Active Thermography for Dimensional Measurements on Gas Turbine Components

Matthias GOLDAMMER, Siemens AG, Munich, Germany
Werner HEINRICH, Siemens AG, Berlin, Germany

Abstract. Thermography using hot-air excitation has shown to be an ideal match to measure the wall thickness of cast gas turbine blades. The measurement principle is demonstrated on a test object and an actual implementation used in a manufacturing plant is introduced. As an example of a real component the measurement of a gas turbine blade is shown. Analytical calculations for optimizing the process and helping calibration complete the discussion.

1. Introduction

Combined cycle plants are hard to beat when looking at the efficiency to generate electricity from fossil fuels. Consisting of a number of gas turbines which drive an additional steam turbine with their exhaust, it is the gas turbine development that drives further improvements in efficiency and dependability. Modern gas turbines heavily rely on advanced materials and manufacturing processes which are unthinkable without accompanying inspection techniques during manufacturing and in service. The single most critical parts of the turbine are the first row of blades of the combustion section of the turbine (figure 1). Theses blades have to withstand rotation at 50 or 60 Hz combined with temperatures of several hundred degrees – this is only possible by advanced materials such as the combination of nickel-based super alloys parts with ceramics coating.

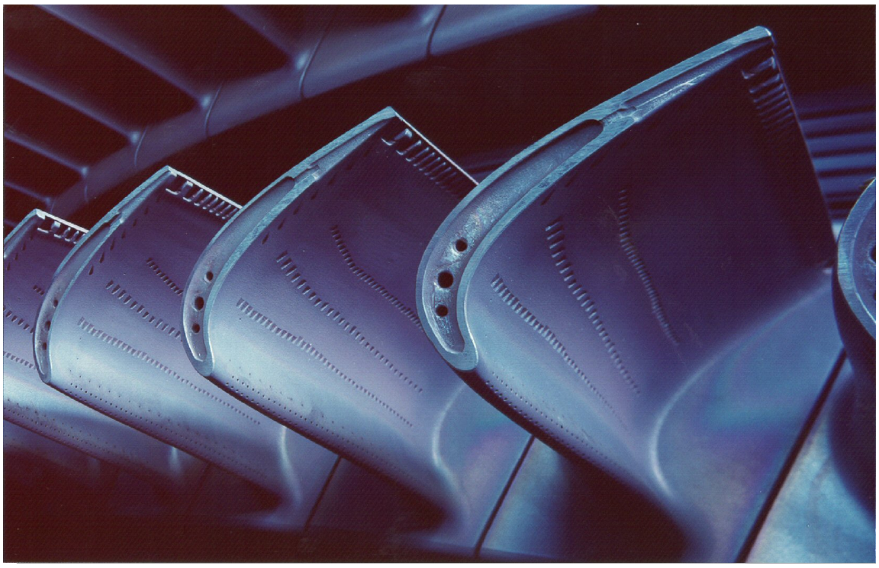

Figure 1, First row of blades of a gas turbine

But even with these materials efficient cooling is needed for the blades: Cooling passages cross the airfoil and root of the blade and also conduct air to holes in the airfoil so part of the air forms a cooler film of gas around the airfoil. For the cooling channels drilled holes used to be the standard in the past, modern blade designs contain complex shaped passages that can only be manufactured by casting the blade around a ceramic core of the exact shape of the desired cavity. After casting this ceramic core is dissolved and the airfoil reaches its final shape apart from hole drilling and minor corrections. Measurements of the outer shape of the airfoil can be done by standard mechanical or optical means but to the cooling passages access is limited. If the ceramic core has shifted during the casting process only inspection methods that provide a glimpse inside can be considered.

Currently an ultrasonic thickness gauge for determining the remaining wall thickness between the airfoil surface and the inner surfaces of the cooling channel is applied to a number of specified points on the surface – if the ceramic core has shifted during the casting process the wall thickness will be too thin at one side and too thick at the opposite side. When applying ultrasonic thickness measurements to turbine blades a number of problems arise: Scattering and attenuation in the material as well as the crystal orientation complicate the measurement, and the curved surface prevents precise positioning of the probe. Therefore the results deviate between different operators. Additionally, an automated scan is not possible because of the complex geometry. An ideal measurement technique to replace ultrasonic thickness gauging would deliver not only measurements at distinct spots but a whole map of the thickness that additionally should not depend on the curvature.

Active thermography has been employed for performing a number of inspection tasks on turbine parts. The most prominent method is using flash thermography for debond testing, but at the Siemens plant in Berlin also the inspection of cooling holes is performed with thermography. The unique advantages of thermography can also help to overcome the limitations of the current wall thickness measurement.

2. Applying Thermography to Dimensional Measurements

Active thermography as inspection method comprises of all techniques which heat a part specifically to induce a heat flow in the component to be tested. This heat flow also affects the surface temperature which can be measured in non-contacting way by looking at the emitted thermal radiation with an infrared camera sensitive to this radiation. A number of active thermography techniques can be directly applied to thickness measurements: For pulsed techniques such as flash excitation the time for the heat pulse to traverse the material correlates with its thickness. Techniques employing a periodic heating induce a thermal wave traveling through the part – the phase can be used to measure thicknesses. Also any heating device can be used depending on the particular properties of the part to be tested. In the past a number of successful applications of thermography to dimensional measurements have been shown: E.g. the thickness measurement of paint has been done with photothermal techniques for quite some time [1]. Also flash thermography has been applied to thickness measurement [2,3]. In addition, a large theoretical background exists to analyze the results [4,5].

Using thermography as a tool for measuring dimensions provides a number of unique advantages that the dimensional measurement of turbine blades can immediately benefit from:

- The non-contacting detection simplifies automation of the measurement procedure.
- The imaging detection with the infrared camera provides not only the measurement at a single spot but a complete thickness map.
- The heat flow initiated by uniformly heating an area of the surface always traverses the material perpendicular to the surface. That means that the measurement can be done

even if the surface is tilted with respect to the sensor. This makes thermography particularly useful for curved surfaces such as the airfoil of a blade.

But the omnidirectional heat flow can also be of disadvantage: The lateral heat flow blurs the resulting image and prevents small detail within the material to be detectable with thermographic techniques.

2.1 Wall thickness measurement using flash thermography

To measure a complete image simultaneously flash thermography is ideally suited. A single flash can deposit several thousand Joule of energy in a few milliseconds which can only be achieved over a small area with lasers. The heat pulse generated on the surface of the material spreads to the back side which results in decreasing surface temperature until equilibration in the part is reached – the necessary time to traverse the part corresponds to the thickness.

Flash thermography applied to thickness gauging offers two specific advantages:

- A large area is accessible with one shot – depending on the thickness the measurement only takes seconds. E.g. a sheet of nickel-based super alloy of 3 mm thickness can be measured in 10-20 seconds over an area of 30x30 cm² per flash used.
- The heating time can be further reduced by switching off the flash which some manufacturers offer of the shelf [6] but which also can be supplemented to the flash [7]. With this technique flash thermography can cover a wide range of accessible thicknesses. E.g. for nickel-based super alloys a range from some tens of a millimeter up to one centimeter can be covered.

Unfortunately for thicker materials the minimum flash energy needed increases with the square of the thickness to be measured. For thick materials – in the case of gas turbine blades thicker than 4-5 millimeters – the noise of the camera becomes comparable with the remaining temperature difference to be measured resulting in a large uncertainty of the measured thickness value.

2.2 Excitation with hot air

The gas turbine blade itself provides a unique way to apply heat for a thermography measurement: The cooling passages of a modern blade can be used to conduct hot air through the blade which heats the material from the inside. Blades are inspected right after casting but before any cooling holes are drilled into the surface. Therefore heating only occurs at the inner surfaces. A complete measurement cycle comprises of the following steps:

- The blade is mounted in an airtight fixture
- An IR-camera records the surface temperature of the blade at one position
- At the same time pressurized air is conducted through the blade – alternating between air at ambient temperature and air heated to about 80°C in 10-20 cycles of 0.5 to 2 Hz. The duty cycle of hot to cold air typically varies between 10 and 50%.
- For each pixel of the resulting IR-video a lock-in calculation is performed resulting in a phase and amplitude value that is converted into a thickness value and displayed in the resulting image
- The measurement is repeated from 4-5 view angles to cover the complete surface of the airfoil

Compared to other thermographic techniques hot-air excitation offer a number of improvements compared to flash heating:

- Turbine blades designed to be cooled by air are a perfect for excitation with hot air: All critical areas to be inspected automatically are also covered by the hot-air.

- Since the heating is achieved by convection the amount of transferred heat does not depend on the optical characteristics of the material as in the case of flash or laser excitation.
- The lock-in detection scheme suppresses effectively noise originating in the IR-camera so the signal can be improved by simply measuring more cycles. This way the measurement time can be matched to the required accuracy.
- The measurement is performed in a transmission configuration: The thermal wave only needs to cross the material once which results in better signal compared to a one-sided setup.
- For all thermography techniques the part temperature increases with every shot. Since pressurized air is already supplied cooling down of the part between measuring different view angles can easily be achieved without additional equipment.

Since not only the phase but also the amplitude is present during the calculation of the resulting thickness in addition to the value itself the accuracy can be calculated. Using this accuracy information also a drawback of the hot-air excitation can be overcome: Due to the specific air flow within the part not all areas of the surface can be heated with the same intensity resulting in large differences in the amplitude across the airfoil. But since for all calculated thickness value the accuracy requirements can be monitored, values not meeting minimum standards can automatically be blanked in the resulting image. The operator can rely on all values provided from the measurement being usable.

3. Calibrating hot-air thermography

3.1 Measurement of calibration curve

To calculate the thickness from the measured phase and amplitude value a calibration curve is inevitable. In contrast to flash thermography not only a calibration object with access to both sides is needed but also the correct air flow within the part has to be achieved. A pipe with steps in thickness from 1 to 15 mm was built as a reference for first calibration tests. The inner diameter of the steel pipe is 20 mm resulting in outer diameters reaching from 22 mm to 50 mm. In order to minimize the influence of lateral heat flow on the calibration each step was 30 mm wide providing a large area for averaging the measured phase values into a calibration curve. Figure 2 shows the phase image taken at a frequency of 0.8 Hz and a duty cycle of 25%: The measurement was performed in three steps and the resulting images joined together. At that frequency the dynamic range reached only to 10 mm therefore the right part of the image is not shown. The thickness values at a line along the test object is shown in figure 3: Between 1 and 8 mm the thickness increases 0.5 mm with each step and 1 mm between 8 and 15 mm.

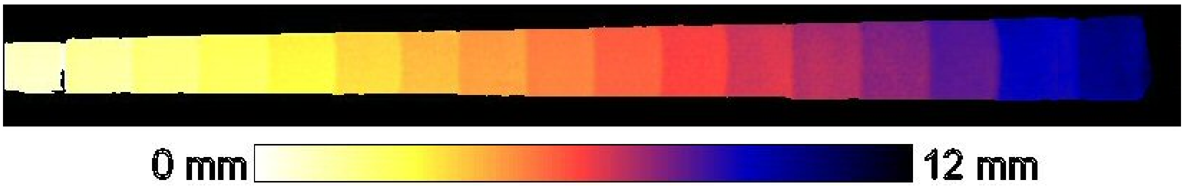

Figure 2, Thickness map of a step pipe

At the edges of the smaller steps the effects of the lateral heat diffusion can be seen: At these positions the measured values deviate considerably from the actual thickness. For a correct interpretation of thermography images the lateral structure of the part has to be taken into account.

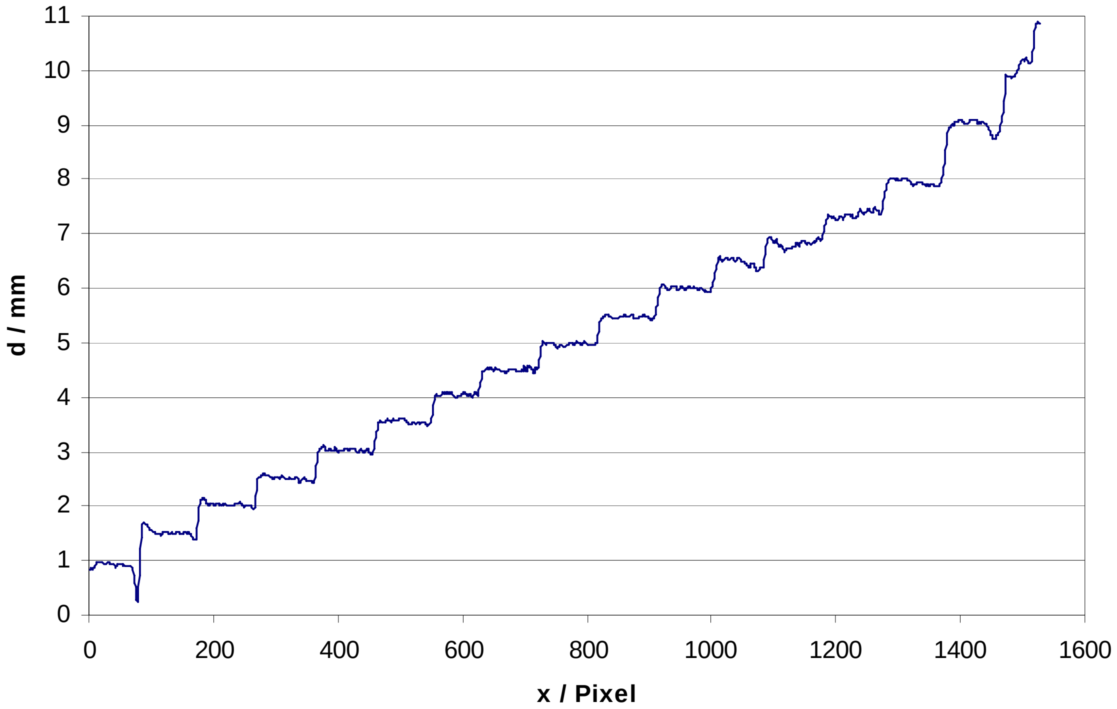

Figure 3, Thickness values at a line along the step pipe

Figure 4 displays the resulting calibration curve for the steel used for the pipe. For values larger than 3 mm the curve approaches a straight line which levels off for smaller thickness values. A higher frequency leads to a steeper calibration curve at the expense of losing the larger thicknesses due to low signal. That means that the frequency has to be matched to the anticipated thickness range of the part, but for a larger range different frequencies could be combined: Since the rectangular excitation also includes higher harmonics of the base frequency the same raw data can be used to extract several frequencies and a single measurement can cover a wider range.

A comparison to an FEM calculation shows good agreement (open triangles in figure 4). Only heat conduction has been included in the calculation which demonstrates that radiation and convection can be neglected.

3.2 Analytical model of the thickness measurement

To simplify the calibration and remove the need to manufacture calibration parts an analytical model using a thermal wave approach was developed. The model is able to completely reproduce the calibration curve (figure 5). The disagreement for small thickness values can also be modeled when taking into account the coupling of the hot air to inner surface of the pipe. But since a measurement at these small values would result in only a low accuracy of the thickness values the simple calibration curve suffices. Apart from parameters such as the frequency and phase offset only a single material parameter is needed to calculate the calibration curve: thermal diffusivity. Thus the simplicity of calibration is another advantage of using hot-air thermography for thickness gauging.

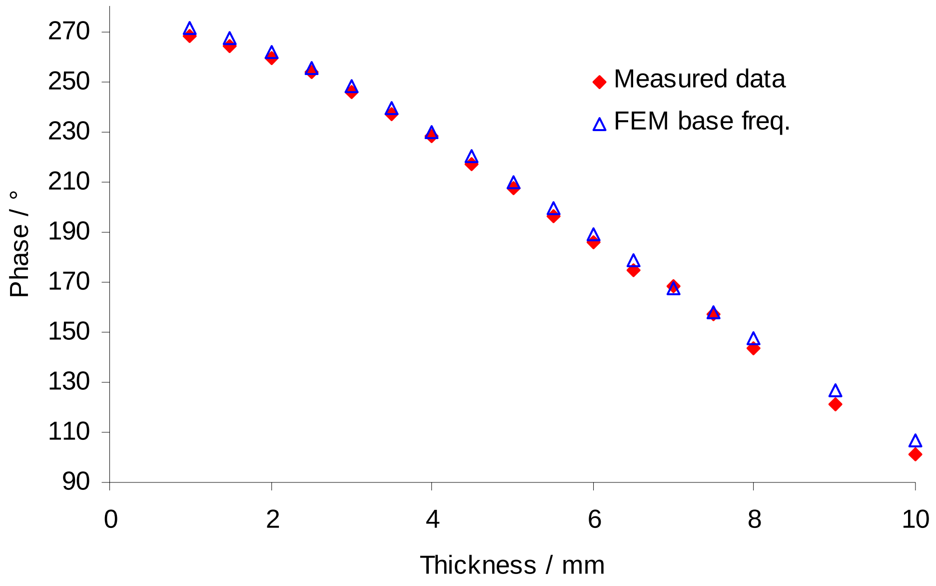

Figure 4, Comparison to FEM calculation of step pipe

Additionally with the analytical model different harmonics of the measurement can be easily used in parallel: For every harmonic a thickness value and the corresponding accuracy is calculated and can be combined into a single value. Due to the lower amplitude available for higher harmonics using rectangular excitation the combination of the harmonics has to take the accuracy into account. For comparison, figure 6 shows the distribution of amplitudes over the airfoil of a blade for the base frequency and the 2nd harmonic.

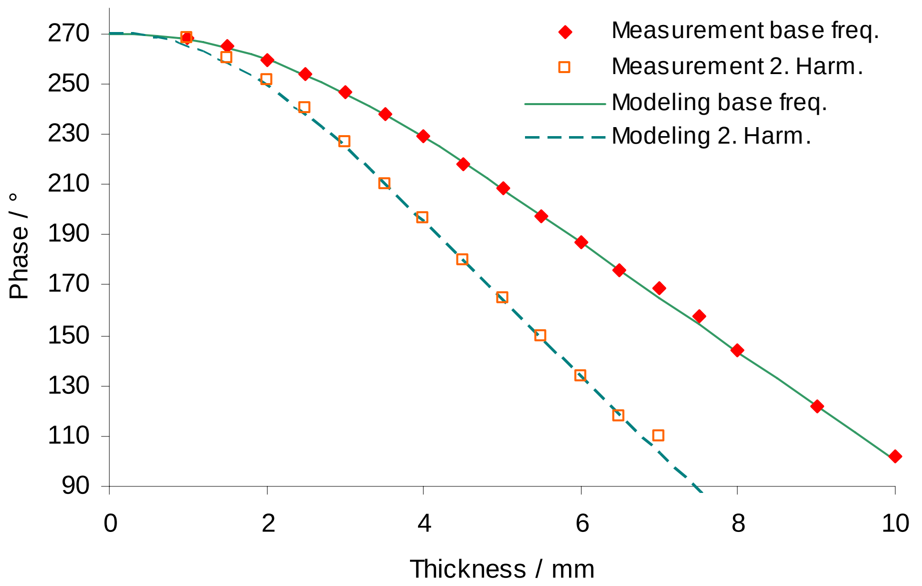

Figure 5, Analytical model compared to measured values

For large thickness values the analytical calibration curve follows a straight line originating at -45° which is identical to the result found for a periodic heat source buried at depth *d* in a semi-infinite body:

$$\varphi = -\frac{\pi}{4} - \frac{d}{2}\sqrt{\frac{f}{\pi\alpha}},$$

where *f* denotes the excitation frequency and *α* the thermal diffusivity of the material. The analytical calibration curve has been confirmed by measuring an actual turbine blade: After cutting the part and comparing to the measured phase values the resulting curve matched the anticipated calibration curve for most of the compared spots. Because of the more complex shape of the blade some deviations could also be observed: Structures such as turbulator rips that are too small to be resolved with thermography result in an average thickness value at that area. Also the curvature has to be small compared to the thickness since the calibration curve has been calculated for flat areas. Alternatively the calibration could be corrected for highly curved areas of the surface.

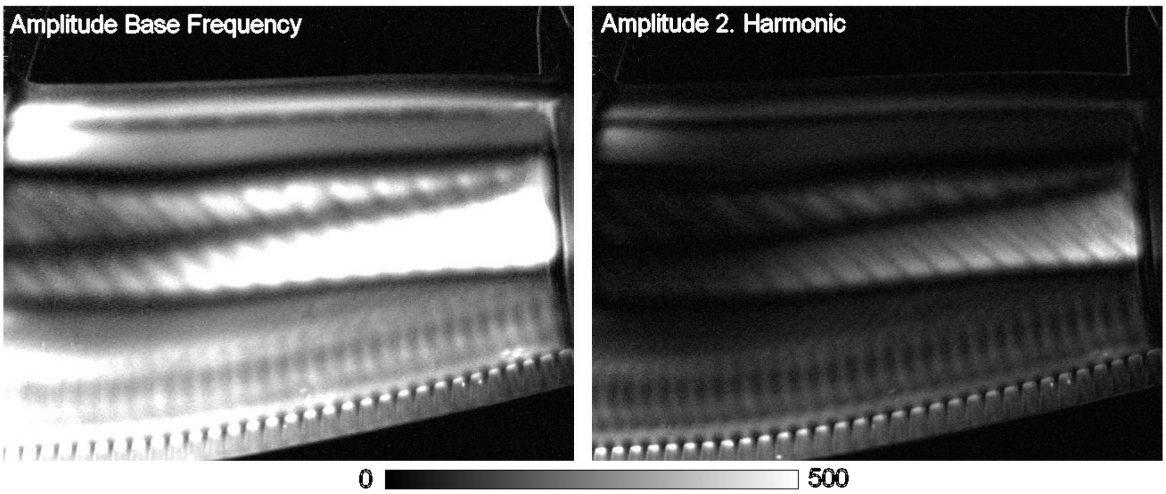

Figure 6, Comparison between the amplitude images of the base frequency and the 2nd harmonic

4. Measurement of turbine blades

With the calibration curve all prerequisites exist for implementing the measurement on the shop level: The thermography system at the Siemens gas turbine manufacturing plant in Berlin (built by Thermosensorik GmbH, Erlangen) already was equipped with a hot-air excitation system and immediately usable for the wall thickness measurement [8]. With this system it is also possible to plug in custom software modules for analyzing the raw infrared signal. A new module has been built to include the complete analysis of the raw data up to the final thickness map. The calculation is done in three steps: First, phase and amplitude are determined for the excitation frequency and higher harmonics. As second step the analytical calibration curve is used to calculate thickness and accuracy values – unusable pixels are blanked. Finally, the thickness values from different harmonics are combined into a single thickness map and presented to the operator.

Figure 7 shows a typical result of such a measurement. Black areas correspond to those parts of the image that are below the minimum accepted accuracy threshold. The remaining image is a composition of the different harmonics. In an image of an actual component another advantage of the harmonic combination becomes evident: By using higher harmonics not only the measurable thickness range is extended to smaller values but also finer details of the image are conserved where lower frequencies would result in more blurring due to lateral heat diffusion.

In the test measurements the accuracy reached with hot-air thermography outperforms the accuracy of ultrasonic thickness gauging which was estimated to 10% for these components. After implementing the measurement in the thermography system a number of repeated measurements were performed to test the repeatability of the measurement. By optimizing the camera setup and parameters for the excitation the agreement of the repeat measurements was better than 0.1 mm. The wall thickness measurement proved to match the required accuracy and repeatability needed for the manufacturing plant and is now a viable alternative to ultrasonic thickness gauging.

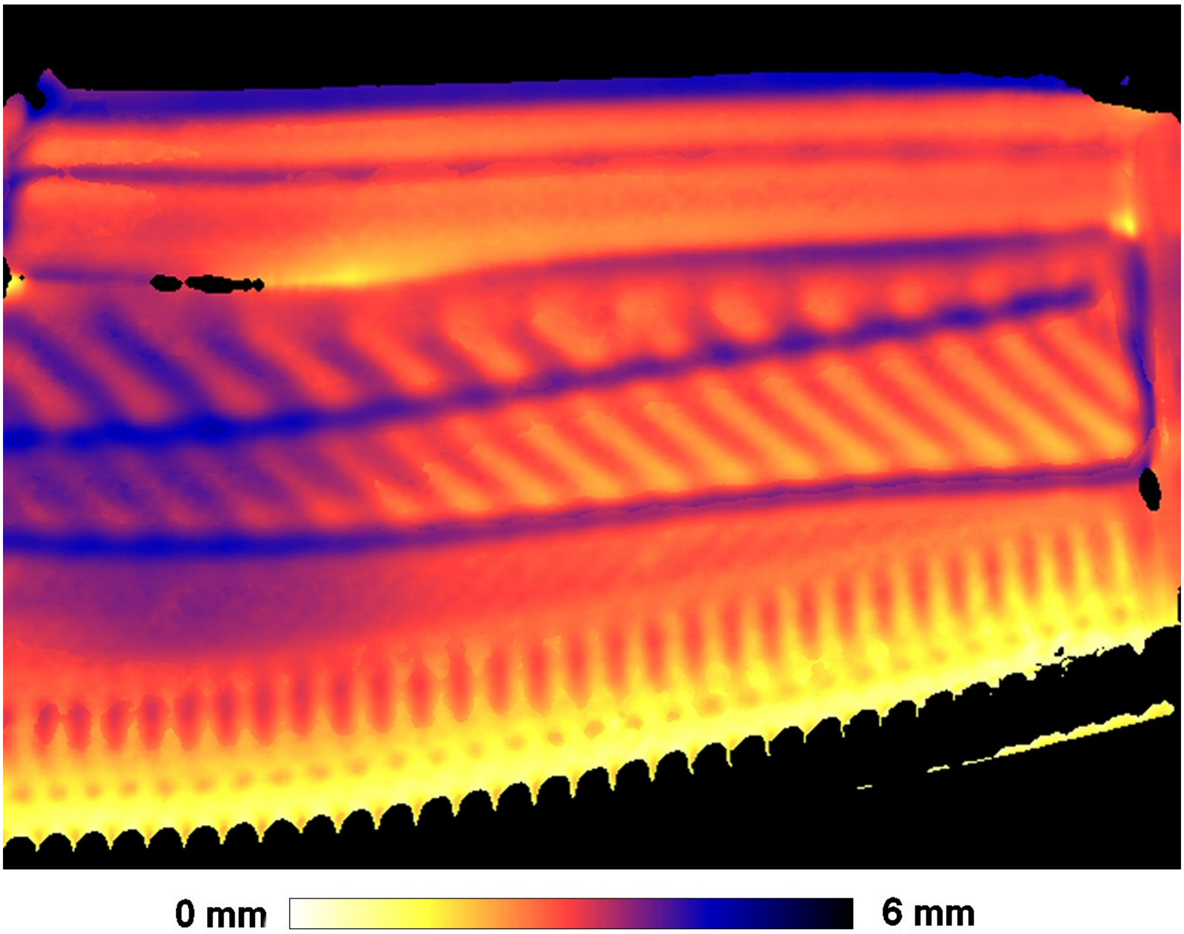

Figure 7, Wall thickness map of the pressure side of a gas turbine blade

5. Conclusion

Specific applications can gain the most from using a thermography technique tailored to the task in question: Employing hot-air thermography for modern gas turbine blades is a perfect match of excitation to the component. The optimized analysis algorithms which make use of multiple frequencies help to increase the dynamic range of the method but also improve the image quality considerably. Analytical modeling supplements the measurement and provides the calibration curves.

Over the last couple of years thermography has evolved from a technique limited to niches where no other nondestructive testing method would work to a widely applied alternative to traditional methods. Part of this maturing process has been the expansion from defect recognition to include quantitative measurements. Dimensional measurements benefit immediately from the advantages of thermography therefore the wall thickness measurement of cast gas turbine blades is only a first step and other areas will follow.

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