A low-cost structural health monitoring device exploiting full-field imaging techniques for fatigue damage detection in aerospace structures

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1. Introduction

The early detection of damage in engineering structures during testing and in-service use is necessary for repair, replacement and/or redesign to be carried out. A range of NDE (non-destructive evaluation) techniques exist which can be used for structural health monitoring (SHM) and fatigue damage detection. These techniques include point-source and full-field techniques, where full-field techniques collect information from a larger region of interest than point-source techniques. For example, thermoelastic stress analysis (TSA) results in a map of surface stresses [1], whereas a map of strain can be calculated using digital image correlation (DIC) [2]. Areas of high strain or stress in these maps indicate locations where damage has occurred or may occur in the future, so monitoring changes in these maps over time will show how fatigue damage evolves.

The interpretation of full-field datasets, often presented as images, can be labour intensive, and when considering long tests or in-service use, a large number of datasets must be analysed. One approach towards a more automated interpretation is the use of orthogonal decomposition. This technique takes a two-dimensional dataset and describes it using a one-dimensional feature vector that is orders of magnitude smaller than the original dataset [3], [4].

Feature vectors therefore require less storage space than the original data, which is an important consideration if arrays of full-field sensors are to be deployed over months or years for long timescale testing or in-service use. It is also possible to use the feature vectors for quantitative comparisons between those datasets. By calculating the difference between the feature vectors representing two images, with the first (reference) image at a low or zero damage state, a measurement of how much those images differ can be found, thereby indicating changes due to damage appearance or growth.

Work carried out in the Horizon 2020, Clean Sky 2 project INSTRUCTIVE (INfrared STRUctural monitoring of Cracks using Thermoelastic analysis In production enVironmEnts) [5] showed the use of orthogonal decomposition of TSA data-fields to generate a quantitative measurement of crack growth during cyclic and flight-cycle fatigue loading. This work was compared to previously published crack length measurement methods, indicating that the decomposition technique gives comparable results to established approaches (Figure 1).

Data were initially collected with a traditional, high resolution photovoltaic detector, but the use of packaged and OEM (original equipment manufacturer) microbolometers was also explored, demonstrating that data from smaller, cheaper detectors could also be used with this approach, to produce a quantitative measure of damage propagation over time.

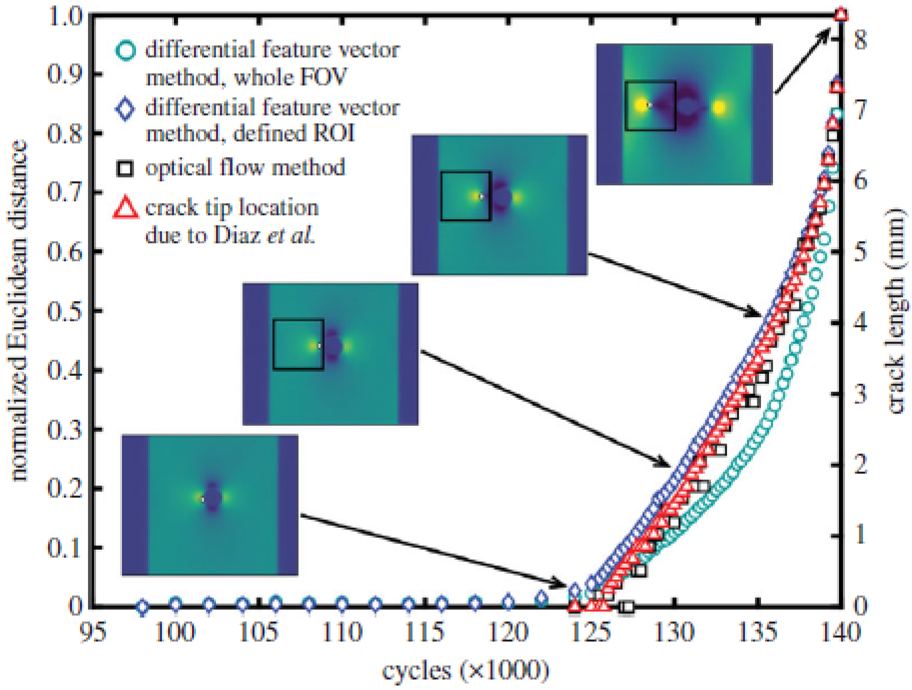

Figure 1. Feature vector difference (normalised Euclidean distance) against load cycles during fatigue crack growth monitored by TSA, insets show uncalibrated TSA maps at given times. Comparison with previous analysis (optical flow, Middleton et al [6]) and crack length measurement method from the literature (Diaz et al [7]). Figure from [5].

Technological developments in board computers and sensors have introduced the possibility that these techniques can be applied in industrial environments which were previously not possible due to spatial or budgetary constraints. The use of these centimetre-size sensors was explored further in the Horizon 2020, Clean Sky 2 project DIMES (Development of Integrated MEasurement Systems).

2. Low-cost SHM system

COTS (commercial-off-the-shelf) components were integrated to construct a sensor system which combines visible and infrared imaging with input from a resistance strain gauge (RSG). Sensor units, comprising a sensor module and a board computer module (Figure 2) can be deployed at regions of interest and connected to a control computer and network attached storage (NAS) server, which can be installed at a distance from the test object. Power and data transfer is achieved through an ethernet cable, and input is taken from a RSG installed locally to the field of interest. Several sensor units can be linked to one control computer, and a bespoke graphical user interface allows a user to both control data collection and access and visualise stored data.

Processing of infrared images makes use of the thermoelastic effect, but is uncalibrated, so is referred to here as CATE (Condition Assessment by Thermal Emissions), to distinguish from traditional TSA processing approaches. Raw data in the form of visible and infrared images are collected, and combined with RSG values and processed locally on the board computer (Raspberry Pi) to generate DIC and CATE outputs respectively. These datasets are processed further using orthogonal decomposition, resulting in a feature vector difference which can be monitored for indications of damage initiation and propagation.

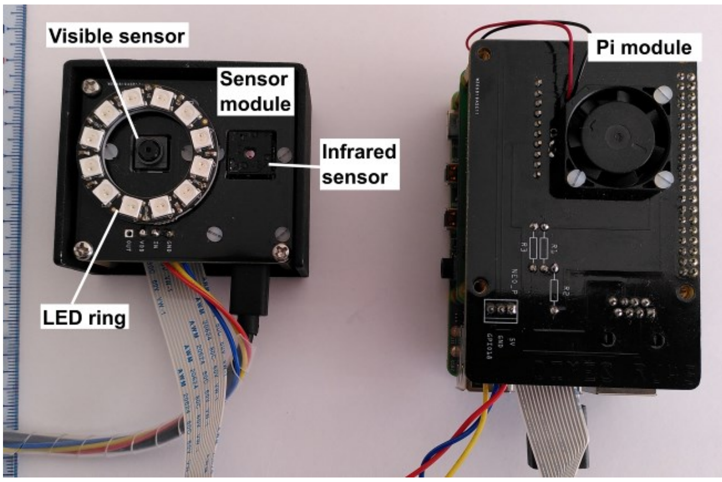

Figure 2. Sensor unit assembled from COTS components: sensor module (left) contains visible and infrared imaging sensors; board computer (Raspberry Pi) module (right). Scale in mm, from [8].

3. Laboratory testing

This system has been tested in the laboratory on coupon specimens, with a particular focus on data processing for extraction of damage information using the thermoelastic effect. Amjad et al. [9] showed that results from the OEM microbolometer are similar to those of the higher resolution photovoltaic detector for damage detection during cyclic loading, although crack detection occurs earlier with the higher resolution sensor.

As the cheaper infrared sensors have lower spatial, temporal, and thermal resolutions than sensors used for traditional thermographic techniques, delayed crack detection is not surprising. However, a slight delay in detection (on the order of millimetres) is likely to be offset by advantages in size, cost and replaceability of the OEM sensors (£100s) when compared to photovoltaic detectors (£10,000s).

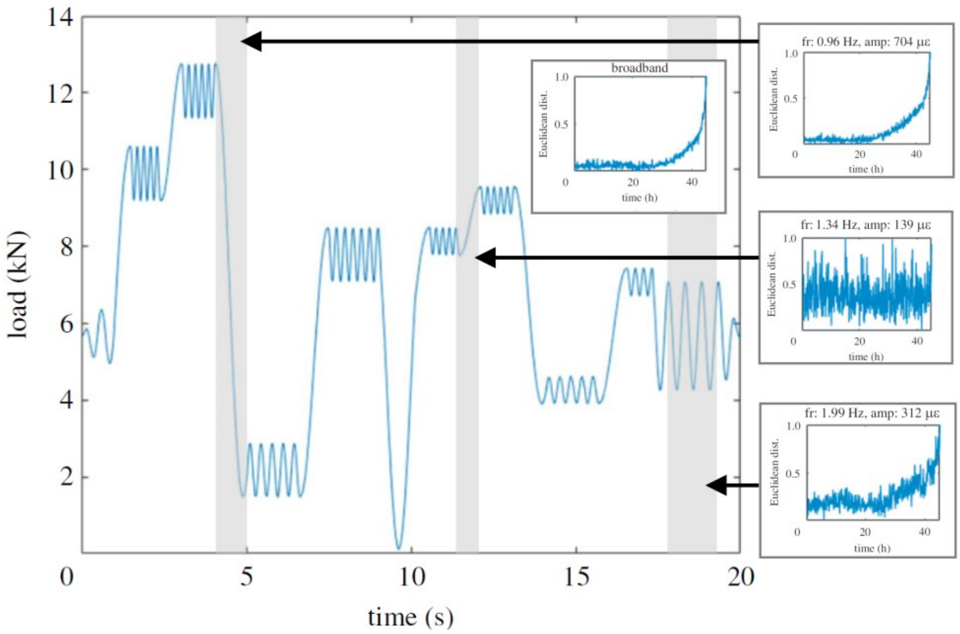

Figure 3. Representative flight-cycle load. Insets show feature vector difference for given sections of the cycle. Adapted from [9].

The data processing algorithms have also been applied to data collected during flight-cycle loading, which is more representative of real-life conditions experienced by an aeroplane in flight (Figure 3). Amjad et al. [9] found that analysis of CATE data collected during crack growth caused by repeated loading of the flight cycle also resulted in a feature vector difference indicative of damage growth. This feature vector difference could be extracted from a broadband analysis of all data, but was also found when certain sections of the flight cycle were analysed separately (Figure 3).

4. Industrial deployment

This prototype SHM system was deployed on full-scale airframe tests, including a fuselage pressurisation test at Airbus in Toulouse. A sensor unit was installed at a known crack site (Figure 4), and data was collected over a period of several weeks. DIC strain data were successfully output from the sensor system, indicating the location of the crack. Growth of the crack was observed in the strain maps, and a subsequent increase in the feature vector difference was also seen (Figure 5) [8].

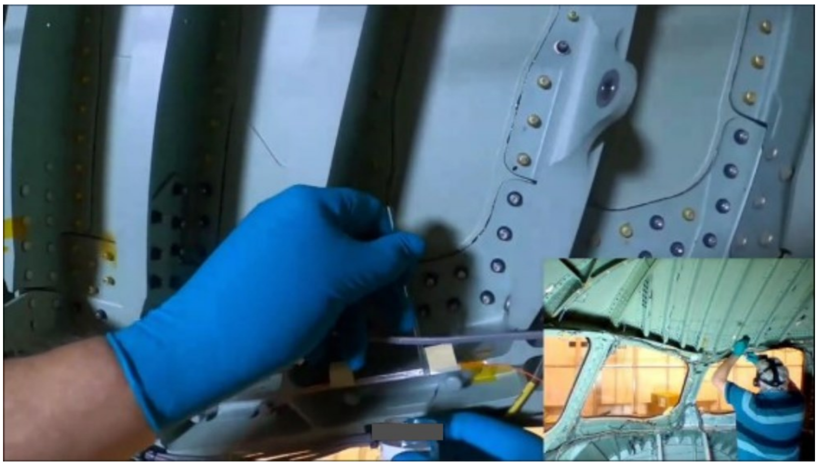

Figure 4. Installation of a sensor unit in the full-scale fuselage test, from [8].

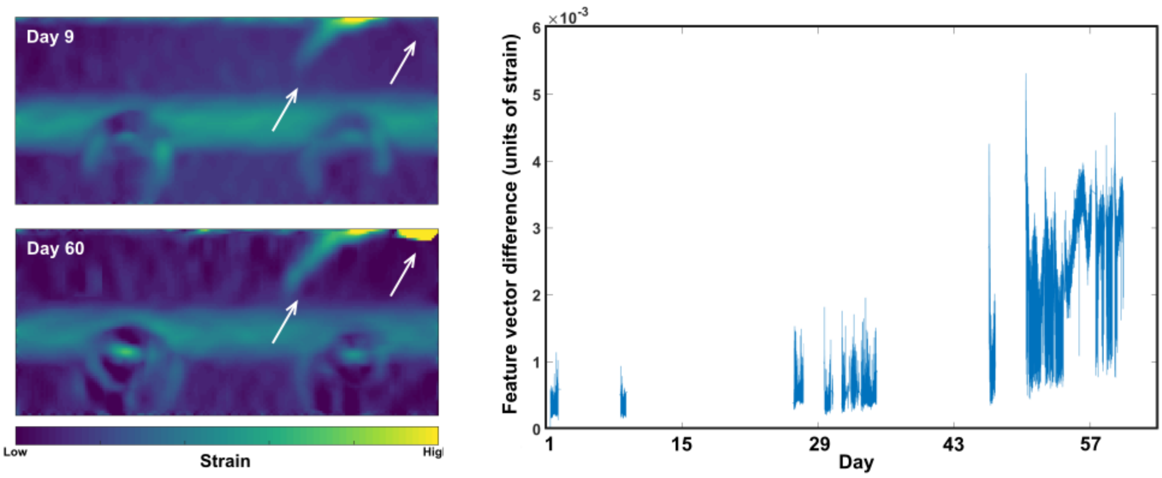

Figure 5. DIC strain maps at two dates during data collection, arrows indicate initial crack location and growth, and development of a secondary crack (left). Feature vector difference over time calculated by decomposition of strain maps (right). Adapted from [8].

5. Summary

A low-cost SHM system has been developed, making use of COTS technologies and advanced data processing techniques. Centimetre-sized visible and infrared imaging sensors have been combined with a board computer to assemble a low footprint unit which is deployed at the region of interest. Data processing occurs in near real-time, on board the unit, outputting DIC and CATE data-maps. These full-field outputs are further processed using orthogonal decomposition to give a quantitative measurement of the changes observed, representing the growth in fatigue damage in the field of view.

This system has been deployed on full-scale airframe tests, successfully collecting and processing data in near real-time. In a full-scale fuselage test, the location of damage and growth of that damage was indicated, demonstrating that this system represents a step towards in-service condition monitoring using these full-field techniques.

6. Acknowledgements

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7. References

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