Non contact measurements of stress fields on rotating mechanical components by thermoelasticity

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Nomenclature

\[ \Delta \sigma_1 + \Delta \sigma_2 : \text{the sum of the stress time fluctuation in two perpendicular directions on the specimen surface (i.e. the first stress invariant time fluctuations)}; \]

\[ \alpha : \text{thermal expansion coefficient}; \]

\[ T : \text{absolute temperature of the component}; \]

\[ \rho : \text{density}; \]

\[ C_p : \text{specific heat at constant pressure}. \]

ABSTRACT

In this paper the possibility to measure stress fields on rotating mechanical components is demonstrated. The test case used is a plastic fan installed on an electric motor over an electrodynamic exciter in order to rotate and vibrate the fan itself. A special purpose data processing software has been developed to process the thermal film recorded while the fan is rotating and vibrating. An experimental method to realize thermal markers on the fan is proposed. The software allow to follow the marker movement and to de-rotate the film frames. On the de-rotated film another data processing technique allow to detect temperature time fluctuations on each relevant pixel. The result is a thermal differential image, accordingly to the thermoelastic measurement principal, proportional to the stress on the fan blades surface. The same stress concentration areas and levels has been obtained on the rotating and vibrating or only vibrating fan blade.

1. INTRODUCTION

Many non contact measurement techniques have been proposed to measure vibrations and stress on rotating blades of fan, compressors and turbine. For example in [1] a set of optical fiber probes, fixed on the turbine stator is proposed, in [2] the possible use of a laser Doppler vibrometer with a rotating measurement point by means of two mirrors is illustrated, while in [3] a laser Doppler vibrometer with a fixed measurement point and special purpose data processing techniques is illustrated. Another optical technique based on holography and a rotating Dove prism in order to de-rotate the target, has also been proposed [4]. Thermoelastic stress analysis (TSA) [5, 6] is another optical (infrared) non contact measurement technique. For more than 10 years TSA has been used for stress measurements on mechanical component surfaces and, because it is a non contact measurement technique, it could be a powerful tool to analyze stress distributions on rotating objects. In [7] TSA is proposed, together with a rotating Dove infrared prism realized by an equivalent set of mirrors, to measure stress concentrations on a car wheel.

2. THERMOELASTIC STRESS ANALYSIS MEASUREMENT PRINCIPLE

Explanation of the thermoelastic effect, measurement principle, history and applications can be found in [6]. Thermoelasticity is based on the thermoelastic effect, i.e. every substance (solid, liquid or gas) changes its temperature if volume changes due to external loading. For an homogeneous solid material, if no heat
exchange takes place (i.e. the loading is sufficiently quick) the temperature changes $\Delta T$ can be related to the stress by the following equation [6] proposed the first time by Lord Kelvin in *Encyclopaedia Britannica 9th edn. In 1878*:

$$\Delta T = \frac{T \cdot \alpha (\Delta \sigma_1 + \Delta \sigma_2)}{C_p \cdot \rho} \quad (1)$$

In order to apply this measurement principle to detect stress maps, it is therefore necessary to measure a spatial distribution of temperature changes. In order to have a non-contact stress measurement technique, temperature changes can be measured without contact on the surface of a loaded mechanical component by a differential thermocamera. Typically temperature fluctuations are measured synchronous with a reference signal, related to the loading cycle of the mechanical component. The data processing is performed by the lock-in technique, that mixes the output signal from the infrared detector with a reference signal related to the dynamic loading. Here the *Delta Therm 1560* system produced by the *StressPhotonics* is used.

### 3. THE TEST BENCH

The mechanical component used as case study is a nylon PA66 fan, typically used on diesel engines of trucks and agricultural machines, illustrated in fig 1 a).

![Image](image1.png)

**a) the fan tested**  
**b) the electric motors and its assembly on the exciter**

*Fig. 1 : The mechanical component used as case study*

To generate fan rotation an electrical CC motor type BC130 by Bonfiglioli (max 2000 rpm, 24 V, power 30 W, torsion 0.16 Nm) has been used. The motor has been assembled on the exciter as illustrated in fig 1 b).

![Image](image2.png)

**a)**  
**b)**

*Fig. 2 : The fan installed on the motor and on the exciter*
The complete assembly over the electrodynamic exciter (an LDS mod. V650 – 1600 N range 5 Hz - 5 KHz) is illustrated in Fig. 2 a). On the shaft connecting aluminium disk of the fan four thermal marker has been installed, as illustrated in fig 2 b), in order to have references followed by the sw. The thermal marker are four little tungsten filament lamps with cotton with alcool around. All these components are assembled inside a plastic little tube of 0.5 cm of diameter.

4. THE REFERENCE STRESS MEASUREMENT ON THE BLADE ONLY VIBRATING

The fan was rigidly joined on the electrodynamical shaker. In this condition a thermoelastic measurement was performed, with the fan non rotating, in order to detect the “reference” stress field. The complete measurement chain is illustrated in fig. 3, the blade was excited generating a sinusoidal table vibration at 20 Hz, with 1 g amplitude. 0.2 kg of mass was added on the blade tip.

![Fig 3: The complete test bench](image)
The following stress field has been obtained. A stress concentration on the tip of the cone is clear from the results. Inside this cone there is the connecting system of the blade to the aluminium flange. This stress concentration is well known from previous studies of this kind of blade [10], so expected.

Fig 4: Stress field on the blade surfaces obtained at 20 Hz (left) and at 61 Hz (right)

5. MEASUREMENTS OF THERMAL FILMS ON THE VIBRATING AND ROTATING FAN

The fan was put in rotation and vibration, as illustrated in fig 5, using the test bench previously described. Vibration was excited using sine signals at 20 Hz – 1 g vibration amplitude measured on the shaker table with a rotational speed of 65 rpm and adding 0.2 kg of mass at only one of the blade tip. In this conditions a thermal film of 20 s, frame rate of 100 frame/s, for a total of 2000 frames was acquired. Some of this frames are illustrated in fig 5 where is possible to see clearly the thermal markers.

Fig 5: the rotating and vibrating fan

Similar test has been performed at 61 Hz, the frequency of the first blade bending mode, with 10 g amplitude of acceleration at shaker table, with no added mass.
Rotational speed of the fan was in this case 15 rpm. In this conditions a thermal film of 2000 frames was acquired at a frame rate of 200 frame/s, for 10 s.

6. THE DATA PROCESSING SOFTWARE

In previous work a special purpose data processing software has been developed. The sw was named Termoimage [9]. The goal of this sw is to de-rotate the image by superimposing the positions of the thermal marker of the different film frames, translating and rotating the frames. The operation to perform are indicated by numbered folder in the user interface illustrated in fig 6. The first operation to perform is the selection of the file with the film to process, in txt format. The next operation is the definition of the reference points, that are the areas of interest of the thermal markers, at least three but no more than six. This is done on the filtered image of a significative frame on the thermal film. The subsequent step is the selection of control points on the reference areas defined. Once defined the references details and some image processing parameters the sw determines the rototranslation matrix and process the film in order to obtain an output film where the positions of the defined markers remain the same, on all the frames.

![Image](image.png)

**Fig. 6: The software “thermoimage”**

The de-rotation of the frames of the film needs the rotation of the frames, as illustrated in fig 7. For this reason the new de-rotated film needs a larger matrix size to store the new frames. Developed sw for each rotated frame calculate a new resolution for the output film. The final output film frame dimension will be the envelope of all the subsequent new frame borders.

![Image](image.png)

**Fig. 7: Derotating the frames needs changes of the new film borders**

Once derotated the thermal film a differential thermography has to be calculated from it. I.e. a map of the amplitude of the thermal fluctuation on each pixel, related to the frequency load applied to the component has to be determined. This is done using two algorithms developed in Matlab. The first is based on the digital processing implementation of the lock-in techniques [7–8], using as reference signal square waves at the loading frequency. The second one is based by means of a direct spectral analysis approach processing the
pixel time history using a classical FFT technique. Both the routines takes as input the thermal film and generate as output a complex image (or two images of modulus and phase) of thermal fluctuation, due to the thermoelastic effect. The image of the amplitudes spatial distributions is proportional to the distribution of the first stress invariant on the surface of the rotating component.

7. RESULTS OBTAINED

The two thermal film recorded while the fan was rotating and vibrating at 20 and 61 Hz, has boths been processed using the thermoimage sw, in order to obtain two de-rotated film; therefore the two processing techniques (digital lock-in and spectral analysis) has been applied on both the film. The four result obtained are illustrated in Fig 8.

![Fig. 8: stress distribution obtained on the blade rotating and vibrating at 20 Hz – film processing by spectral analysis](image)

![Fig. 9: stress distribution obtained on the blade rotating and vibrating at 61 Hz – film processing by spectral analysis](image)
Both the results obtained at 20 and 61 Hz show, as expected, a strong stress concentration at the cone of the blade tip, typical and previously in deep studied for this kind of blade [10]. The phase distribution on the blade surface was sufficiently uniform in space indicating a good quality of the thermographic acquisitions, i.e. a phase match on all this surface with the blade loading. Some little differences can be put in evidence between the two processing techniques of the de-rotated film: using spectral analysis the stress gradient obtained are a bit larger.

**CONCLUSIONS**

In this work a thermal film data processing technique is proposed in order to perform, without contact, stress distribution measurements on rotating mechanical components. The measurement methodology validity has been demonstrated in general on a test case: stress distribution on rotating a plastic fan. Expected stress concentrations have been obtained in all the measurement condition tested, up to a blade vibration frequency of about 60 Hz and up to a rotational speed of 65 rpm.
References


