Thermoelastic investigation of a large helicopter component under a multi-axial load

Antonio SALERNO, Stefano DESIDERATI
Department of Energy, Politecnico di Milano, via Lambruschini 4, 20156 Milano, Italy
E-mail: antonio.salerno@polimi.it

Abstract
A large aluminum alloy helicopter component under a modulated multi-axial load was investigated using thermoelastic stress analysis. Due to the considerable size of the component, the frequency of the test could not exceed 0.7 Hz. This low frequency and the high thermal diffusivity of the aluminum alloy did not allow the achievement of adiabatic conditions, thus producing an attenuation of the thermoelastic amplitude signal. While TSA allowed to precisely locate the region of appearance of a crack close to the rear vertical attachment, the fatigue crack in the region of the front vertical attachment appeared in a region not corresponding to that of the maximum thermoelastic signal. This inconsistency was explained by the presence of a considerable static component in the loads applied by two of the hydraulic jacks. A correction procedure was performed on the raw TSA amplitude values, in order to recover the adiabatic temperature distribution.

Key words: thermoelastic stress analysis, non adiabatic conditions, correction procedure.

1. Introduction
Understanding the stress distribution in a component under load is important for introducing modifications able to extend its fatigue life. Thermoelastic stress analysis (TSA) can be quantitatively applied to obtain the distribution of the modulated part of the first stress invariant on the surface of a component under a fatigue test, if adiabatic conditions are achieved. TSA can only measure the modulated part of the stress invariant. However this does not normally prevent the identification of regions of maximum stress concentration when the static stress distribution corresponds to the dynamic one.

Often, in tests of real components, especially if of large dimensions, adiabatic conditions cannot be achieved, due to the limits of the fatigue machine in applying and control the load.

TSA produces an amplitude image, which corresponds point by point to the thermoelastic signal, and a phase image, which, in case of adiabatic conditions, presents the value of 0° or 180° depending on the fact that for a given load, one point is under traction while another point is under compression.

If adiabatic conditions are not reached, the temperature peaks are attenuated. In this case the value of the phase shift can be used to implement pixel by pixel a correction procedure(1) to recover the adiabatic temperature and the corresponding stress.

If a static load is present together with a dynamic one, the sum of the static and the dynamic stress can cause a failure in points different from that located by the TSA.
Nomenclature

\( T \): absolute temperature  
\( \delta \sigma = \delta (\sigma_I + \sigma_{II} + \sigma_{III}) \): variation of the first stress invariant  
\( K_0 \): thermoelastic constant  
\( \lambda \): linear coefficient of thermal expansion  
\( \rho \): mass density  
\( c_p \): specific heat at constant pressure  
\( \Gamma \): attenuation  
\( \alpha \): thermal diffusivity  
\( j \): complex index

Subscripts

\( \text{ad} \): adiabatic

2. Thermoelastic effect and correction procedure

The thermoelastic effect was firstly studied by Kelvin in 1855\(^{(2)}\). The basic equation describing the thermoelastic effect was introduced by Darken and Curry in 1953\(^{(3)}\):

\[
\frac{\delta T}{T_0} = -K_0 \cdot \delta \sigma
\]

(1)

where \( T_0 \) is the average temperature of a point and \( K_0 \) is the thermoelastic constant:

\[
K_0 = \frac{\lambda}{\rho c_p}
\]

Considering the linear stress distribution like the one in a beam fixed on one side and loaded on the other side with a sinusoidally modulated force normal to the longitudinal axis, the solution of the Fourier equation gives an attenuation \( \Gamma = 1 - \delta T/\delta T_{\text{ad}} \) which depends on the phase shift according to Fig. 1 (linear). In Fig. 1 are also reported the dependence of the attenuation on the phase shift in case of quadratic and cubic stress distribution\(^{(1)}\).
The use of diagram of Fig. 1 together with a right assumption on the stress distribution (which can be made by an operator considering the shape of the component, the constraints and the loads applied to it), allows for the recovery of the adiabatic temperature when the experiment was made in non adiabatic conditions\(^4\).

A further development of this technique\(^5\) allows for an automatic correction of the temperature of every pixel of an IR amplitude image, on the base of the diagram phase – attenuation obtained for a plurality of stress distribution functions, selected automatically pixel by pixel.

3. Component and loading conditions

The component examined is a helicopter aluminum alloy carter shown in Fig. 2a (rear side) and 2b (front side). It is a large component with a complex shape, subject to a fatigue test. Being the component obtained by casting it presents a considerable surface roughness.

Nine jacks apply a load which simulate the working conditions. The two horizontal jacks clearly visible in Fig. 2a and 2b apply a static load, which is much higher than the dynamic load applied by the other jacks. This suggests caution in the interpretation of the TSA data. The complexity of the test and the large dimension of the component allowed to apply a maximum modulation frequency of 0.7 Hz, which is far from the frequency necessary in this case to reach adiabatic conditions.

The thermoelastic constant \(K_0\) was determined theoretically on the base of the thermophysical properties of the material and experimentally using a sample of a similar aluminum alloy put in a stress test with a pre-determined load. The sample surface was painted with a acrylic black paint. A discrepancy between the theoretical value and the experimental one was attributed to the surface emissivity, which also has a dependence on the roughness of the surface. The part of the component surface used for the thermoelastic inspection was painted with the same acrylic black paint (black region visible in Fig. 2b and in Fig. 3).

Critical regions of the component were located by previous tests in which one crack in the front and one in the rear region appeared close to the vertical jacks.

Figure 3 shows a detail of the front region inspected by TSA.
The reference signal, important for a correct evaluation of the phase, was taken from a strain gauge close to the inspected region.

3. Results and discussion

Figure 4 is the amplitude (a) and phase (b) thermoelastic image obtained on the front part of the component close to the vertical jack. The phase showed that adiabatic conditions had not been reached.

The amplitude image (Fig. 4a) was corrected on the base of the correction procedure and the diagram of Fig. 1. A strain gauge positioned in the region of the TSA inspection gave a first stress invariant of 84 MPa, while the value obtained for the same position by the TSA without correction was 50-51 MPa. After the linear correction the value was 65 MPa and after the parabolic correction the value was 80-85 MPa. Figure 5 shows the result after the parabolic correction.
Figure 5 Corrected image assuming a parabolic stress distribution.

Figure 6 is the image obtained for the same region on a similar component which was previously tested. In this test a crack developed in a region which did not correspond to the one located by the TSA.

The fact that a crack appeared in a different region from that located by the TSA, can be explained with the presence of a strong static load applied by the horizontal jacks.

This is clearly a limit of TSA, which is capable of measuring only the dynamic component of the first stress invariant.

Figure 7 is the amplitude (a) and phase (b) thermoelastic image of rear part of the component close to the vertical jack. Also in this case an attenuation appears in the region of the maximum stress concentration.
Fig. 7 Amplitude (a) and phase (b) image of the rear part of the component

Figure 8 shows an image of the crack appeared during the test and revealed with a penetrating liquids inspection. In this case the region of highest stress concentration corresponds to the position of a crack.

The maximum value of the first stress invariant in the rear region without correction was about 115 MPa, as it is inferable from Figure 7. A reference value of a strain gauge can be useful to understand the kind of correction to apply and extend the results to the whole region under thermoelastic investigation. In this case a reference value of a strain gauge was not available. However in this region phase shifts of about 30° were revealed from the phase image. This is not compatible with a parabolic correction (see the diagram of Fig. 1). Therefore a linear correction was applied, reaching a maximum value of the first stress invariant close to 160 MPa. This value is considered compatible with a fatigue failure.

Fig. 8 Crack in the rear position of the component, made visible with a penetrating liquid inspection

4. Conclusion

Very often real components can be tested at frequencies which do not allow the achievement of adiabatic conditions. The correction procedure showed to be able to recover the adiabatic temperature and give quantitative results in good agreement with that of a strain gauge, in the front region, and with the values considered compatible with a fatigue
crack, which occurred in the rear region. Even after the recovery of the adiabatic temperature, TSA results must be considered with caution in case of multi-axial load with the presence of static components. In case of a mono-axial load a static component does not varies the position of a critical region. In our case, with a multi-axial load, a strong static component caused a fatigue failure in the front region in a position not corresponding with the highest thermoelastic signal.

References


