Evaluation of a low-cost setup for quantitative Thermoelastic Stress Analysis

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Abstract. An uncooled microbolometer and a cooled sensor IR camera are simultaneously used to measure the temperature and evaluate the thermoelastic signal from Tensile and Single Edge Notched Tension steel samples, under fatigue loading. The attenuation in the thermoelastic signal measured with the microbolometer is characterised, allowing to evaluate a correct Stress Intensity Factor.

Introduction

Thermoelastic Stress Analysis (TSA) provides full-field stress information on cyclic-loaded materials and structures, after a relatively quick data-processing of thermograms, sampled over a short time window by IR cameras. Since its first appearance in the late eighties, diffusion of TSA has been rather limited, considering the extent of potential application fields and case studies. Two main reasons are believed to have hampered such TSA diffusion: the high costs of cooled sensor IR-cameras, required for optimal temperature measurement; a low awareness of the data-processing, which can be easily developed in-house rather than committed to closed-box and sometimes IR-camera manufacturer dependent commercial codes.
Recently, Rajic et al. [1] have investigated the implementation of TSA with lower-cost, handier microbolometer sensors. They have shown that cross-correlation of temperature data achieves low noise-to-signal ratios, comparable to those obtained with cooled sensors, thus making microbolemeter+TSA able to detect stress concentration features at least in a qualitative way. Some works have started to exploit this outcome, proposing portable and efficient setups for structural health or crack-growth monitoring applications [2–4]. More recently, Jimenez-Fortunato et al. [5] performed some calibration tests on tensile samples, showing that the thermoelastic signal attenuation ratio is not dependent on the load amplitude applied, and a semi-logarithm law was proposed to model the influence of the loading frequency. Such approach suggests a specific calibration procedure to evaluate useful quantitative data from TSA performed with microbolometers.

Experimental setup

In this work, two IR cameras: a microbolometer Flir A655sc and a cooled Flir X6540sc are used simultaneously, each staring at a different face of the sample. A tensile coupon (T) is analysed first, to investigate the behaviour of the thermoelastic constant with varying load amplitude, loading frequency (Lf) and temperature sampling frequency (Sf). A Single Edge Notched Tension (SENT) sample is then tested in Mode I, load ratio R=0.1 and in presence of a fatigue-grown crack, to evaluate the Stress Intensity Factor (SIF).
The temperature is collected over a time of 60 s and processed in MATLAB according with the following steps:

1. The time interval between each grabbed thermogram is retrieved from the IR-camera software Flir ResearchIRmax v. 3.4. This allows to check for the absence of frames, likely to occur with both Giga-ethernet and USB interfaces between the IR-camera and the PC. In fact, even a sporadic loosing of frames is found to generate significant errors. In this work the missing frames are artificially restored by generating an averaged frame between the previous and successive acquired thermograms.
2. The signal from a sample local area is then analysed with the Discrete Fourier Transform (Matlab *fft*) to identify the frequency carrying the thermoelastic signal. An algorithm is implemented which optimises the number of frames to eliminate spectral leakage caused by the discrete sampling (see Fig. 1a and [6]).
3. A filtering operation is performed on each sample pixel to evaluate the amplitude and phase components of the thermoelastic harmonic, by cross-correlating the measured temperature with a reference signal built upon the frequency determined at stage 2 (Fig. 1b shows an example of amplitude map) [6].

The SIF in the SENT sample is calculated from the $\Delta(\sigma_x+\sigma_y)$ stress map, obtained after measuring the thermoelastic constant *C* from the T sample, according to the Thermoelastic law:

$$\Delta T = -T_o C_{th} \Delta\left(\sigma_x + \sigma_y\right) \quad (1)$$

The SIF is obtained with a least square fitting of the Williams' series model, using 5 terms and an annular fitting-area centred around the crack tip, with fixed min and max radius. The crack tip is identified as the one maximising the R^2 coefficient, applying the procedure iteratively over a small guess area [7].

Results and discussion

Tensile tests have been performed with 4 stress amplitudes, $\Delta\sigma$=57.3±(10.4, 26, 36.5, 46.9) MPa, 5 loading frequencies, Lf=1, 3, 5, 10, 15 Hz and 3 sampling frequencies, Sf=12.5, 50, 200 Hz.

In the casa of data measured with the A655sc, and for each combination of Lf and Sf, the R^2 value of the linear regression of ΔT vs $\Delta\sigma$ was comprised between 0.9996 and 0.9999. Figure 1c plots values of the logarithm of the inverse thermoelastic constant ln(1/C_{th}) versus Lf. It is seen that data from the X6540sc are horizontal and overlap for each Sf, as expected. Data from the A655sc exhibit a thermoelastic constant attenuation with the loading frequency. This attenuation is well interpolated with a linear regression, confirming results from [5]. It is here noticed that curves at Sf of 12.5 and 50 Hz are almost overlapped, while the curve at Sf=200 Hz has an unexpected and significantly lower slope (smaller attenuation compared to the reference cooled sensor performance). It is noticed that the A655sc uses a full frame of 640×480 pixels at the frequencies of 12.5 and 50 Hz and a sub-windowed 640×120 pixels frame at 200 Hz. This means that the number of data to be sent to the read-out circuit of the FPA sensor is smaller at Sf=200 Hz, and this could somewhat allow the sensors to collect more irradiated energy and thus reduce the temperature signal attenuation.

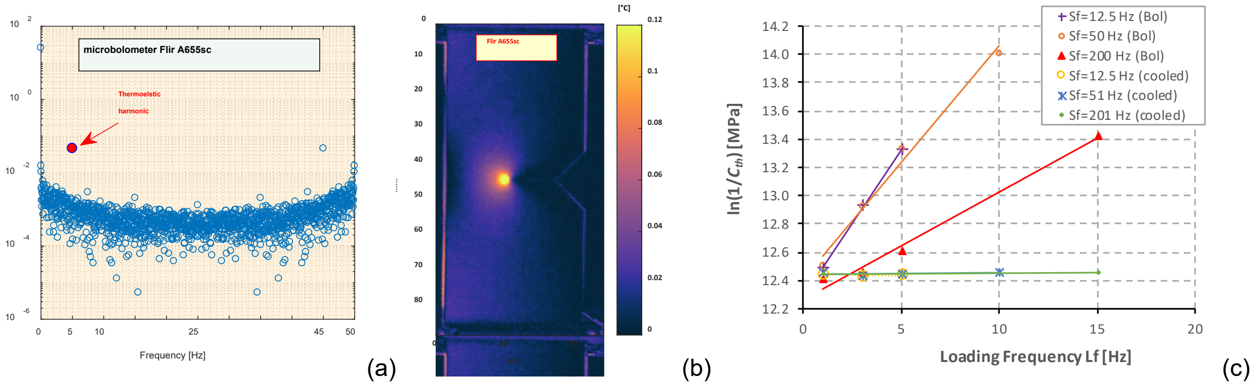

Fig. 1: a) power spectrum of the temperature from a point after spectral-leakage correction; b) map of thermoelastic signal from A655sc; c) Semi-log plots of 1/C_{th} at various load freq., sampling freq. and IR-camera type.

Fig. 1b shows a map of the thermoelastic signal from the SENT specimen (loaded between 500 and 5000 N). It is observed that the microbolometer camera is able to retrieve the correct shape of isopachic contours, since the signal is only rescaled by a constant coefficient. If the true material thermoelastic constant were used, the value of the SIF would be smaller than that calculated with the cooled sensor, by an attenuation factor that is the same of that evaluated in the tensile tests and modelled by the curves in Fig. 1c. Table 1 reports the SIF calculated with the cooled sensor, compared with those obtained with the microbolometer sensor, using a calibration constant C_{th} derived from Figure 1c for each value of Sf and Lf.

Table 1: Values of the SIF in [MPa×m0.5]

Sf [Hz]	50		200	
Lf [Hz]	5	10	5	10
X6540sc	*13.96 ± 0.27*			
A655sc	*12.99*	*14.90*	*13.61*	*13.50*

Conclusions

The present work concludes that microbolometer sensors still provide an excellent linear correlation between the thermoelastic effect induced temperature change and the stress change, even if now the thermoelastic constant is attenuated and becomes dependent on the loading frequency and, to some extent, on the sampling frequency. The Stress Intensity Factor (SIF) obtained with the microbolometer sensor is close to that obtained with the cooled sensor, if a modified thermoelastic constant is used, derived from the tensile tests performed at the same load frequency and sampling frequency.

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