3D Decomposition of uncalibrated thermoelastic emission data for automated damage monitoring

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Abstract. A technique utilising the data dimensionality reducing method of volumetric decomposition is used to identify various levels of damage in a plate undergoing vibration. The plates were monitored by a sensitive thermal camera and the images processed to obtain uncalibrated thermoelastic emission maps. These maps were then decomposed into feature vectors and their difference used to compare vectors from different specimens. This technique could be used to detect damage in specimens.

Introduction

Fusion reactors are expensive, with one expense being the need to give plasma facing components, such as armour plating and divertor monoblocks, conservative lifetimes rather than risk catastrophic failure. There are many forms of damage that these components can experience that may not be obvious without shutting down or removing the affected component and conducting an extensive inspection. If these components could be monitored for damage without their removal, then it would reduce the maintenance requirements of the components and improve the economic viability of fusion reactors. Using thermal cameras would also mean no new equipment would need to be installed in the reactor, as these cameras are already present for monitoring the plasma.

One way the captured thermal data can be used is to create uncalibrated thermoelastic emission maps that can be analysed for potential damage in a component [1]. The thermoelastic effect is a phenomenon whereby changes in the stresses experienced by the component cause minute changes in the thermal emissions produced. By applying a sinusoidal vibration load to a component one can record the temperature fluctuations across the surface of a specimen. The amplitude at each position in the temperature data can be used to produce a thermoelastic emission map. The temperature fluctuations are proportional to the amplitude of the fluctuations of the first stress invariant in the component, and if damage causes a change in this stress field, then the maps would also change. Thus, damage could potentially be detected by comparing maps from an in-service component with a baseline map from an undamaged component under the same loading conditions.

2D thermoelastic emission maps can often consist of several tens of thousands of data points. While 3D thermoelastic emission volumes, where the third dimension is time, contain millions of datapoints. This can create the need for high performance computing to monitor for differences in the datasets. There could also be issues storing the terabytes of information that can be gathered from fusion reactors. Volume decomposition [2] can be used to decompose the datasets into a series of tens to hundreds of coefficients. This would reduce the computational and storage requirements of the method by several orders of magnitude.

Method

A tungsten plate measuring 210mm by 149mm and 1mm thickness was manufactured by wire electrical discharge machining (V650G Plus, Excetek, Tiawan). The damage monitoring test plates were made from Aluminium 2024-T3 with the same dimensions and were cut by water jet machining (Omax-Maxiem-1530, Omax, USA). Material was removed from the top-right corner of the plates with a 45° cut to simulate damage. Prior to loading, each plate was coated with matt black paint to improve the level and uniformity of their thermal emissivity. The tungsten plate was subjected to sinusoidal excitation, whereby a range of 50Hz to 850Hz was swept through at a constant increase of 0.1Hz per second. The aluminium plates were excited similarly, but frequencies were swept from 60Hz to 360Hz at a rate of 1Hz per second. For both tests, thermal data was captured at 10 second intervals using a FLIR SC7000 photon detector camera (Teledyne FLIR, USA) and the uncalibrated thermoelastic emission maps calculated using the DeltaTherm (Stress Photonics, USA) software package. A broadband excitation signal was applied to the tungsten plate and a laser vibrometer (OFV-503, Polytec, Germany) used to deduce the resonant frequencies of the plate.

Results

Figure 1 shows the average strength of each thermoelastic map for the tungsten plate at 1Hz intervals during a frequency sweep. The figure also shows the frequency response function produced by the laser vibrometer for comparison. For the progressively damaged aluminium plates, the maps from each test were collected into volumes which were then decomposed into feature vectors [2]. The vectors were comprised of 560 coefficients, where the coefficients related to Chebyshev polynomial kernels. Figure 2 shows the Euclidean distance between the feature vectors for each combination of tested aluminium plates expressed as a correlation matrix.

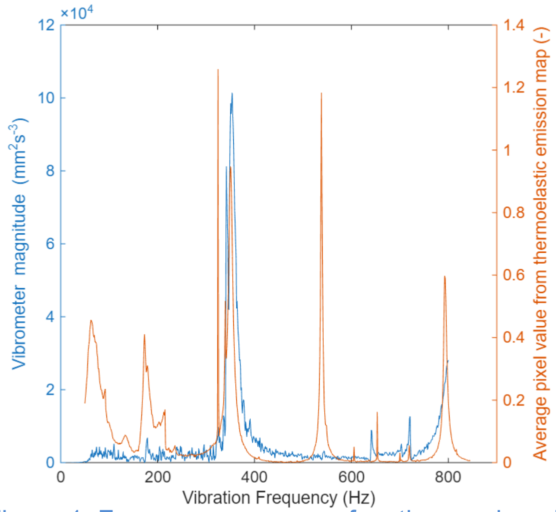

Figure 1: Frequency response function produced by a laser vibrometer (blue) and the average strength of the thermoelastic emission map (orange)

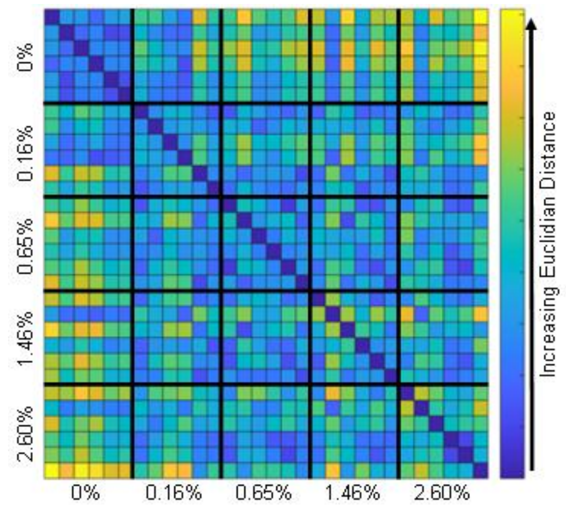

Figure 2: Correlation matrix showing Euclidean distances between plates with varying amounts of material removed

Discussion

For the tungsten plate, the frequency response function measured using the laser vibrometer and the equivalent obtained from uncalibrated thermoelastic emission maps show good agreement. Where the methods differ is in determining the magnitude of vibrations that each resonant frequency presents. While the vibrometer determines this magnitude from a single point on the plate, the thermoelastic map considers the entire plate. Hence, there are frequencies at which the magnitude of vibrations measured by the vibrometer is reduced due to the lack of significant movement in the plate at the measurement location. One key difference is the large spike at 328Hz in the thermoelastic map strength function. This is due to the applied frequency being the same as the frame rate of the thermal camera, so the perceived thermoelastic signal has a frequency of 0Hz. The resultant map at this frequency is thus comprised entirely of measurement noise, the average strength of which is random.

Figure 2 compares the decomposed thermoelastic maps from the frequency sweeps of progressively damaged aluminium plates. By looking down the left-hand side of the matrix, a trend in increasing Euclidean distance with the increase in damage can be observed. It has been found that environmental conditions affect the thermoelastic maps and thus further work is being conducted to reduce this effect. The thermoelastic effect is sensitive to ambient temperature fluctuations, and the average temperature of the tests increased over time due to the operation of equipment, such as the shaker. This also caused a change in the Euclidean distance between feature vectors that is not related to damage.

Conclusions

The method of sweeping through vibration frequencies whilst capturing thermoelastic emission data is a novel approach for determining the resonant behaviour of specimens. By analysing the differences in emission data from damaged and undamaged plates, the severity of damage can be quantified. Once issues regarding environmental factors are accounted for, this method could provide a new approach for health monitoring of components undergoing vibration such as the first wall armour in a fusion reactor during reactor ignition.

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References

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