DEVELOPMENT AND DEMONSTRATION OF AN AUTOMATED SYSTEM FOR LIMITED ACCESS WELD INSPECTION BY USING INFRARED ACTIVE THERMOGRAPHY

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Abstract. Weld inspection for surface breaking defects detection has been traditionally performed by using NDT methods such as Fluorescent Penetrant Inspection (FPI), Visual Inspection (VI) or Eddy Currents (EC). All those well-known techniques have as common drawback the need of skilled operator intervention in order to analyse obtained results. In the specific case of inspection of welds with limited access, the application of those traditional methods is even more complex, thus increasing inspection time and reducing the defect detection capability. Therefore, the development of a fully automated non-contact method overcoming these limitations is desired.

Active thermography (IRT) represents one of the most promising techniques for replacing traditional techniques for surface breaking defect detection in welds. This technique makes use of an excitation source in order to heat the sample under test and an infrared camera for thermal evolution monitoring. With the combination of these excitation-monitoring techniques, heterogeneities in the heat flow caused by surface breaking cracks can be detected.

In this work, a robotic solution was developed and demonstrated for the inspection of welds with real cracks in a representative environment with limited access. The system consists of a continuous laser-line excitation source together with a FLIR SC 655 microbolometer thermographic camera. In order to access limited areas, two different aluminium polished mirrors have been used for both infrared radiation monitoring and laser excitation respectively. The inspection results, analysis and comparison with traditional methods will be shown.

Introduction

In order to accomplish the future targets of reducing the environmental impact of aviation, effective, cost efficient and reliable aero engines need to be developed. By using the light weight technology based on fabrication, engine components can be built that meet these targets (fabricated components are components assembled from smaller sub-components in mixed material forms preferably joined together by welding.) With lighter structures the margin of safety might be reduced, and this makes the requirement on the inspection to be even more important to maintain the safety levels.

For fabricated components and structures, such as the component shown in Figure 1, different inspection and NDT methods are today being used for weld inspection. Reliable detection of defects and inspection of weld geometry is critical with respect to component life and flight safety. Current techniques such as Visual Inspection, Fluorescent Penetrant Inspection (FPI), Eddy Current and Radiography have limitations in applicability and detectability, especially for inspection of parts with complex geometries and difficult to reach access, such as the inside of the guide vanes of the component shown in Figure 1. This may thus reduce the design freedom which may result in a poorer and possibly heavier component.

Inspection of welds with limited access puts specific requirement on the NDT-method to be used. For example, the occurrence of surface cracks and lack of fusion in hidden welds need to be detected by a reliable inspection method. Given the need of weld inspection of fabricated aero engine structures with limited access, and the drawback with the conventional NDT-methods available, there is a necessity to develop new inspection methods. A non-contact method without many of the limitations of conventional methods and with the possibility of automation is therefore desired for reliable and cost efficient inspection.

Thermography has been known for quite a long time and it is today mainly used for inspection of composite structures [1]. Thermography has been shown to have the capability to inspect metals as well, for example inspection of spot welds [2] and to detect surface cracks [3]. The method allows an object to be inspected without contact and likely without preparation. The technique is based on an infrared camera that registers the heat on the surface of the structure. The method requires an excitation source to locally heat the inspected area. One key aspect is the method of excitation, and how to optimize the excitation to have robust measurements. Several methods have been used previously with success, such as laser pulse, flash lamp and induction. For inspection of welds with limited access it is also important to study the conditions for miniaturization of inspection equipment.

The goal of this work has been to develop a method and to present a system able to locate, quantify and size weld defects such as surface cracks in hidden welds in an aero engine component.

The resulting demonstrator is a step forward to secure the introduction of future engines by conceptually designing a valid NDT system for inspection during production and maintenance. Several approaches have been analysed and the preliminary implementation of a conceptual system is presented.

1. Challenge and Approach

The objective of this section is to present the general challenge and develop the conceptual flow of an automatic NDT-cell for inspection of welds with limited access. The miniaturization issues related to the active thermography work both with respect to the excitation and to the sensing unit will be discussed. Automation issues were also addressed.

Figure 1. Turbine Exhaust Case: fabricated non-rotating turbine exit component which is located after the low pressure turbine within a jet-engine

IR Sensor and Excitation Miniaturization

As already discussed a first challenge was the accessibility of the thermal sensing device. Thermographic cameras are based on sensors which gradually are becoming more compact. Initially the possibility of miniaturization of the IR camera itself was identified as potential solution but the cost of a new design of camera was far beyond the scope of the project, and thus abandoned.

However, a small IR camera was found to be available with good resolution, the only restriction would be the area around the weld inspection. The actual miniaturization of the IR camera and the Laser Excitation source was proven to be difficult. The access point to the internal surface of the engine component is very small, so that the potential use of mirrors to manipulate the Laser beam onto the area of the inspection and also the resultant image capture by the IR camera was considered. These tests were proved to be fruitful. In this case the mirrors used were highly polished aluminium. It is true that a gold coating would have been a better option due to the high transmission percentage of not only the laser heat production but, moreover, the transmission of the infrared light to the thermal camera.

Following this approach, a prototype holder (borescope), with a set of 2 mirrors attached, was designed and produced. The holder was attached to the IR camera and the laser was placed alongside this at an angle that allowed the alignment of both to the object under inspection.

2. Thermography based NDT for surface inspection of metallic welds

Previous related work, [4], studied the potential of active thermography for the inspection of surface breaking cracks in metallic welds for aero engine applications. Three different excitation sources were evaluated in the project with respect to the requirements defined at the beginning. These were “Continuous laser”, “Induction” and “Flash lamp”. Among the three techniques continuous laser based method prove to be the most controllable and prone to be automatized.

In this section the performance, physical basis and results of the laser based system will be briefly described, as being the selected technique for the further Automated System for Limited Access Welds Inspection.

Among different laser excitation strategies that can be applied (pulsed laser, spot-heating…), the laser line excitation is an interesting strategy given the nature of this challenge. The major advantages of this method include the application of excitation in a more controlled manner compared with other excitation methods which makes the analysis step much easier. Besides, it makes it possible to excite the entire welded region in a single scan. Additionally this method allows the analysis of a single line instead of the whole imaging increasing the processing speed. In this case, see Figure 2, a set of lenses were used to generate a thin line. These set of lenses may be modified according to the inspection requirements.

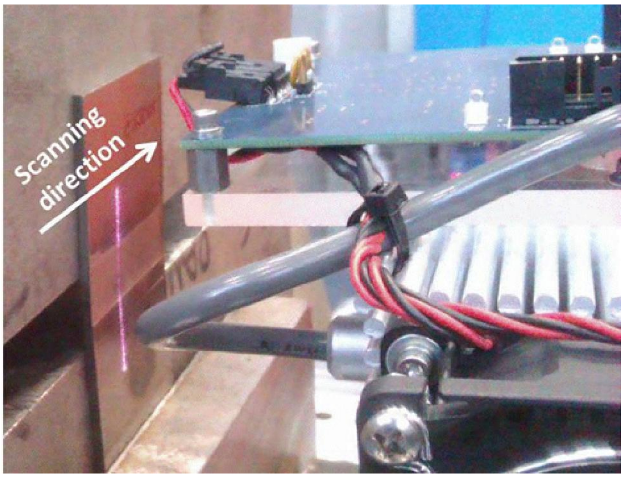

Figure 2. Laser scanning system on a welded plate.

Some test evaluations were made with welded plates, and the results are presented here. Two different samples were analysed all of them containing EDM-manufactured (Electro Discharge Machining) artificial defects. In both cases the width of the notches was about 0.1 mm, the length between 0.76 and 3 mm and the depth between 0.38 and 1.5 mm. In both samples (see Figure 3), notches were clearly detected but also non-defective areas, such as surface irregularities and oxides areas due to over-heating. Due to this, distinguishing between defective areas and false positives can be a problem unless other more advanced processing techniques are used.

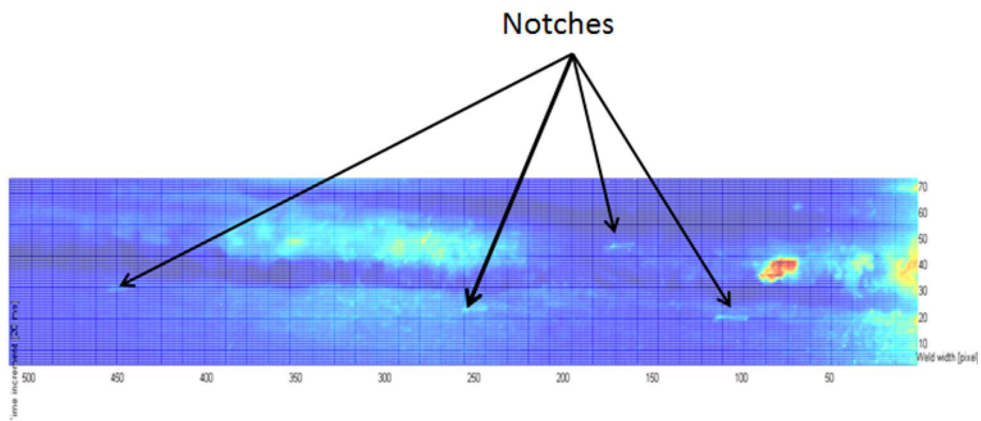

Figure 3. Sample result after line scanning (P=30 W/cm^2). The presence of the notches can be detected

by the given thermal contrast.

For defect detection, over the last few years several methods and algorithms of thermographic sequence processing have evolved. Many of these have been based on the traditional artificial vision. Within these processing techniques, smoothing operations for noise removal (median or Gaussian filters), gradient operations for edge detection or morphological filtering for object recognition (thresholding, object parameter identification, Hough transform…) may be found. Advanced processing techniques, on the other hand, are based on thermal properties such as conductivity or diffusivity, being consequently less sensitive to surface conditions. The development of such a processing technique is crucial in order to build a reliable NDT inspection cell.

Influence of scanning speed

Another important aspect to analyse is the scanning speed. The combination of scanning speed and the acquisition speed of the thermal camera determine the minimum size of detectable defects due to the step every frame (mm/frame).

In addition to the minimum detectable size, the scanning speed also affects the resulting temperature increment and therefore, detectability (due to differences in the absorbed energy). For this assessment, some experiments were carried out by keeping the camera and the work piece stationary while the laser scanned the defects at a constant velocity. Tests were conducted at 50 Hz acquisition rate.

After this analysis two main conclusions were drawn. With respect to temperature increment, it was observed that radiation increment (which is the equivalent to temperature increment) may be reduced by a factor of 2 when increasing the scanning speed from 100 mm/min to 600 mm/min. In addition to this, the transient response may also be affected, which clearly represents a key aspect in the analysis part. The parameter that represents this behaviour in the temporal processing is the time constant of the cooling curve. Due to scanning speed increment the time constant is reduced considerably to 7 frames, as can be seen in the image (see Figure 4). This obviously represents a challenge when trying to characterize the thermal response that may determine whether the area is defective or non-defective. Due to this fact, the scanning speed with the current system was bounded between 100 mm/min and 500 mm/min.

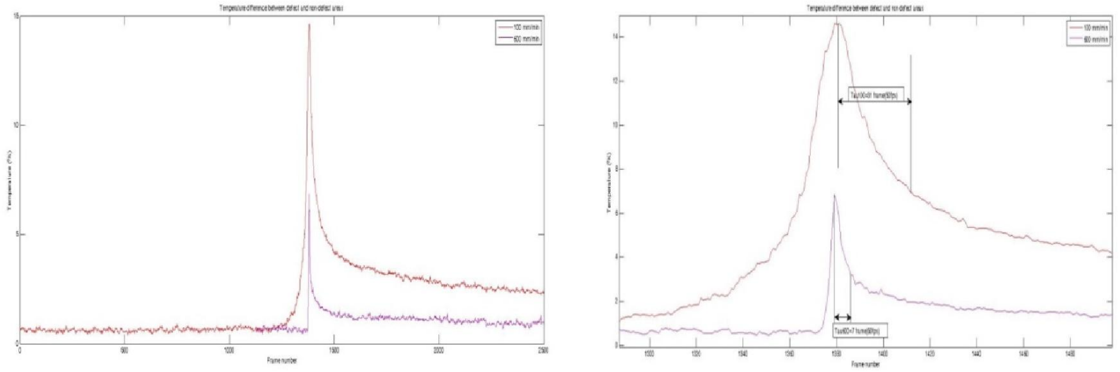

Figure 4Temperature differences at different speeds (image on the left) and the corresponding cooling behaviour (image on the right)

3. System implementation/realization

The automated inspection of welds implies that different strategies need to be adopted for all the involved aspects: motion (scanning), data acquisition and defect detection. In this case, the additional need to reach non accessible zones includes the development of a borescope. With regard to scanning movement during measurement, a common approach consists of using robots [5] that offer great flexibility and the possibility of tracking complex geometries.

As mentioned before a prototype holder (borescope), with a set of 2 mirrors attached, was designed and produced. The holder was attached to the IR camera and the laser was placed alongside at an angle that allowed the alignment of both to the object under inspection.

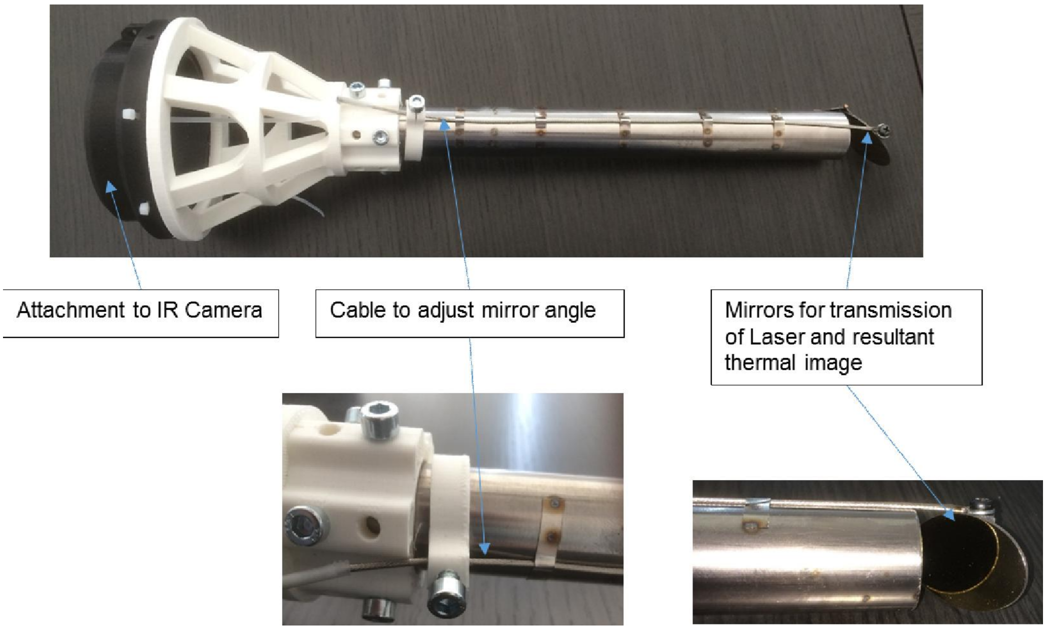

Figure 5. First prototype of borescope.

This first prototype, see Figure 5, was tested and found to work, but it had some design issues that had to be addressed.

- The mirror had only one angle of movement change, therefore 2 mirrors with separate adjustment would have to be used.
- The borescope was too large and inflexible for the application. Something more flexible would have to be designed so that the mirrors could easily be manipulated into the small opening.

The final design, the second prototype, for the mirrors was somewhat different and was not connected directly to either the laser or the thermal camera, but directly to the manipulation robot, see Figure 6. The laser and the thermal camera were also placed on the arm of the robot to ensure cohesion between all three components of the system. In the mirrors the image of the weld can be clearly seen, see the lower part of Figure 6. The adjustment of the angles of the mirrors, in this case, was done by hand. In future this adjustment would be carried out automatically or remotely using small actuators.

This second prototype was tested and demonstrated in the final NDT cell.

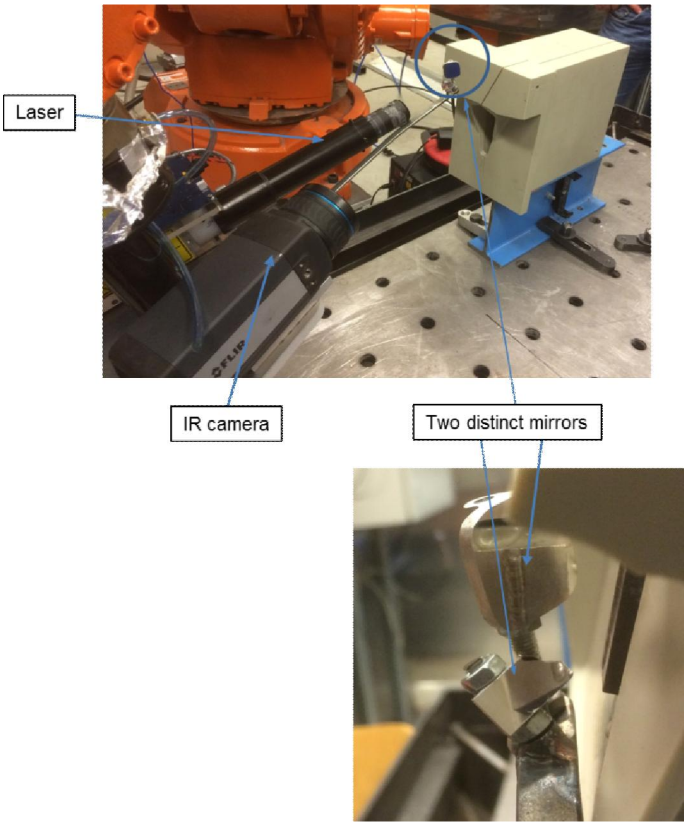

Figure 6Second prototype of borescope solution mounted in the final NDT cell for weld inspection inside a mock-up of a guide vane with limited access.

The automatic motion during inspection includes the manipulation of the testing apparatus (NDT equipment), i.e. the scanning. The scanning equipment can be of different types and several manipulators exist that are used with automated NDT-systems. Most of these are specialised to be used for specific and simple weld geometry, although some more advanced and flexible ones do exist. Welding in the production industry today is most often performed using industrial robots. A similar robot was used in this project for inspection of welds inside a mock-up of a guide vane, similar to the fabricated component shown in Figure 1. An industrial 6-axis robot offers great flexibility, excellent support organization and the know-how about such equipment is often high since robots are used extensively in the production industry. Another benefit is that a robot can carry several types of equipment.

4. Conclusions

Laser line based thermography as a method for non-destructive inspection of welds with limited access has been developed.

An automatic prototype NDT cell was produced and demonstrated. The NDT cell was based on a six axis industrial robot. An IR camera was mounted on the robot arm for scanning the inspected area. The excitation source was selected to be a continuous laser, generating a focused laser line on the inspected weld seam. The laser head was also mounted on the robot arm. A borescope solution was designed and prototyped in order to be able to inspect hidden areas inside a mock-up of guide vane with welds, both for the excitation (laser) and the IR image acquisition to a commercial IR camera. The solution has proved to work.

This case study has demonstrated that the laser line based thermography method may be a good solution for Automated System for Limited Access Welds Inspection.

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