Steps to Modern Thermoelastic Stress Analysis

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Introduction

Today, Thermoelastic Stress Analysis (TSA) is being used by engineers and scientists to solve practical problems in structural and material design. The combination of infrared array detectors and advanced signal processing has made TSA a practical tool for characterizing the performance of materials and structures.

Thermoelastic Stress Analysis is based on the principal that when a solid is compressed it heats slightly. When the pressure on it is released it returns to its original shape (elasticity) and its original temperature (therm-o-elasticity). The thermoelastic equation expresses the change in temperature of a solid in terms of the change in the sum of the principal stresses is

$$\Delta T = \frac{-\alpha T}{\rho C_p}(\Delta\sigma)$$

where ρ is density, C_p is heat capacity at constant pressure, α is coefficient of thermal expansion and T is ambient temperature. The equation assumes adiabatic conditions (no significant heat loss).

As a practical matter the adiabatic assumption is met by continually and "rapidly" changing the load on the structure. Often this is done with a constant amplitude loading, but variable amplitude or transient loading can be sufficient to make a measurement.

Heat loss by conduction (a non-adiabatic condition) only becomes an issue in the case of high thermal gradients. For instance, a small aluminum structure would be a case where special attention to the adiabatic assumption is important. It is clear that significant convective or radiant heat loss is not common.

History

An excellent history of TSA has been compile by Harwood, Cummings, and MacKenzie. The history is presented graphically in Figure 1. In the 1850's Lord Kelvin described the thermoelastic effect in scientific terms. In 1915 Compton and Webster reported confirming experiments of high accuracy.

Once the fundamental work was done there were just four critically important steps that remained. In 1967 Belgen made the connection to infrared sensing thereby making the measurement **non-contact**. Then in 1982 the first **commercial instrument** became available as the Ometron SPATE 8000. The SPATE had scanning mirrors and a single point detector, which provided the first **full-field measurements**. In 1994 Stress Photonics introduced a **fast imaging** array-based instrument. The implementation of the infrared array shortened the time to produce a high quality full-field image to under a minute.

Practical Concerns

As with every measurement technique there are limitations to TSA. Fundamental physical limits determine maximum spatial resolution, measurement time, and thermal (stress) resolution. There are also practical limitations in the measurement conditions and the implementation of the technique.

The maximum spatial resolution is set by the "diffraction limit". TSA systems can be built to be sensitive in either the 3-5μ or 8-12μ band. At these wavelengths the atmosphere is transparent to infrared radiation. Therefore, resolution better than about 5μ is not possible.

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Thermal resolution is set by the practicalities of optical design and by the quantum nature of light. Infrared detectors used in the modern TSA instruments have noise limits that are very near that of the background thermal noise. They are said to be “background limited”.

As a practical matter an optical system must be designed that balances spatial resolution, aperture, and depth of focus. The combination of an array detector with 128 x 128 pixels on 30μ centers with f/2.3 aperture is a good general-purpose combination. Larger array sizes can also be a good choice, but there is a trade-off between array size and framing rate. If the framing rate drops below about 300f/sec then measurement speed and accuracy begins to suffer.

Measurement time must be balanced with temperature resolution. Because of the statistical nature of the measurement, image averaging techniques are used to improve the stress resolution. The inverse square rule that applies to most noise limited measurements describes this trade-off. Improving the stress resolution by a factor of two requires lengthening the measurement time by a factor of four.

It is important that the surface of the structure being measured be an efficient and diffuse emitter of infrared radiation. This is most often accomplished by preparing the surface with a flat black paint.

The effect of loading frequency on the physical and instrumentation systems is complex. The coating causes attenuation of the signal as a function of frequency. The instrumentation has alias and sampling frequency limits. And the adiabatic condition must be met. Researchers have studied the frequency effects and considerable understanding has been gained. However, no compensation for frequency effects is available as part of a commercially available TSA system. Guidelines have been suggested to keep practitioners from making mistakes. 1) When design comparisons are needed, try to make them at the same frequency. 2) Try to make comparisons at more than one frequency, and 3) use the phase information provided by the instrument to indicate areas where frequency effects might be present.

An extensive bibliography of TSA from 1830 through 1990 with almost 200 entries is available at www.stressphotonics.com.

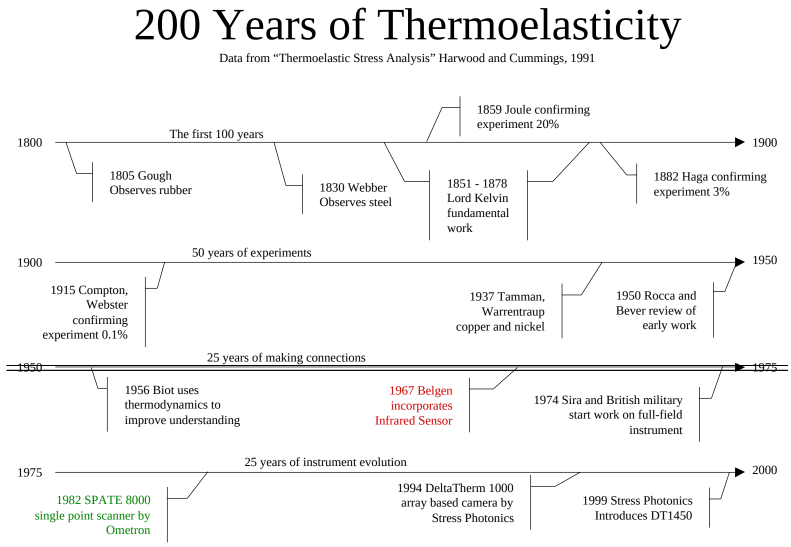

Figure 1. Timeline of some important steps in the development of Thermoelastic Stress Analysis