predicted. These can be for example irregular shapes of plate edges, varying radius of the weld and curved surfaces. Tolerance to scratches and different surface conditions should be verified, as well as behaviour with zero width gap subjected to pressure from fixturing and tack welds.

It is also important to verify the method under realistic conditions rather than idealized laboratory conditions. The probe needs to be mounted on an actual welding robot, and used during welding. For a practical method, calibration procedures adapted to industrial conditions are necessary and practical solutions to varying dimensions must be found.

If the method proves useful in additional testing and deployment as indicated above, some future possibilities could be worth investigating. For example, lower frequencies might give the opportunity to measure deeper into the plates. This might give the chance to track beneath shallow tack welds, and possibly to get an indication of plate thickness, or the shape and direction of the plate ends forming the gap. Thus, research into pulsed and spectral eddy current methods could be rewarding.
One natural extension of the method would be to use an array of sensors that would allow a wider measurement range, and make it possible to estimate the orientation of the work pieces.

While the current setup of coils and instruments are proven useful, it may be possible to find better choices to improve sensitivity for certain conditions or materials.
8 References


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9 Summaries of appended papers

9.1 Paper A. A complex response inductive method for improved gap measurement in laser welding

Laser welding needs precise measurement of weld gap position to avoid weld defects. Most often, optical measurement methods are used, but well-aligned narrow gaps can be difficult to detect. An improved inductive method capable of detecting zero gaps in square butt joints is proposed. The new method uses two eddy current coils, one on each side of the gap, and measures the complex response of the individual coils, i.e. both the inductive and resistive response. By combining the coil responses, both the position and the dimensions of the weld gap can be estimated. The method was experimentally investigated by traversing a single coil over an adjustable gap between two plates and combining the measured coil responses into a simulated two-coil probe. The gap was adjusted in both alignment and gap width up to 0.40 mm. Comparing the results to known settings and positions shows that gap position is measured to within 0.1 mm, if the probe is within a working area of 1 mm from the gap in both position and height. Results from the new method were compared to simulations, from the same experimental data, of a previously reported method where the coils were electrically combined by wiring them together. The previous method can give accurate results but has a much smaller working area and depends on servo actuation to position the probe above the gap. The improved method gives better tolerance to varying misalignment and gap width, which is an advantage over previous inductive methods.

The author planned and performed the experiments, planned and performed data processing and led the writing.

9.2 Paper B. Evaluation of non-contact methods for joint tracking in a laser beam welding application

The use of automated laser welding is a key enabler for resource efficient manufacturing in several industrial sectors. One disadvantage with laser welding is the narrow tolerance requirements in the joint fit-up. This is the main reason for the importance of joint tracking systems. This paper describes an evaluation of four
non-contact measurement methods to measure the position, gap width and alignment between super alloy plates. The evaluation was carried out for increased knowledge about the possibilities and limitations with the different methods. The methods are vision-, laser-line-, thermography- and inductive probe systems, which are compared in an experimental setup representing a relevant industrial application. Vision is based on a CMOS camera, where the image information is used directly for the measurements. Laser-line is based on triangulation between a camera and a projected laser line. Thermography detects the heat increase in the gap width due to external heat excitation. Inductive probe uses two eddy current coils, and by a complex response method possibilities to narrow gap measurement is achieved. The results, evaluated by comparing the data from the different systems, clearly highlights possibilities and limitations with respective method and serves as a guide in the development of laser beam welding.

The author participated in planning of experiments and writing, performed experiments and data processing for the inductive method and wrote corresponding sections of the paper.

9.3 Paper C. Model based compensation of systematic errors in an inductive gap measurement method

A previously reported inductive method for measurement of weld gap in high precision applications, such as laser beam welding of square butt joints, demonstrated improved results for gap position, width and alignment over previous inductive methods. To further improve that method by reducing systematic errors that affected results, a compensation scheme based on a model of the error behaviour is proposed in this paper. The model is designed from observation of experimental data, and adjusted from a small set of typical calibration measurements. The combined information about gap properties from the two coils in the probe is used to estimate a correction for each of the coils, and a more accurate result can then be calculated. Comparing the compensated results to the uncompensated, most parameters are improved to within 0.1 mm in the working range. Gap width measurement still suffers from combined gap width and misalignment.

The author planned the paper, performed the data processing and led the writing.
Inductive measurement of narrow gaps for high precision welding of square butt joints

In laser beam welding without filler material, the gap between the parts to be joined must be narrow. Optical sensors are often used to measure the gap, but with precise machining, it may become so narrow that it is difficult to detect, with the risk of welding in the wrong position. This thesis proposes the use of an inductive sensor with coils on either side of the gap. Inducing currents into the metal, such a sensor can detect even gaps that are not visible. The new feature of the proposal is based on using the complex response of each coil separately to measure the distance and height on both sides of the gap. This information allows measurement of gap width and misalignment as well as position. The properties of the new method have been examined experimentally, showing useful results for gaps with up to 0.4 mm width and misalignment.