A robot inspection system allows the detection of defects in adhesive bonds between CFRP components by using active thermography, leading to reduced cycle times

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The bonding of large industrial components made of carbon fiber reinforced plastics (CFRP), as they are used in the aviation industry in case of structural components, requires an inspection system which is able to verify these bonds. In this contribution, the advantages of a robotic inspection system, which will be achieved through continuous testing, will be introduced. Of particular interest here are the bonds with which, for example shell elements and reinforcements (so-called stringers) are bonded together. In order to make a qualitative statement about the bond, it is measured using a non-destructive testing method, the active thermography. For elongated part geometries or large components, an advantage can be achieved by a continuous testing. In this variant of testing with active thermography, the positioning time for the measurement system is eliminated and by spatial shifting, the contrast of failure measurement, a much shorter testing time will be achieved. The inspection system consists of an excitation source (infrared quartz radiator) and an infrared camera for the far-infrared spectral range (FWIR) which are both attached to a lightweight robot.

Keywords: active thermography / carbon fiber reinforced plastic CFRP / inspection system

The competitiveness compared with low-wage countries shows a great challenge for enterprises resident here. These exist and are convincing less by the price of a product rather than by high-class standards and high loyalty of delivery. A zero-defect production or manufacturing processes can be hardly reached, therefore, 100 % testing of the manufactured products is often necessary to do justice to the high quality standards and to reach a competitive advantage. An advantage can also be reached by the increased application of carbon fiber reinforced plastics (CFRP) in different industrial branches, like in the automotive or in the aviation industry, by weight savings. By the application of new materials the joining technology is also of essential interest. The claim of the security relevance becomes particularly obvious if for joining, the adhesive technology is used. The advantage of this joining technology is, in spite of low weight to reach high demands for the rigidity and stability. The application of non-destructive testing methods in this area is gaining in. If new materials like CFRP and the joining technology infers it is necessary to verify the quality of the bonded joint. A procedure which admits reliable statements about the adhesive bond is necessary moreover. A non-destructive testing method which meets the requirements for these demands is the active thermography.

1 Thermal Sensors

A part of the IR radiation going out from an object is displayed with optics which shows the transmission $\tau$ on a sensor element and is absorbed by this (Figure 1: action principle of thermal sensors, $\Delta \phi_r$ radiant flux of the object, $\Delta \phi_s$ radiant flux of the sensor, $\tau$ transmission of the optic, $\Delta T$ temperature difference, $\Delta U$ output voltage of the sensor). Thereby a temperature difference $\Delta T$ arises in the sensor element, which is leading to a change of an electrical quantity, though. Depending
on the type of sensor there is a changing value of electrical resistance ($\Delta R$, bolometer), electrical charge ($\Delta Q$, pyroelectric sensor) or electrical voltage ($\Delta U$, thermoelectric sensor).

Figure 1: action principle of thermal sensors

Thus the temperature change is very big in the sensor element; this must be isolated thermally very well to not be influenced by neighboring elements. Figure 2 shows the construction of one pixel of a microbolometer array like it is installed in the infrared camera which is used for this work.

Figure 2: microbolometer element

A pixel is performed as a MEMS element (Micro-Electro-Mechanical Systems) with an upset resistance layer. The resistance bridge above the selection circuit is about 2.5µm. The incident infrared radiation is absorbed by the micro bridge. This is leading to a change of temperature $\Delta T$ and therefore a modification of resistance $\Delta R$. To ensure the thermal isolation, the micro bridge is located into vacuum. Besides the construction (leg supports and bridge) enables a lower thermal conductance to the selection circuit, which can be assumed as thermal mass[1].

1.1 Thermal resolution

The thermal resolution of a sensor element can describes with the NETD (Noise Equivalent Temperature Difference). It declares the smallest resolvable temperature difference of an object. This value is mostly given for objects with a temperature of 27°C, whereas the aperture of the lens is assumed by one.

1.2 Geometric resolution

The spatial or geometric resolution describes the capability of a system to separate nearby structures of an object. The geometric resolution is limited by the Fraunhofer-diffraction. The smallest illustratable measuring point is the Airy-slice, which arises by the Fraunhofer-diffraction on a perforated disc.

1.3 Temporal resolution

The temporal resolution describes the capability of a system, to detect temporal subsequent temperature changes of an object; it is described by the time constant $\tau$. In a microbolometer the time constant is defined by the behavior of the micro bridge[1].
2. active thermography

To identify failures in adhesive bonds between CFRP-components, there are various thermography processes which were developed in the last years. This various processes can be distinguished by the excitation which is used. Firstly, on all active thermography processes, a thermal flow will be generated and the subsequent balancing process within a certain period will be observed. Additionally, the various processes can be distinguished in qualitative and quantitative thermography processes. The so called active thermography is characterized by generating a thermal flow into a component by different excitation sources. Different thermal conductivity within the component is leading to temperature differences at the surface of the component which can be measured. As contactless excitation sources for generating a thermal flow, mostly optical sources in visual spectrum (halogen lights, flash lights or laser) or infrared spectrum (quartz- or carbon radiators) are used. Components made of metal can also be excited inductively by eddy current. Furthermore, a thermal flow can be generated by ultrasonic. Depending on the position of the infrared camera and the excitation source relative to the surface of the component a distinction can be made between reflection (Figure 3) and transmission setup.

Figure 3: active thermography in reflection configuration

Choosing a suitable setup occurs appropriate to the accessibility and the depth of a relevant defect. For the analysis of the recorded data with regard to possible defects, three methods come into consideration. These methods are called pulsed thermography, lockin thermography and pulsed phase thermography[2].

1.1 pulsed-thermography

Pulsed thermography is based on a high-energy pulse which is bringing the component into a thermal instationary status. For analysis the procedure of excitation and decay behavior is observed. The excitation for pulsed thermography is a high-energy pulse which is as short as possible. The thermal excitation can occur either inside or outside of a component. The heat sources for pulsed thermography should have a preferably wide and homogeneously distributed thermal flow density.

2.2 lockin-thermography

Just like the pulsed thermography, the lockin thermography is used to detect defects in components. The lockin thermography is using continuous sine signals of a defined frequency for excitation. The modulated response signal is recorded by an IR-camera and analyzed relating to pulse and phase. The lockin thermography is using digital Fourier transformation for the lockin-technique by four measurement points each period for every pixel of the infrared image. The phase data is of particular interest because it is almost independent of external perturbation[3].

2.3 pulsed-phase-thermography
The pulsed phase thermography was introduced to combine the advantages of the pulsed thermography and the lockin thermography:

- pulsed thermography: rapid data acquisition with flexible setup and with a high-energy pulse suitable for a larger surface
- lockin thermography: a better resolution for the depth and a smaller influence of optic and infrared perturbation

The pulsed phase thermography is using the Fourier transformation according to the method of the pulsed thermography. The results of the pulsed thermography on the time level remain entirely and are only replenished by the results of the frequency domain[4].

2 continuous inspection with thermography

To inspect adhesive bonds between reinforcement components and shell elements made of CFRP with non-destructive testing, a continuous inspection process is appropriate. With this alternative approach of testing the positioning time for the inspection system is eliminated and with the displacement of the failure contrast measurement, a distinctly shorter inspection time can be reached. This is in case of large component assembly leading to smaller cycle times, lower costs and establishing a competitive advantage. Figure 4 shows the setup for active thermography in reflection configuration for continuous testing. Here, the component which has to be inspected is passed over by the inspection system with the velocity v, which is adapted to a light weight robot with a defined path. As a result the excitation source with the intensity $I_{exc}$ and the effective excitation width e is moving in a defined distance to the infrared camera over the component. A continuous heating of vertical component areas occurs.

![Figure 4: process parameters of the continuous inspection](image)

First of all, the amount of parameters must be restricted to identify the optimal process parameters by design of experiments. Figure 5 shows two characteristic cooling curves which represent the temporal temperature behavior of an intact and a failure containing component area. If defects are contained in the adhesive layer, a failure contrast is visible after a certain time $t_1$ which is reaching its maximum at the time $t_{max}$ and disappears until $t_2$. 
Figure 5: characteristic cooling curves of an intact and a failure area

Depending on what defect the adhesive layer consists, different characteristic times after a thermal excitation occur. The smallest measurable defect in the adhesive layer $d_{min}$ is limited by the geometric resolution. Due to this reason, at a given velocity only a particular temporal sector of the balancing process can be detected. To optimize the probability of defect detection, the excitation source is positioned ahead of the IR camera in such a way that the most significant measurable failure contrast occurs while the camera with the detection area $A$ is into the position just above the component. The best distance between excitation source and IR camera can be defined by the time $t_{max}$ and the velocity $v$ of the lightweight robot. Therefore the cooling curves are measured in static test setup [5].

3 results

3.1 specimens

In order to enable a quality assessment about defects in adhesive bonds between CFRP components, the performance and the provability of the inspection system has to be specified. To achieve this objective, specimens with different defects were produced. At this point of the contribution it should be noticed that a standardized specimen such as for ultrasonic testing is available does not exist yet. Figure 6 shows how to simulate different kinds of defects into the adhesive layer:

Figure 6: template to establish specimens containing defects

To gain a better access for measuring, a single adhesive layer for each kind of defect was made.

3.2 parameter setting of the continuous inspection
After optimal process parameters are specified, the geometric setup of the inspection system can be build up. Based on the smallest measurable defect, firstly the appropriate image field of view must be chosen. The smallest measurable defect must be mapped on three pixels at least to enable a safe distinction of the measured noise. In a subsequent step, a suitable excitation source must be selected. This excitation source must be comparable in intensity and resulting pulse length to the source which is used in the static test setup. The length of the pulse can be adapted by an aperture which is attached in front of the excitation source. The area which is available for data acquisition can be calculated by the detection area $A$ and the velocity $v$.

![Results of continuous testing](image)

Figure 7: results of continuous testing, the upper CFRP layer was 1.5mm

4 summary

In this contribution, the advantage of an inspection system which is using active thermography to detect defects in adhesive bonds between CFRP components is shown. The advantage is due to the continuous testing process which is enabled by adapting the inspection system on a lightweight robot. Cycle times are reduced because the positioning time of the robot and the thermal balancing process within the component are eliminated. Additionally the automation of the entire method is simplified.
References

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