Remote Sensing of Temperature-Stress Coupled Effects

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Abstract— **The aim of this paper is concerned with the use of an infrared imaging device to measure the very small temperature variations which are linked to thermo-elastic effects. The latter are associated with material volume variations undergone by a cantilever beam under cyclic bending load. This is a difficult task since the temperature variations are very small and at the edge of the instrument resolution. However, with the aid of a reference sample it is possible to eliminate most of the instrumental and environmental noise so as to obtain reliable measurements. This method allows extending the use of an infrared imaging device outside its resolution range.**

Keywords-infrared thermography; cyclic bending; thermo-elastic effect; temperature variation; radiation sensing.

I. Introduction

Temperature represents a key parameter in almost all the industrial processes. In particular, owing to composite materials, the production of a sound laminate strongly depends on the processing temperature. In fact, the polymerization cycle of a thermoset matrix based composite is generally performed in autoclave and strongly depends on the temperature ramp and absolute value. However, temperature is important also for the forming of a laminate involving a thermoplastic matrix. The possibility to obtain a laminate free, or of low content, of porosity strongly depends on the combination of temperature and pressure during the fabrication process. In these cases the temperature values to be controlled are quite high and measurable with different types of sensors.

It is not easy to measure very small temperature variations, which can be easily affected by the several sources of error that are always present and which become progressively more important as the quantity to be measured becomes smaller. Of course, the measure becomes more complex in the presence of dynamic, or unsteady, phenomena. As an example, trying to measure the temperature variations, which develop over the surface of a cantilever beam under cyclic bending tests, may be a very difficult task.

This measure appears complex from two points of view. On one side, depending on the material under test, the temperature amplitude may be very small. On the other side, the temperature variations are generated by the oscillation of the sample and depend on its geometry.

Then, no contact sensors are allowed since their presence can alter the geometry and jeopardize the measurement. In addition, contact sensors suffer from contact resistance and are vulnerable to thermal conduction effects, which also affect the measurement accuracy. The only solution may be to perform measurements through remote detection of thermal radiation, which mainly means with infrared thermography (IRT). Indeed, IRT thanks to its non-contact character and its multifarious applications, is consolidating increasing attention from both the industrial and academic communities.

In particular, IRT has proved its capability to visualize the surface temperature variations, associated with thermo-elastic/plastic effects, which are experienced by a body under load [1][2]. These temperature variations supply information useful for assessing the material's characteristics and performance. This represents a great advantage since it makes possible getting information on the material by simply monitoring it under load. This can be done using the thermo-elastic equation [3], which expresses the change in temperature (ΔT) of a solid in terms of the change of the sum of the principal stresses ($\Delta\sigma$). In particular, under adiabatic conditions, positive dilatation (tension) entails cooling of the material and vice-versa.

In this regard, a difficult task is to perceive the temperature variations which develop under relatively low loads. In these circumstances, a detector able to sense the small difference in thermal radiation, associated with light surface temperature variations, is required. Previous works [4][5] showed that a long wave (LW) quantum well infrared photodetector (QWIP) is well suited for sensing the small thermal radiation associated with thermo-elastic phenomena, but the QWIP is affected by noise, mainly dark current, effects [5]. This noise exhibits a random temporal character that cannot be easily removed through the commonly in use signal restoration methods. Conversely, it seems that it can be accounted for and suppressed in a simple manner with the use of a reference area [4][5].

The aim of this work is to further investigate the reference-area method by highlighting its potential and likely limitations for a better exploitation of infrared imaging devices in presence of feeble thermal radiation.

Apart from the introduction, the structure of this paper includes four sections. In particular, a description of the test setup and the testing procedure is given in Section II, to follow in Section III with some theoretical hints, which justify the use of infrared thermography to monitor cyclic bending tests. Section IV, which represents the core of the work, is involved with post-processing of thermographic images. In particular, it is shown how the reference area method is effective to account for and eliminate most of the instrument and environmental noise; this is illustrated with some key examples. The work ends with some concluding remarks and future trends.

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II. EXPERIMENTAL

The reference-area method can be deployed in different applications and for different purposes. In the following, an example of application concerning cyclic bending tests is illustrated. This involves the measurement of very small temperature variations and is well suited for the purpose.

A. Test Setup and Procedure

The test setup is shown in Fig. 1. The specimen bending is operated with an electro mechanical actuator through a taut wire and a return spring. As it can be seen, two specimens are clamped nearby on their bottom side (fixture) as cantilever beams. One remains unloaded and is used as source to apply the reference-area method. The other one (the specimen under test) is inserted, with its upper end, into a clip attached to the wire which forces the specimen to bend back and forth under the wire alternate displacement.

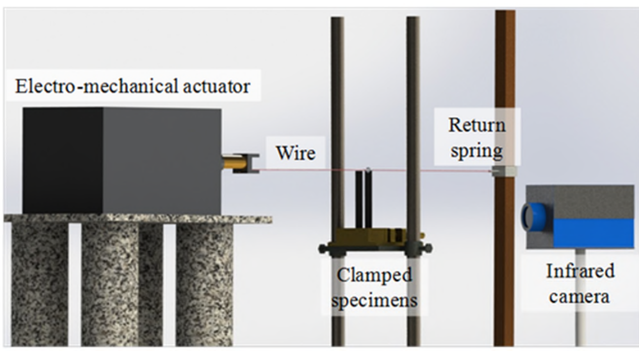

Figure 1. Setup for cyclic bending tests

The infrared camera is positioned so as to see both specimens at once (from one surface). The used infrared camera is the SC6000 (Flir systems), which is equipped with a QWIP detector, working in the 8-9 µm infrared band, NEDT < 35 mK, spatial resolution 640x512 pixels full frame with the pixel size 25 µm x 25 µm and with a windowing option linked to frequency frame rate and temperature range. Sequences of thermal images are acquired during loading, or better, to allow for a complete visualization of thermal effects evolution with respect to the ambient temperature, the acquisition starts few seconds before load application and lasts for some time after.

III. SOME THEORETICAL REMARKS

The case study involves variations of temperature induced by thermo-elastic effects, which can be traced to the classical thermo-elastic equation, formulated by Biot [3]:

$$\Delta T = -KT_a \, \Delta\sigma \qquad (1)$$

which expresses the change of temperature (ΔT) of a solid in terms of the change of the sum of the principal stresses ($\Delta\sigma$). In particular, T_a is the absolute body temperature, $\Delta\sigma$ is the mean stress amplitude, and K is the material thermo-elastic constant. Equation (1) relates the temperature variations to the volume variations and applies to isotropic materials under reversible and adiabatic conditions (i.e., in the elastic regime and neglecting heat transfer within the body and to the environment). Under adiabatic conditions, positive dilatation (tension) entails cooling of the material and vice-versa.

The interest is to extract ΔT values from the sequences recorded during cyclic bending. The amplitude of ΔT values, for a given material, depends mainly on the location over the specimen length, i.e., the distance from the fixture and on the bending frequency if temperature relaxation occurs.

IV. IMAGE PROCESSING AND DATA ANALYSIS

The recorded sequences undergo post-processing by using the Flir ResearchIR software (available from the Flir systems package) and specific routines developed in the Matlab environment [4]. The first image (t = 0 s) of the sequence, i.e. the specimen surface at ambient temperature, before starting of loading, is subtracted to each subsequent image so as to generate a map of temperature difference ΔT:

$$\Delta T(i,j,t) = T(i,j,t) - T(i,j,0) \qquad (2)$$

i and j representing lines and columns of the surface temperature array. Several measurement positions, as depicted in Fig. 2, are considered over solicited (A) and unsolicited (P1, P2, P3) specimens.

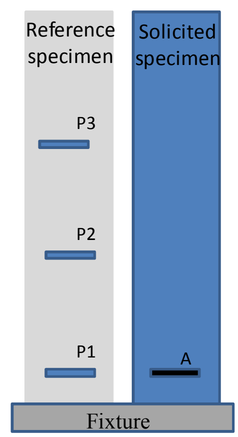

Figure 2. Sketch of measurement positions over the two specimens

A. Some Examples

A ΔT plot is extracted in the position A (i.e., close to the fixture) and is shown in Fig. 3. In more details, the resulting curve corresponds to the mean value in an area of width 40 pixels and height 20 pixels by suppressing, of course, border appraisals. This plot refers to the original raw signal ΔT_R taken with cyclic bending at a frequency f_b = 0.8 Hz. As it can be seen, ΔT_R displays quasi-sinusoidal variations coupled with the cyclic load; more specifically ΔT_R goes up and down following the alternate tension/compression load. However, the sinusoidal trend is not a regular one, but disrupted by a jumping-like effect that is due to the instrument noise [5].

To separately account for the instrument noise ΔT_N, a plot is meanwhile extracted on the unloaded reference specimen and shown in Fig. 4. In particular, the ΔT_N curve corresponds to the mean value in the P1 zone, which is placed at the same distance from the fixture of the zone A and has its same dimensions (see Fig. 2).

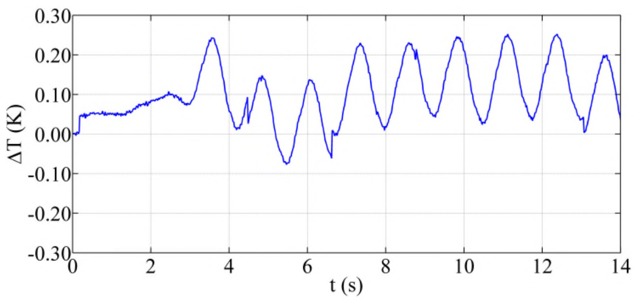

Figure 3. ΔT_R plot for f_b = 0.8 Hz

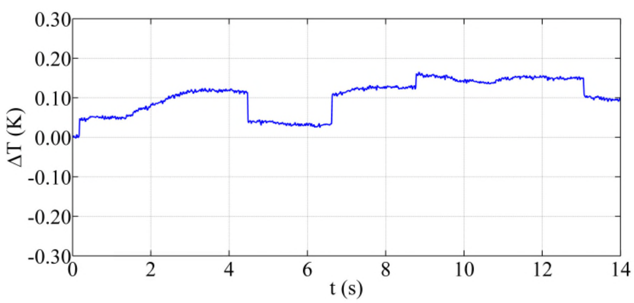

Figure 4. ΔT_N plot over the unloaded specimen

By comparing Fig. 4 to Fig. 3, it is possible to clearly distinguish the detrimental effects the random noise has on the quasi-sinusoidal pattern. Such effects include macro (jumps) and micro (slight slopes) scale phenomena. The two plots ΔT_R and ΔT_N are characterized by the same trend, even if they are extracted from two different zones, i.e. one on the specimen under test (Fig. 3) and the other one on the reference specimen (Fig. 4).

As a major effect, the quasi-sinusoid has lost the alignment of peaks and valleys with respect to the horizontal axis. These displacements of the ΔT_R signal are perfectly coupled with the position of ramps and jumps in the ΔT_N signal. In particular, by looking at the first portion of Fig. 3 within the first 2.5 seconds (before starting of the bending) it is possible to see that, by changing zone, the noise amplitude remains the same. In fact, on both graphs, $\Delta T = 0$ for t = 0, but soon after ΔT undergoes an abrupt rise, followed by a steadiness and then a ramp.

To better underline this aspect, three ΔT_N plots, taken in three different zones P1, P2 and P3, are compared in Fig. 5. As depicted in Fig. 2, the three zones are differently displaced along the reference specimen, with care to avoid boundary effects. In particular, P1 represents the zone from where the ΔT_N signal already shown in Fig. 3 has been extracted.

Looking at Fig. 5 it is possible to see that the three signals are practically superimposed. More specifically, they are perfectly superimposed with regards to the appearance of jumps in time, which means the macro-scale temporal noise. Instead, small variations of amplitude can be discriminated by changing zone. Such variations may be ascribed to several factors involving either the spatial noise of the instrument, or environmental noise, or surface emissivity changes. This type of noise, whatever its origin, is very small and surely negligible with respect to the major temporal component.

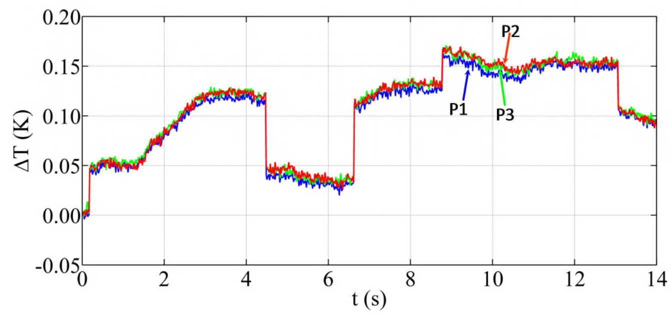

Figure 5. ΔT_N plot in three places over the unloaded specimen

B. Noise Correction

First of all, the correction is intended to eliminate temporal noise while spatial noise is considered as negligible. The noise can be eliminated through correction by the use of the unloaded reference specimen [4]. The signal in the reference specimen, which accounts for the noise ΔT_N, is subtracted from the original raw signal ΔT_R. Then, the corrected ΔT_C signal is obtained as:

$$\Delta T_C = \Delta T_R - \Delta T_N \tag{3}$$

An example of corrected ΔT_C signal is shown in Fig. 6, which is practically the result of the subtraction of Fig. 4 from Fig. 3. As it can be seen, the noise is eliminated and a sinusoidal pattern is practically recovered, which perfectly synchronizes with the specimen alternate displacement. In addition, also the constant (on the average) $\Delta T = 0$ value in the first portion before starting of the load is recovered.

It is worth underlining that the correction method appears able to eliminate different types of noise: the jumps effect, but also the slight ramp effect like that present in the first portion of the ΔT_R signal of Fig. 3.

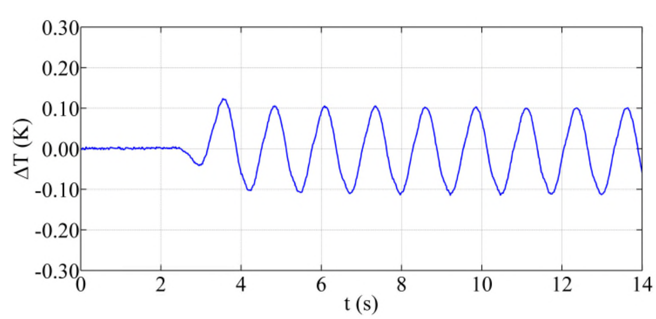

Figure 6. Corrected ΔT_C plot for f_b = 0.8 Hz

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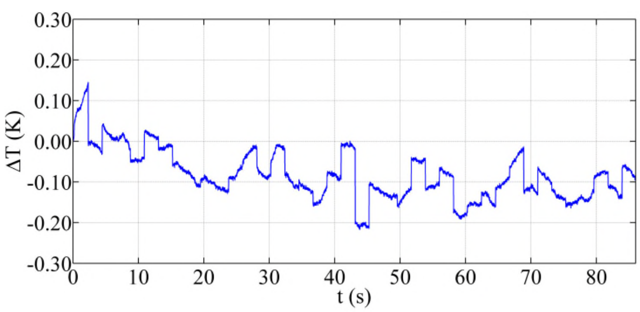
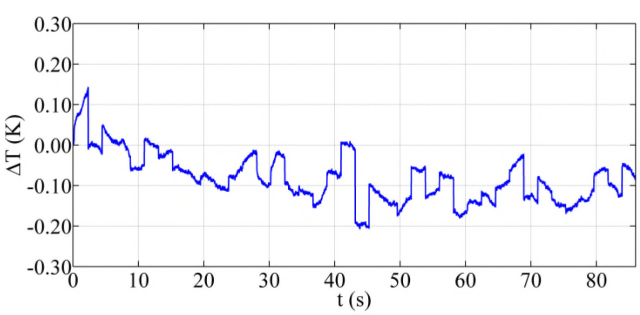
Of course, the noise effects become ever more pronounced as the ΔT amplitude decreases. Thus, to further investigate the effectiveness of the reference-area method, a much lower amplitude signal is analyzed. This signal is obtained by recording thermal images in time sequence during cyclic bending at the lower frequency of f_b = 0.05 Hz. The three signals ΔT_R, ΔT_N. and ΔT_C are compared in Fig. 7.

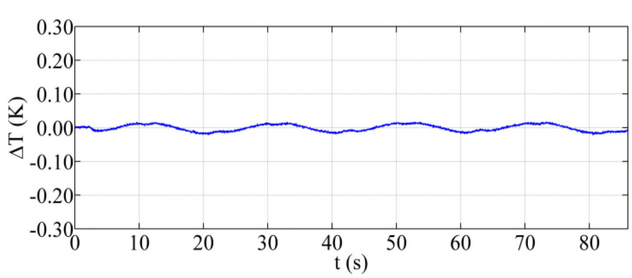
The first thing to notice is the predominant effect of the instrument noise. In fact, by comparing Fig. 7a to Fig. 7b, it is practically impossible to distinguish any difference between ΔT_R and ΔT_N trends, or better between the solicited specimen and the unsolicited one. It is worth noting that the ΔT_R signal has been recorded with a specimen undergoing cyclic bending at frequency f_b = 0.05 Hz and deflection D_F = ± 7.5 mm. The temperature variations associated within this pair of parameters are very small and then, it is normal to see the noise fluctuations to prevailing and completely disrupting the sinusoidal pattern (Fig. 7a) produced by the thermo-elastic effects. Surprisingly, the sinusoidal pattern is again recovered (Fig. 7c), through correction with the reference-area method.



a) ΔT_R



b) ΔT_N



c) ΔT_C

Figure 7. ΔT_R , ΔT_N and ΔT_C plot for bending at f_b = 0.05 Hz

However, the resulting ΔT_C signal is very small to be exploited for material characterization purposes. In fact, it is affected by heat transfer mechanisms and other phenomena, which should be taken into account to make the ΔT values usable, but this is outside the aim of this work and is not herein discussed.

V. Conclusion and Future Work

Through some practical examples, it has been shown that it is possible to use an infrared imaging device to detect and also evaluate also the feeble thermal radiation, which is of the same order of magnitude as the instrument noise and that is commonly considered outside the instrument resolution range. In particular, it has been demonstrated that this is possible with the help of a reference area, which allows for estimation of the instrument noise. Then, the noise is separately evaluated and eliminated from the raw signal.

It is worth noting that cyclic bending tests have herein been used as reference, for convenience, since the sinusoidal pattern coupled with the specimen alternate displacement is well suited to demonstrate the validity of the method. In fact, by changing the bending frequency and so the amplitude of the sinusoid, it has been possible to visualize noise effects of different types and of different orders of magnitude. In addition, the capability of the method to either restore a fairly affected curve, or recover a completely destroyed one, has been demonstrated.

Conversely, this method can be exploited in a broader context whenever the measurement of small variations of temperature is required. Of course, this method may be applied to a larger extent, even in the presence of not-too-small values that are less affected by noise. It is worth nothing that the possibility to perform measurements with a remote imaging device offers countless benefits. Amongst them, it prevents any alterations to the testing objet and to the quantity to be measured. But, it eliminates also the trouble of placing a great number of contact sensors and managing with cables. As a last point, it can be inferred that, with the application of this simple method, it becomes possible to resolve small variations of temperature, which may be otherwise impossible.

As future work, we will investigate other study cases such as monitoring composite materials under impact tests with an infrared imaging device. Indeed, due to the ever broad deployment and development of composites, assessing their resistance under impact is of great concern to both academic and industrial communities. While it has already been demonstrated the capability of infrared thermography to catch thermal signatures induced by impact tests [6][7], outlining in an accurate way the boundaries between sound and damaged zones remains still an open question. This task, due to the small size of temperature variations at these boundaries, may benefit of the application of the reference area method. On the other hand, the evaluation of the extension of the damaged zone is very useful for material design purposes to assess the material performance.

However, in the future, this method may be improved and exploited in other study cases to get the best from thermographic images also in consideration of the vast variety of applications which may be addressed with infrared thermography.

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