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New developments in Thermo Elastic Stress Analysis by Infrared Thermography.

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Abstract

It is well know that Infrared Thermography is a powerful full field non contact technique to measure temperature. Its field of applications covers all industries from chemistry to agriculture without forgetting medicine. Most of applications deal with high temperature measurements and measurements on moving, very small or inaccessible objects. It is less known that infrared thermography can be used to measurement minute changes of temperature and associated quantities.

The article will present an industrial application of infrared thermography based on measurement of a very small change of temperature.

Thermo elastic effect is known since the middle of the 19th century as the conversion between the mechanical forms of energy and heat. It occurs when changes of stresses within a material element alter its volume. Density of energy created in material element is transformed into local change of temperature. As specific heat of metal is high this phenomena is very small in terms of temperature change. Roughly 1MPa change in stress produces a temperature change of 1mK in steel. Moreover conversion takes place only during dynamic test. So it is not surprising that t the equation relating the elastic and thermodynamic theory for material element with isotropic proprieties implies that adiabatic temperature increments

1. Introduction

Thermography is a well known technique to measure temperature on the surface of object. The main advantages of infrared thermography are to provide a full field image of temperature without contact and at a high frame rate.

It has been used for forty years to measure temperature on inaccessible, moving and very small objects. Moreover engineers and researchers use it for very high temperature and minute temperature changes as well.

One of the most famous minute changes of temperature produces on the surface of material is due to thermo mechanical couplings. These couplings are usually separated into reversible coupling and dissipated phenomena. The first effect has been described since the 19th century by Lord Kelvin [1] as Thermo-elasticity. The theory based on the thermodynamics of quasi static processes shows that the temperature change is proportional to the change of stresses. It corresponds to a reversible exchange between mechanical energy and heat.

Since the beginning of the 80th, a commercial system has been used in the industry and research centers [2] & [3]. This first model was a dedicated system which could be used only for stress analysis purpose. More recently (end of the 90th) commercial systems are available for multi-purpose applications. The first use is obviously temperature measurement in a range of -20°C to 3000°C. The second is the stress analysis and the last is the measurement of the dissipated energy. The last application opens a new field of studies for fundamental and engineering research centers.

Thermographic stress analyzer (TheSA) is nowadays a unique non contact full field system to measure stresses and dissipated energy. Thanks to a high sensitivity new generation camera and a dedicated signal processing (Lock-in Thermography and Fourier analysis) it is possible to measure directly stresses (sum of principal stresses) on the surface of real component under going dynamic load.

Most of applications concern FEM comparison, fatigue testing and vibration analysis in automotive industry, naval, aircraft industry and steel industry.

The aim of this paper is to introduce the theoretical background and the newest application.

2. Theoretical background

The theory is based on the Thermo mechanical framework. The stress tests can be described within the framework of quasi-static processes under small perturbation hypothesis (SPH) (Chrysochoos and al. [4], [5]). Within such a thermo mechanical framework and combining the first and second principles of thermodynamics the local heat changes can be described by equation (1):

$$\rho C\dot{T} - k\nabla^2 T = r + s_{the} + d_1 \quad (1)$$

The left-hand term consists of a differential operator applied to the temperature, while the right-hand groups energies. As the left hand is a diffusion equation term it is common to consider the right-hand terms as heat sources. Here ρ represents the mass density, C the specific heat (at constant pressure), k the conduction. The different heat sources are cumulated in 3 terms:

- r external source supply,
- s_{the} thermo elastic source,
- and d_1 the intrinsic dissipation.

To simplify the heat diffusion equation, the following hypotheses are required:

- mass density and specific heat are material constant,
- convective term is negligible because of velocity amplitude is very small,

- the material is isotropic from the heat conduction point of view,
- external sources are time independent and give the equilibrium temperature of the specimen (T_0).

Under the above hypotheses the heat diffusion equation could be written as:

$$\rho C\dot{\theta} - k\nabla^2\theta = s_{the} + d_1 \quad (2)$$

Where $\theta = T - T_0$ is the temperature variation.

At this stage one notes that energy can be measure whether we can measure the change of temperature and the spatial gradient of temperature. As infrared cameras provide a full field temperature image and its changes versus time, one understand easily that this technique is the adapted sensor for energy measurement. The following question is how to calculate the first term.

2.1 Simplified heat diffusion equation

To simplify the equation (2) one uses to consider that the rate of temperature change ($\dot{\theta}$) is much larger than the Laplacian term ($\nabla^2\theta$). That condition is usually expressed in term of minimum frequency to assure that the equation can be written as (3):

$$\rho C\dot{\theta} = s_{the} + d_1 \quad (3)$$

In practical point of view that condition is easy to control by increasing the load frequency applied to the component under test. Calculation of adiabatic condition for common materials shows that the frequency is around 3Hz for steel and 10Hz for aluminium**.** However the exact value of frequency limit is difficult to calculate as it depends in the local gradient of the stress field [6].

For low level of stress (under the yield condition and at low strain rate), the dissipated energy is negligible compared to the thermo elastic production of heat. This last one is roughly 100time larger. So the equation (3) is simplified to:

2

$$\rho C\dot{\theta} = s_{the} \quad (4)$$

2.2 Thermo elasticity

For linear isotopic material, under the hypothesis of plane stresses, the thermo-elastic energy can be written as

$$s_{the} = -\alpha T_0\dot{\sigma} \quad (5)$$

where σ is the sum of principal stresses.

Finally equations (4) and (5) give the equation of Thermo-elasticity described by Lord Kelvin [1]:

$$\rho C\dot{\theta} = -\alpha T_0\dot{\sigma} \quad (6)$$

The equation shows that for linear isotropic, homogeneous material loaded so that adiabatic condition prevail, the change of temperature is proportional to the change of the sum of the principal stresses.

Moreover under sine loading the above relationship between temperature and the sum of principal stress is valid for the peak to peak value as well.

$$\Delta\theta = -\frac{\alpha}{\rho C}.T_0.\Delta\sigma = K_m.T_0.\Delta\sigma \quad \text{..............................(7)}$$

where Km is the thermo-elastic coefficient of the tested material. Stress measurement requires a measurement of ΔT and T for every pixel.

2.3 Signal processing

Thermographic Stress Analyzer (TheSA) uses the above equation (7) to measure stress thank to a measurement of temperature rate or peak to peak change of temperature. One can note at this stage that the energy can be expressed in temperature rate (°C/s). Then mechanical energy is calculated with physical parameters of material as density ρ and specific heat C.

The principle of signal processing used in Thermographic Stress Analyzer consists on extracting in real time the peak to peak change of temperature. Additionally TheSA is able to measure the temperature rate.

The latest technique to measure peak to peak change of temperature is a Lock-in technique coupled to a Fourier analysis [7]. In the latest technology of infrared camera Lock-in processing is included into the camera.

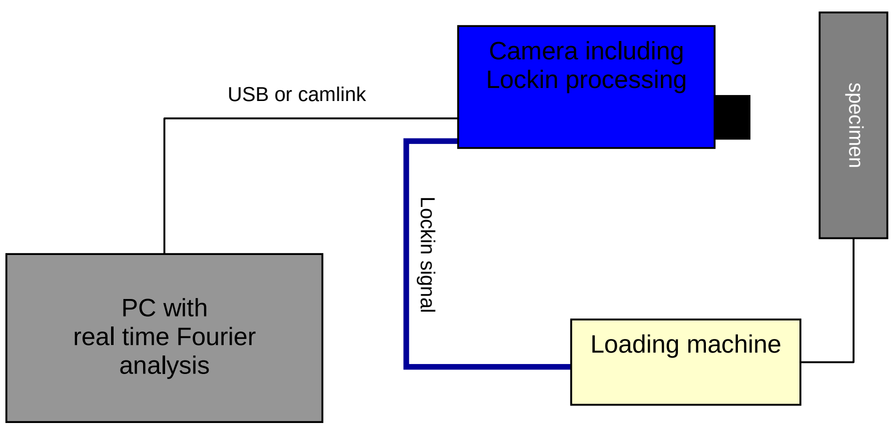

Figure 1. Signal processing into Thermographic Stress Analyzer

3. Thermography Stress Analyzer

3.1 Infrared camera

Advanced infrared cameras use a high quantum efficiency focal plane array MCT or InSb detector, cooled by a high reliability Stirling cooler. Infrared radiation is captured with snapshot mode. That means that all single detectors integrate synchronously infrared radiation emitted by objects within the exposure time (duration time) to produce a thermal image.
Each exposure time produces a single calibration curve so a single temperature range. To cover a wide range of temperature at different exposure times are required.
New cameras have a Hypercalibration™ which allows producing a calibration curve for every exposure time between 1µs to 2ms.
The Read Out Circuit (ROIC) integrated onto the detector allows to transfer thermal images to PC for recording, conversion into temperature and visualization on monitor. The frame rate depends on the technology used in the ROIC. The latest development produces a high frame transfer to PC thanks to an Integrated While Read (IWR) technique. The following table gives typical specifications of infrared camera for Thermography.

Table 1. Infrared camera specifications

Camera specifications	
Spectral response / material	MWIR : 2 to 5µm / InSb LWIR : 7 to 9 / MCT
Resolution / pitch	320 x 256 / 30µm 640 x 512 / 15µm
Integration type / Exposure time	Snapshot / less than 1ms @ 25°C – MWIR Snapshot / less than 100µs @ 25°C – LWIR
Frame rate / ROIC	383Hz / 320 x 256 / IWR 100Hz / 640 x 512 / IWR
Frame rate range / triggering	Programmable frame rate / external triggering
Maximum frame rate / windowing	25 kHz / 64 x 8
Filter wheel	4 positions
Temperature range	-30°C to 3000°C
Thermal resolution	20mK @ 25°C
Extended temperature range	MultiTI™ (4 simultaneous exposure times)
Calibrations	Continuous from 1µs to 2ms by Hypercal.™

3.2 Applications of thermography

Typical applications of infrared camera concern:

- very large temperature range like in Tokomak study (200°C to 2000°C by MultiTI™)
- rotating object (cutting tools, tire or disk brake)
- small object (electronics integrated circuit (spatial resolution down to 4µm)
- small temperature change during fast tests (aerodynamics - LWIR camera)

For minute change of temperature under the thermal resolution of infrared camera lock-in technique should be used. One of the most famous minute changes of temperature is generated by heat production of thermo-mechanical mechanism.

3.3 Thermographic Stress Analyzer

Thermographic Stress Analyzer uses cameras described above. The key specifications for stress analysis are:

- snapshot mode,
- short exposure time,
- low thermal resolution
- external synchronization
- programmable frame rate

So cameras have a cooled detector. Lock-in process is now included into the optical head to allow a precise dating of image and recording of the lock-in signal for load cell force, strain gauge, accelerometer or function generator depending on the application. The specimen or the object to be analyzed is painted with a high emissivity coating in order to improve the infrared radiation and eliminate reflection from the testing room. The following figure shows a TheSA system in a calibration situation.

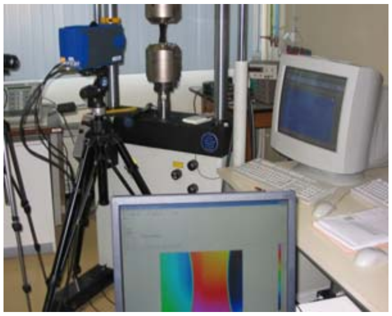

Figure 2. Setup of Thermographic Stress Analyzer.

3.3.1 Calibration

The calibration of infrared camera of Thermographic Stress Analyzer is made usually in laboratory in temperature on black body. To measure stress one can perform a calibration in MPa first of all to confirm that thermo-elasticity effect is linear versus the level of load, and then to measure the thermo-elastic coefficient of the material. A specimen is used. Its surface is paint with high Emissivity coating. One draw the magnitude of temperature (mK) measured by Lock-in processing versus the level of load (N). The slope of the calibration curve gives the value of Km. Industrial users prefer to extract from data sheet the value of Km and apply the value into the TheSA system. Usually manufacturers include a material library of common material which can be update by the user.

The following images present a thermal image on the left obtained by Lock-in processing. The frequency applied is higher that the adiabatic condition (here 10Hz). The material is steel and the value of Km is 3.5 10^{-12} MPa^{-1}.

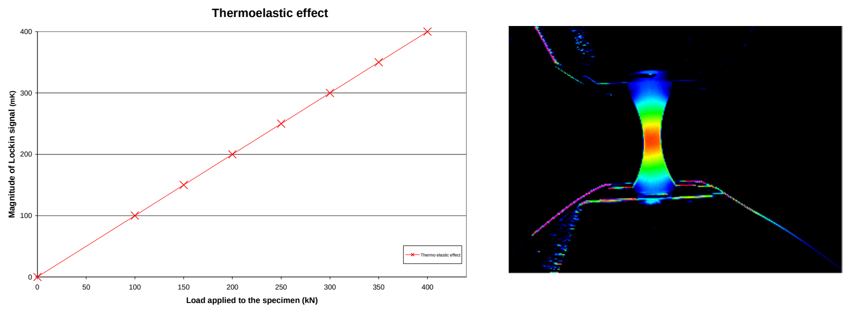

Figure 3. Magnitude image (°C) obtained by Lock-in and Fourier analysis and the correspond calibration curve obtained for load between (100kN to 350kN)

3.4 New developments

3.4.1 Signal extraction

TheSA requires a lock-in signal for the loading machine. In some case the signal is not available or the object is too far to be connected. It is possible to extract from the thermal image itself the lock-in signal to process thermal images.
The software extracts the mean value of temperature inside a surface that the user can place on a high stress zone.
Stress value is obtained by post processing. One should note that the result has more noise. So that technique should be used only when no other solution is available.
The typical application which requires a signal extraction from zone is the stress on very structure large structures like bridge or buildings. There is an example of crack detection on the page 8.

3.4.2 Fast Fourier Analysis

TheSA software offers usually a fast Fourier analysis for periodic loading (not pure sine) and random excitation. This function includes a calculation of the harmonic frequencies of the load. The main application is the stress analysis of component under random loading and road simulation. The structure vibrates on some limited modes.

The FFA can also be used during the test of rubber during fatigue testing. The harmonic frequencies are created by the non linear behavior of the rubber even under sine load.

3.4.3 Motion Compensation

More often, the object under the dynamic load is moving and deformed. To calculate the correct value of stresses lock-in processing should be coupled to motion compensation software.
Whether the load is sine, TheSA can be synchronized onto the load. The signal can be processed in real time by the prediction of the position of the component under stress. In case of more complex loading like random testing with large deformation another technique can be used. The principle of motion compensation used is to record the test. and apply motion compensation. The best method is to use an image correlation method on the thermal image. This technique doesn't require any external sensor, any synchronization and allow using in post-processing all functions of the real time processing.

3.4.3 Dissipated energy measurement
Dissipated energy is used for different applications. The first is to measure the limit of fatigue of material [7]. But the most powerful result for stress analysis is to determine a shear zone. It is well known that the TheSA cannot detect shear zone as the sum of the principal stresses is null. The principal stresses are equal and their signs are opposite.
In order to determine whether there is shear stress zone user can measure the local dissipated energy. The value is given by a D-Mode technique developed by CEDIP using for the first time a Fourier Transform analysis of the thermal images.

It is well known and proven that the dissipated energy is produced when the material start to be damaged. The production of dissipated energy is linked to growing of micro cracks.

3.5 Typical TheSA specifications

The following table shows the specifications of Altair-LI system.

Table 2. TheSA specifications

TheSA specifications	
Spectral Range	MWIR : 0.1* to 1kHz LWIR : 0.1* to 20kHz
Material	All material** including metals and polymers
Results of measure	Peak to peak Temp. change (°C), phase (deg)
Resolution in temperature	1mK with 1000 image accumulation
Time processing	Less than 2 seconds for 1MPa resolution
Load shape	Sine, periodic, random
External signal	For Lock-in process For random loading (2) For motion compensation
Stress range	1MPa to yield stress value***
Stress resolution	1MPa***
Spatial resolution	Down to 4µm
Motion compensation	Sine loading Random loading

* depends on the adiabatic condition.
** orthotropic material and rubber required dissipated energy measurement
*** depends on the material

4. Thermographic Stress Analyzer applications

The size range of objects on which Thermographic Stress Analyzer can be used to measure stresses is very large. The following figures show the map of stress on a diesel fuel injector during a fatigue test with a spatial resolution of 35µm and a stress concentration at the end of a crack on a bridge.

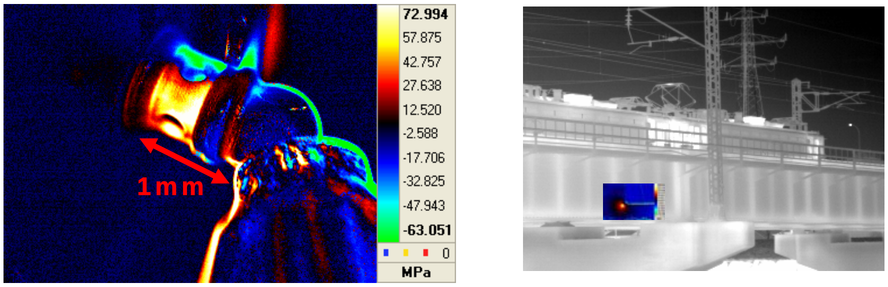

Figure 4. Size of object analyzed by TheSA

TheSA systems have a large panel of applications. Basically the use of imaging measurement systems is required when localization of high stress is unknown or to compare to another full field data like FEA results.
It could be simply used to locate the zone where a contact sensor (strain gauge or rosette) should be fixed for further analysis. But main application deal with the localization of stress concentration.

4.1 Fatigue testing in automotive industry

With automotive components to undergo fatigue test, the position to be destroyed can be estimated by a short time measurement. In consequence the efficiency of fatigue test is drastically improved. Full field measurement capability eliminates the possibility of overlooking stress concentrated portions. Tests are then performing with a very low number of local sensors installed at the right place.
Additionally the value of stress measured locally can help to identify the reason of the fatigue breakdown. A lot of car manufacturers use that technique to determine as fast as possible whether fatigue breakdown is due to the design, material or production tools.
In case of design problem the optimum shape can be seek by using the same method. Different shapes or material can be tested in a very short time. The advantage is the test all specimen or real components in exactly the same condition.

4.2 Complex structure and Finite Element Analysis comparison

In welding component or on composite material, the prediction by FEA could be not enough to predict the level of stress. The shape of weld cannot be described as the welding depends on a lot of production parameters. The worst situation for modeling is the spot welding component.
It is possible by TheSA to carry out the area of measurement of the objects complicated in shape including high concentration stress.

4.3 Fracture mechanics

The effect of elastic parameters such as mode I and II stress intensity factors can be explored using the TheSA technique. The stress concentration factor is directly accessible from the full field measurement. On some materials like PMMA, the measurement doesn't require any high emissivity coating. The following images show stress pattern along the crack on a CT specimen.

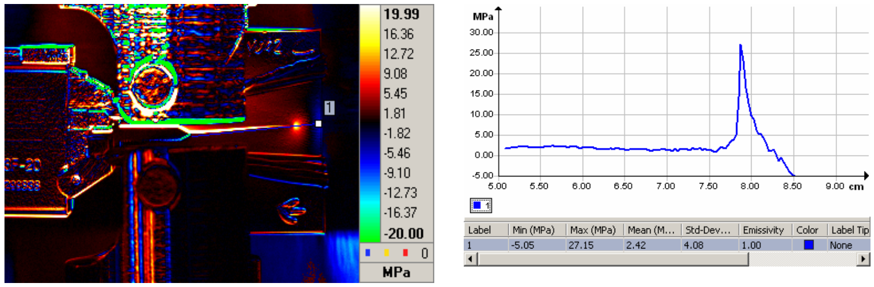

Figure 5: PMMA specimen during crack propagation test. Stress along profile 1

As level of stresses at the tip of crack is high TheSA can be used to detect crack tip on component under fatigue testing. For example it is used as a Non Destructive Testing in aircraft industry to shorter the time of detection of the first crack. The main advantage is that TheSA can be used during the test. The competitive technique requires to stop the test and to use a liquid penetrant control.

4.4 Vibration analysis in aircraft industry

The frequency limit of Lock-in technique is not in relation with the frame rate. The key parameter is the exposure time. As LWIR camera has a shorter exposure time at room temperature they are required for high frequency analysis. The following images are made with a TheSA system using a Long Wave Infrared camera. They show the stress pattern on turbine blade. Blades are tested on shaker in order to measure the level of stress as a function of the frequency. The complementary imaging technique is holography in order to provide the image of displacement.

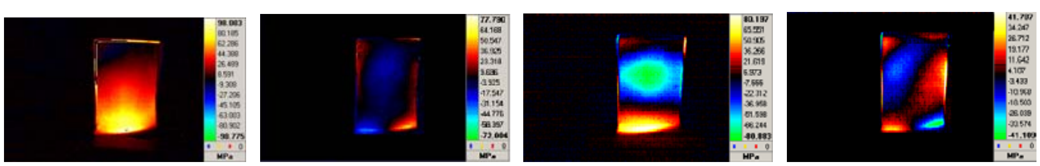

Figure 6: Stress pattern on turbine blade
(1st mode: 717Hz, 2nd mode: 2136Hz, 3rd mode: 3418Hz, 4th mode: 5911Hz)

5. Conclusions

In stress measurement, strain gauges are still used in many cases. As this measurement technique is local a large number of strain gauges are required. That is at the same time and price consuming to carry out pattern measurement.
Methods to compensate that point measurement are imaging techniques. Some of these are well known for a long time like photo-elasticity method. But this old method requires a special coating different to the component to be studied. It is time consuming and the measurement concern another material.
New Digital Imaging Processing methods using video camera and correlation image technique is more powerful. The result is a kind of optical strain gage. The result is similar to the strain gauges with the advantage to provide a full field pattern. The frame rate is limited and the result is similar to local strain measurement.

Thermographic Stress Analyzer gives a completely different piece of information than all the previous methods. Sure enough the quantity measured by TheSa is energy. Even if the thermo-elasticity is related to the volume change, the dissipated energy is really a new quantity which gives to mechanical engineering a tool to measure the local damage. Some results obtained during the last 5 years showed that it is possible to predict the fatigue crack occurrence and to measure the fatigue limit [8].

The new developments in thermal stress analyzer concern mainly industrial uses. One of the most difficult issues to be solved is the motion compensation. By an image correlation technique of raw infrared images the displacement can be directly measured and then compensated by post processing technique in order to correct the localization of every pixel.

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