Low-Cost Thermoelastic Stress Analysis

Melissa Weihrauch[1], Ceri Middleton[1], Richard Greene[2] and Eann Patterson[1]

[1] School of Engineering, University of Liverpool,
The Quadrangle, Brownlow Hill, Liverpool, L69 3GH, U.K.

[2] Strain Solutions Ltd, Dunston Innovation Centre,
Dunston Road, Chesterfield, Derbyshire, U.K.

ABSTRACT

The popularity of thermoelastic stress analysis (TSA) has been hampered by the high capital cost of the equipment, the need for a cyclic load and for a surface with uniform emissivity. Current commercially-available TSA systems allow data to be collected when the component of interest is subject to random loading which has broadened the potential applications of TSA. Recent work has shown that matt black paint, which is traditionally applied to achieve uniform emissivity, is not necessary and aerospace primers are adequate for TSA work. At the same time, a number of investigators have explored the use of microbolometers as a lower cost alternative to the staring array cameras that form the core of the commercially available TSA systems and are a major component of the high price tag. However, the cost of microbolometers is still measured in the thousands of dollars; and so, the use of low-cost, chip-mounted infrared sensors has been explored in the EU H2020 project INSTRUCTIVE. The results demonstrate that, using a simple algorithm implemented in MATLAB and a sensor costing a few hundreds of dollars, it is possible to obtain TSA data from a cyclically-loaded test specimen. The quality of the results is proportional to the investment in the sensor but nevertheless the low-cost affordable approach yields useful results and offers the potential for TSA to be used in structural health monitoring to provide early warning of damage to a structure.

Keywords: Thermoelastic Stress Analysis, Microbolometer, Damage tracking.

INTRODUCTION

Thermoelastic stress analysis (TSA) is a technique well-grounded in theory since its discovery over 160 years ago by Lord Kelvin [1]. In adiabatic conditions and under variable loading, temperature fluctuations observed in a body are proportional to the sum of its principal stresses. This has allowed the distribution of stress to be visualized by monitoring temperatures across a loaded object. Over the past decade, the technique has increased in use through the development and improvement in the resolution of thermal cameras and this has sparked interest in industrial applications [1-3].

The advantages of TSA are that it is a non-contact technique in which no laborious surface preparation is needed, as a result it is suited for *in-situ* applications. Objects can be continuously monitored while results can be obtained in near to real-time. Additionally, changes in stresses and stress concentrations, an indicator of crack initiation, can be detected and their propagation can be monitored [2]. This has led to industries, such as the aviation industry, showing interest in TSA as a method for early damage detection. However, the large capital cost associated with photon detectors that have historically been used for TSA is a major inhibitor of the technique’s use in damage detection [3].

More recently, microbolometers have been used as a relatively cheaper alternative to these traditional cameras [3]. Microbolometers have the added advantage of being lighter and smaller in size than photon detectors allowing them to be placed in hard to reach areas. However, these instruments still cost on the order of thousands of dollars, making simultaneous monitoring of large areas expensive. If costs can be reduced even further, using arrays of cameras to monitor objects and detecting damage over larger areas could become feasible. Hence, the use of low cost microbolometers has been explored in the EU H2020 project INSTRUCTIVE.

METHODOLOGY AND RESULTS

An uncooled VOx (Vanadium Oxide) microbolometer (*Lepton 3 from FLIR, Wilsonville, OR*) that is capable of capturing images at a resolution of 160 by 120 pixels at a frame rate of 8.7fps [4] was used. The microbolometer has a fixed lens assembly and can detect wavelengths between 8 µm to 14 µm, making the sensor suitable for operation at room temperature where peak photon emittance occurs at a wavelength of 12 µm. The microbolometer was connected to a Raspberry Pi 3 B+ (*Raspberry Pi, Cambridge, UK)* using a camera-specific break-out board (*Sparkfun, Boulder, CO*) and, hence, could be controlled remotely. The collected raw IR frames were given titles containing a time stamp with millisecond accuracy, which was later used to generate a reference signal for the processing of the TSA data and to more accurately estimate the frame rate of the sensor. A case to hold the Lepton and Raspberry Pi was 3D printed (see Figure 1). The sensor's small size of 11.50 x 12.70 x 7.14mm means that it can be placed in inaccessible or hard-to-reach areas.

Figure 1: Experimental setup to monitor crack propagation

The performance of the microbolometer has been evaluated in a series of fatigue tests, in which TSA data was computed using a short script written in MATLAB that was capable of estimating the test frequency under cyclical loading conditions. A specified number of raw infrared images were accumulated over a time period, during which corrupted frames were discarded, and the frame rate of the camera was estimated. A region of image containing the specimen was identified manually, and the values of the pixels within the region used to estimate the testing frequency. The Fast Fourier Transform (FFT) was computed for each selected pixel and the frequency corresponding to the maximum magnitude of each pixel found. The mode of these frequency results for the selected pixels was then taken to be the test frequency. A sinusoidal reference signal was generated using the obtained frequency and the time stamps associated with each frame. The product of the reference signal and the accumulated raw data was then found and the mean of these results along the time dimension was taken. Lastly, the resulting amplitude data were normalized by the mean value of the data field.

The fatigue test was performed using a servo-hydraulic test machine (*Instron 8501*, *Instron, Buckinghamshire*, *UK*) to load a rectangular 200 by 40mm aluminum 2024-T3 specimen with a 6mm diameter hole in its center to introduce stress concentrations. The aluminum specimen was covered by a thin Graphit33 coating (*Kontakt Chemie*, *Iffezheim*, *Germany*) to increase emissivity. Figure 1 shows the experimental setup used in the fatigue tests. The sensor was placed close to the specimen to maximize the amount of relevant information captured and ensured that most of the camera's field of view was the object of interest rather than the surroundings.

Fatigue tests were performed using cyclic loading at a nominal frequency of 1Hz with a maximum load of 17.90 kN and a minimum of 1.79 kN. The results in Figure 2 were obtained when the sensor was placed approximately 100mm from the specimen, whereas for those in Figure 3 the sensor was moved much closer to the specimen.

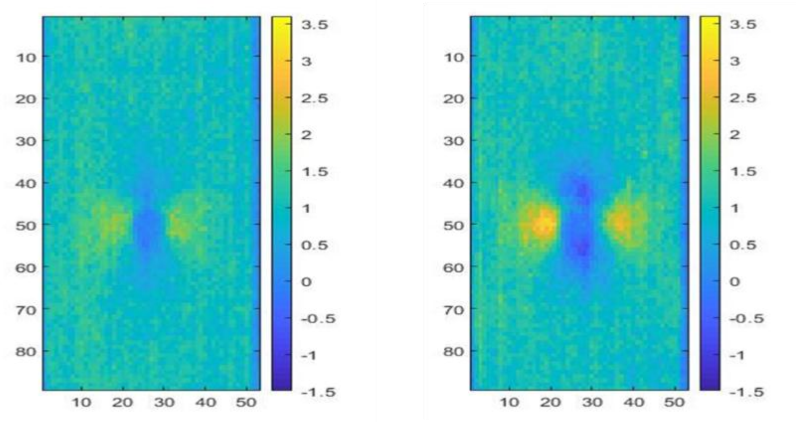

Figure 2: TSA normalized signal magnitude from a typical fatigue test acquired with the sensor approximately 100mm from the specimen (1 pixel = 1.325mm) at 3340 cycles (left) when no crack is apparent and at 8180 cycles (right) when cracks have initiated.

Figure 2 shows a comparison between the stress distributions detected in a sample before and after crack initiation. The color bar shows the values of a normalized TSA signal that is integrated over 128 frames, equivalent to approximately 15 seconds of collection time. In other words, 128 frames are collected and then processed cumulatively. The axes of the images are in pixels and 1 pixel is equal to 1.325mm. The images have been cropped to show the test specimen only.

The left image in Figure 2 was taken after approximately 3340 cycles and stress concentrations are visible adjacent to either side of the hole, indicating that a crack has probably not initiated yet. The image on the right shows the same specimen after 8180 cycles; the stress concentrations are higher in magnitude and have begun to move away from the edge of the hole, indicating that cracks have initiated and have started propagating towards the edges of the specimen from the hole. The crack on the right of the hole is possibly longer that the one on the left which causes some eccentricity to the geometry and causes more load to flow through the left ligament.

The TSA data in Figure 3 were acquired with the sensor placed closer to the specimen, which increased the magnification to 1 pixel = 2.425mm, i.e. almost twice the value in the other fatigue test. Similar observations can be made from Figure 3 at high magnification; however, the fixed lens on the microbolometer causes distortion of the image that could be corrected by image processing. As in the previous test (Figure 2), the initial image shows small stress concentrations adjacent to the hole; which are enlarged, more intense and starting to move away from the hole after 5600 cycles, suggesting the presence of two cracks. It would appear that the crack on the left is slightly longer causing eccentricity in the loading, so that more load is transmitted through the more substantial right ligament leading to a higher stress concentration.

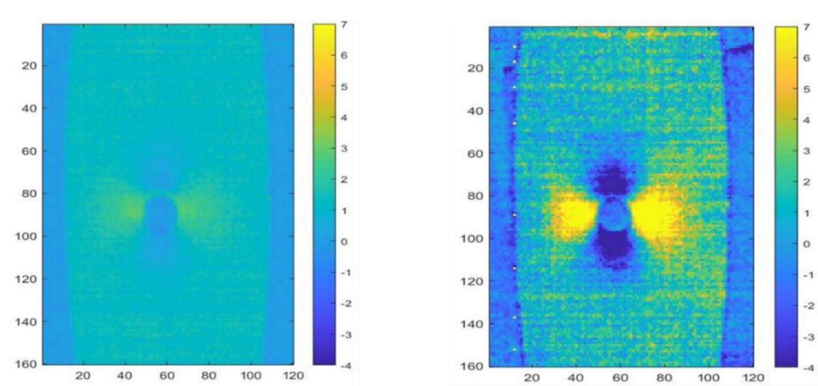

Figure 3: TSA normalized signal magnitude from a typical fatigue test acquired with the sensor approximately 55mm from the specimen (1 pixel = 2.425mm) at 574 cycles (left) when no crack is apparent and at 5600 cycles (right) when cracks have initiated.

DISCUSSION AND CONCLUSION

Fatigue tests monitored by an uncooled VOx microbolometer bought for a few hundred dollars have shown that useful TSA images can be obtained using a low-cost microbolometer. Tests on undamaged tensile specimens with a central hole initially yielded less severe and, hence, less visible stress concentrations; however, as cracks initiated the stress concentrations became more severe and visible, indicating that the technique could be used to identify crack formation. In a fatigue test performed on a pre-cracked specimen, during loading at 1 Hz at the same R-ratio as previous tests, but with a lower maximum load (11.6 kN), it was possible to capture data showing crack propagation. This is shown in Figure 4, where the stress concentrations associated with the crack tips have moved to the center of the ligaments.

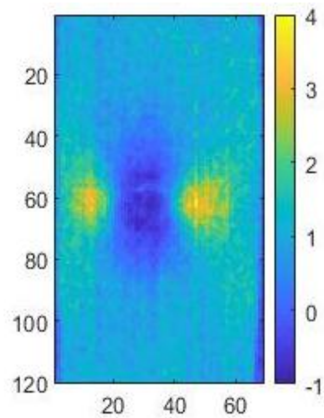

Figure 4: TSA data collected during fatigue crack propagation in a pre-cracked specimen, TSA data collected during loading at 1 Hz, with the sensor approximately 90mm from the specimen.

A challenge associated with using the Lepton 3 with its fixed lens is that for relevant data to be obtained, the sensor must be in close proximity to the object being monitored. A comparison of the results in Figures 2 and 3 shows that monitoring from relatively large distances is feasible even though it comes at the expense of resolution and sharpness of the image. Future work could attempt to improve results at large separations between camera and specimen using different lens assemblies. The low resolution of the microbolometer can also be compensated for through the use of arrays of sensors while additional information on crack propagation could be obtained by monitoring specimens from both sides.

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