ISSN (e): 2250 – 3005 || Volume, 10 || Issue, 6|| June – 2020 ||
International Journal of Computational Engineering Research (IJCER)

Thermoelastic stress analysis on rotating and oscillating mechanical components

L. Capponi, R. Marsili, G. Rossi, T. Zara

Abstract
Thermoelastic stress analysis on mechanical components has been already conducted in static conditions. The present study aims to develop a thermoelastic stress analysis in a dynamic state, in particular on a fan blade during its working condition. The test was conducted by capturing the data through a thermal camera, analysing them with a proper software, that is able to de-rotate the frames using particular markers, applied on the fan flange. The data were processed using two different approaches. The first one is based on Discrete Fourier Transform (DFT), while the second uses the digital lock-in technique. The obtained results were compared with those from the study conducted in static condition.

Nomenclature
$\Delta\sigma_1 + \Delta\sigma_2$ = *trace of stress tensor plane-stress isotropy;*
α = *thermal expansion coefficient;*
C_p = *specific heat at constant pressure;*
ρ = *density;*
T = *absolute temperature of the component.*

Keywords: *Thermoelasticity, thermal camera, thermal marker, lock-in, Discrete Fourier Transform.*

I.

II. INTRODUCTION

The Thermoelastic Stress Analysis (TSA) is a full-field, no-contact technique, that detects the temperature changes caused by a dynamic load. The thermoelastic effect is explained using the first law of thermodynamics: an increase in volume, under adiabatic condition, is associated with a decrease in temperature and vice versa [1-2]. The thermoelastic principle is expressed using the Kelvin equation by:

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

During thermoelastic measurements, the rigid displacements of the body in object need to be reduced to assure the measurement accuracy and avoid edge effect that can lead to unreadable results [3-4]. Thermoelastic Stress Analysis is commonly applied for to experimentally determine stress concentration distributions [5]. Moreover, since in the last years experimental vibration fatigue damage evaluation methods were grown [6-7], thermoelasticity was also used in order to identify modal damage using modal damage decomposition [8].

In this article, a methodology to perform TSA on moving and/or rotating mechanical component is presented.
This methodology is applied on a fan blade, in order to obtain the stress distribution on its plastic shell; the main steps are:

- development of test bench
- recording the thermal film of the fan blade during rotation and movement
- post-processing the thermal film

The stress map distribution has been compared with that one of the fans in static condition (i.e., no rotation or movement), to verify if the stress distribution is the same of the previous one.

III. MATERIALS AND METHODS

The test bench

As already said, the test case used to develop the methodology is a plastic fan blade, and this investigation method is applied to obtain the stress distribution on its surface.

Figure 1. The fan analysed.

A thermal marker (Fig. 2) with high IR emission is developed, to allow to follow the rotation of each fan blade using the software Termoimage. This marker (Fig. 2) is a micro tungsten-filament-lamp, covered with alcohol cotton soaked. All these components are assembled inside a plastic tube of diameter about 5 mm.

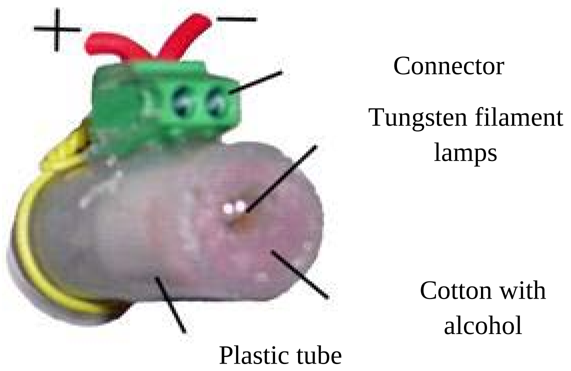

Figure 2. The thermal marker.

The marker is connected to the electric wire, using wrapping techniques, and they are powered by a battery (9V).
Finally, the marker and the battery are glued on the fan flange as shown in Fig. 3:

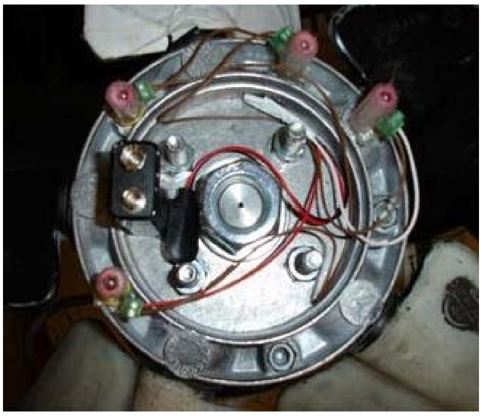

Figure 3. The four markers and the battery on flange.

The test bench is designed to be assembled on the electrodynamical shaker (Fig. 4), and at the same time the shaker stresses and spins the fan. In order to guarantee the fan rotation as in working condition, it was decided to use an electric engine that is powered by a voltage generator.

Figure 4. The shaker LDS 650, its amplifier 1000 PA (on the left), and the HP voltage generator.

The motor is rigidly joined to the vibrating head of the shaker, using a support, as shown in Fig. 5. Subsequently, the fan is joined to the motor shaft. The assembly is performed using the fan flange as in Fig. 5.

Figure 5. The test bench assembled on the shaker, and the CAD model.

Data Acquisition and Elaboration

Full-field thermal images were acquired using a DeltaTherm 1560 thermal camera (Fig. 6) [9], produced by Stress Photonics.

Figure 6. The thermocamera DeltaTherm 1560, and the zoom for high spatial resolution.

Two thermal acquisitions were performed, in the following load conditions, shown in Tab. 1:

Table 1. The testing conditions.

	Load Frequency (Hz)	Applied mass (kg)	Acceleration level	Rotational speed (rpm)
Test #1	20	0,2	$1g$	65
Test #2	61	-	$10\,g$	15

During the Test #1, a mass 0,2 kg was applied on the free edge of the blade, to increase the stress condition; the thermal acquisition was about 20 s, and the frame rate was 100 frame/s.
In the Test #2, the fan was stressed at the first resonance frequency (61 Hz), with an acceleration amplitude of 10g, measured on the shaker table; the sampling frequency was set at 200 frame/s for 10s length.
At a later time, all the film frames were processed by the software Termoimage, that it compensates the rotation of the fan.
The main steps to process the files of the thermal segment film are:

- selection of the folder where the files are
- setting of filter value to represent thermal images
- contours location of the areas on thermal image
- coordinates location of mass areas centre
- selection of reference areas

Now the software calculates the displacement and/or rotation of the frames as regards the reference one; once the computation is completed, the compensate frames are saved. Analysing the files processed, it can be observed that the de-rotation of the film frames needs the rotation of the frames respect to marker, as illustrated in Fig. 7.

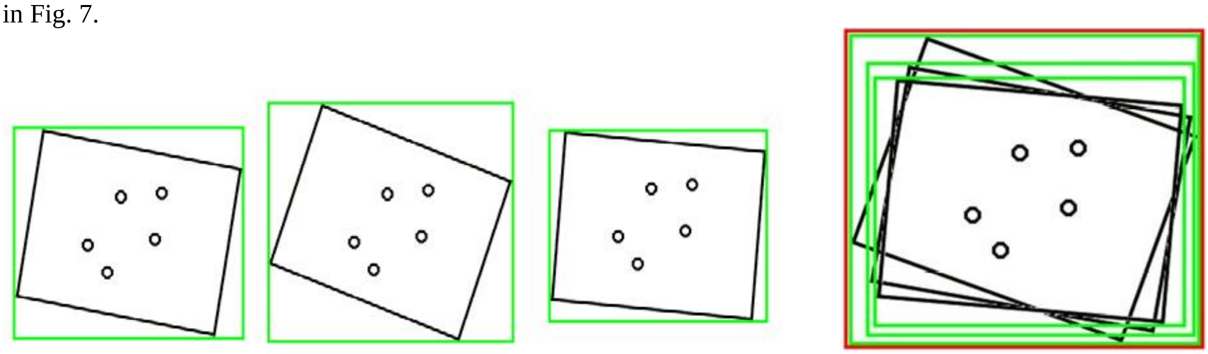

Figure 7. The frames de-rotated with the new borders (green); the resulting new border (brown) processing all frames.

For this reason, the new de-rotated films need a larger matrix to store the new frames.
The second part, consists in the files processing obtained using Termoimage: two algorithms were developed to filter thermal signal of the frames, and to calculate thermoelastic effect.

The first is based on DFT [10], and this algorithm was performed on every pixel time history; the second is a digital processing implementation of the lock-in techniques [11], that uses square waves at the loading frequency as reference signal.
Both the routines have as input the de-rotated thermal film and generate as output two images that represent modulus and phase of the thermal fluctuation due to thermoelastic effect.
Therefore, the amplitudes spatial distributions image is proportional to the distribution of the first invariant stress of the blade.

TSA on the fan rigidly join on the shaker
It was performed a full-field stress analysis on fan fixed on the shaker; these maps were compared with the one of the fans not in motion. The frequency loads, acceleration amplitudes were the same of Test #1 and #2 (Tab. 1).
The maps of the blade are reported in Fig. 8, and show an elevated stress concentration on the zone near the blade cone; this element joins the blade to the aluminium fan flange. This stress concentration is expected, because they confirm the results obtained from previous studies [12].

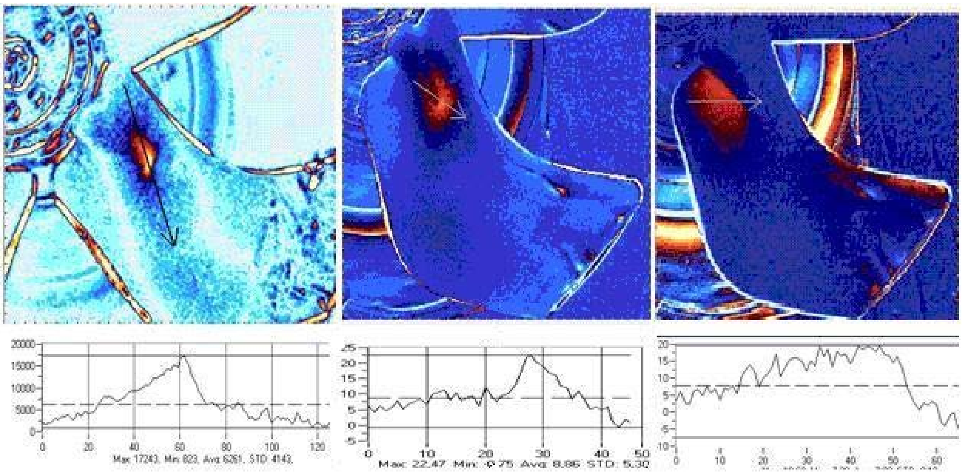

Figure 8. The stress maps of the blade (test 1: on the left, test 2: on the right).

Results and discussion
Total we obtain the fan thermoelastic maps, using the two algorithms previous described.

- ***DFT algorithm***

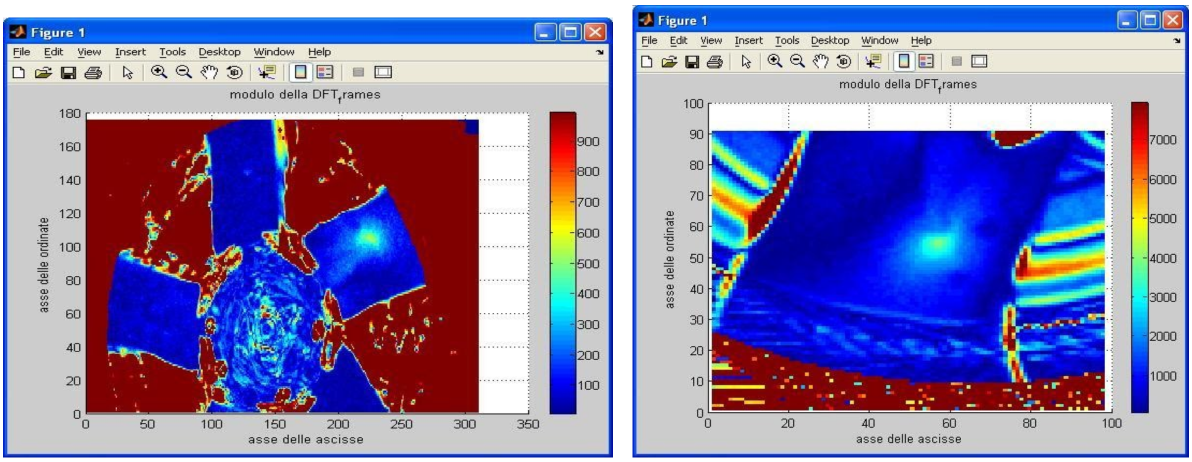

Figure 9. Stress maps of the fan (on the left), and the blade (on the right) relative to test 1.

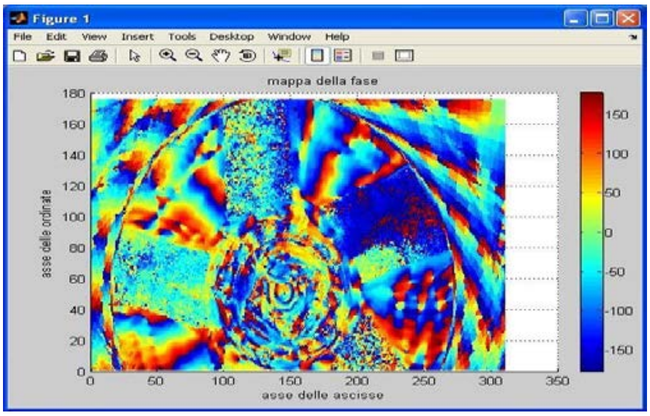

Figure 10. Phase maps of the fan relative to test 1.

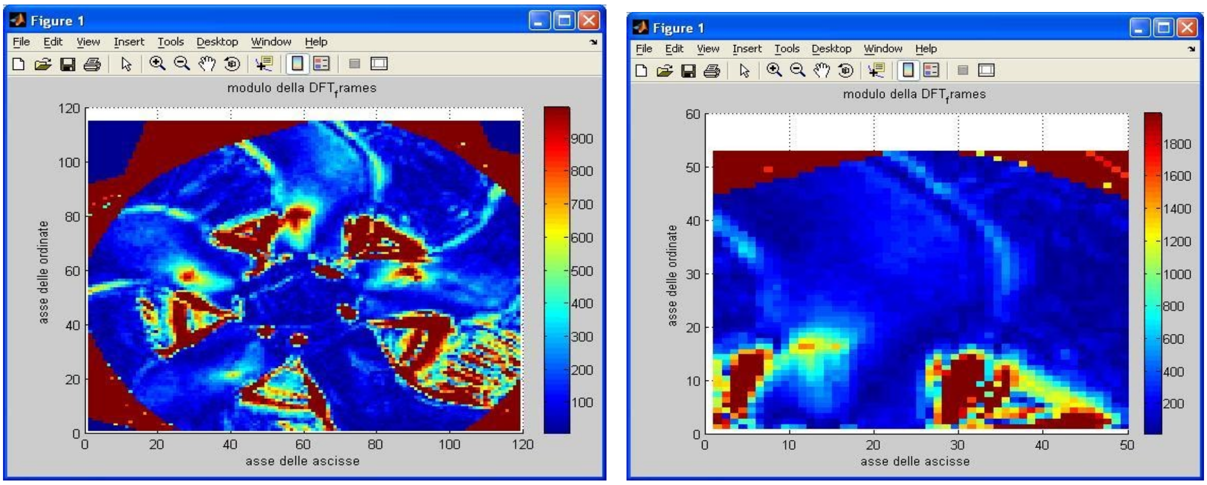

Figure 11. Stress maps of the fan (on the left), and the blade (on the right) relative to test 2.

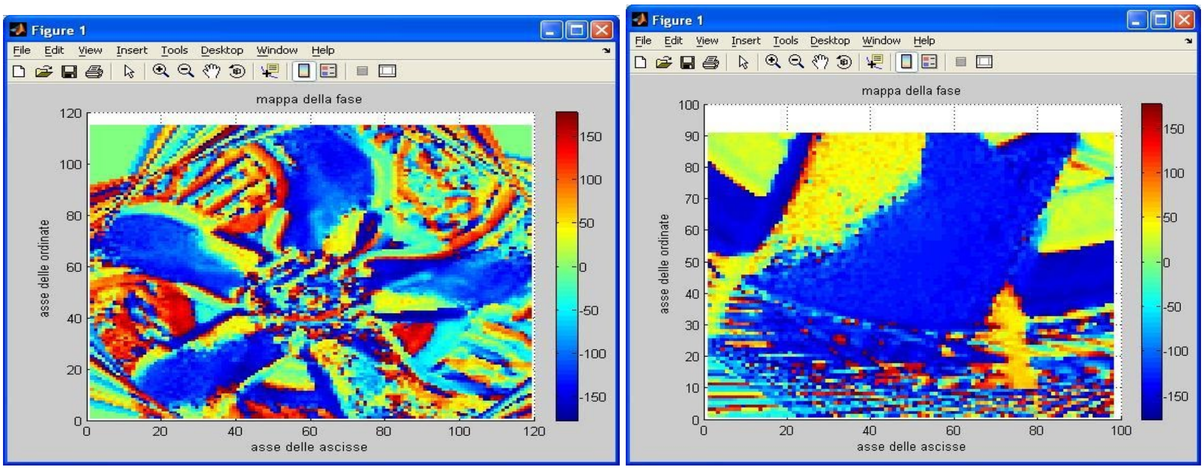

Figure 12. Phase maps of the fan (on the left), and the blade (on the right) relative to test 2.

All these maps show the same stress concentration zone, that is localized near the cone tip; in fig. 11, the fan map highlights the stress concentration zone on three blades, on the contrary in Fig. 9 only one. This is due to the different acceleration level of Test #2 respect Test #1; in fact, we can see thermoelastic effect only on the blade not painted. The phase on blade considered, has constant fields that shows low noise level.

- ***Lock-in algorithm***

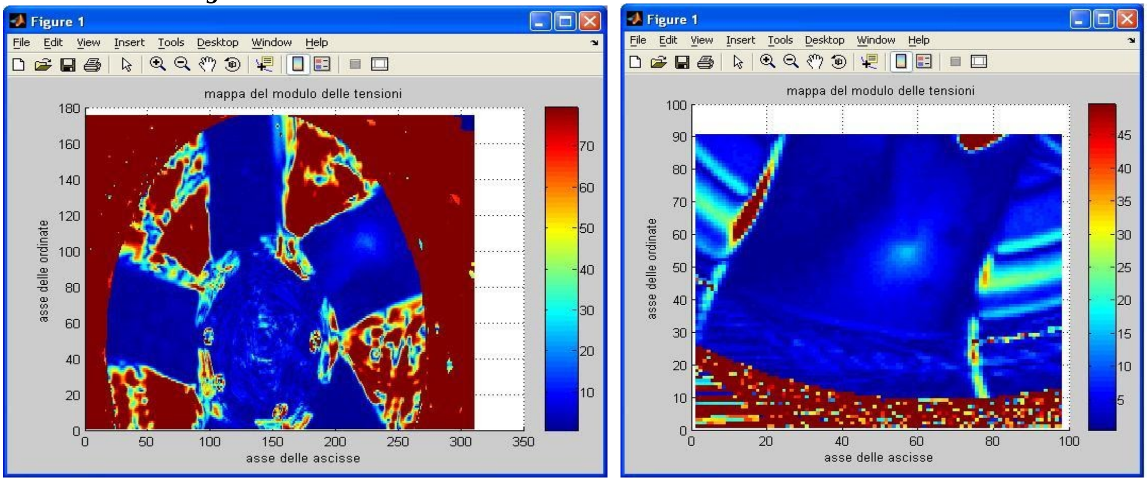

Figure 13. Stress maps of the fan (on the left), and the blade (on the right) relative to test 1.

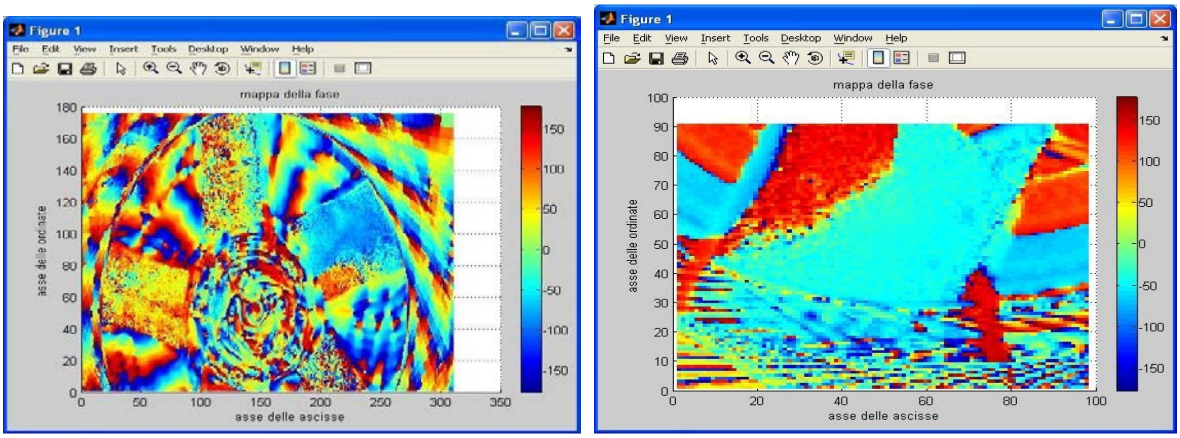

Figure 14. Phase maps of the fan (on the left), and the blade (on the right) relative to test 1.

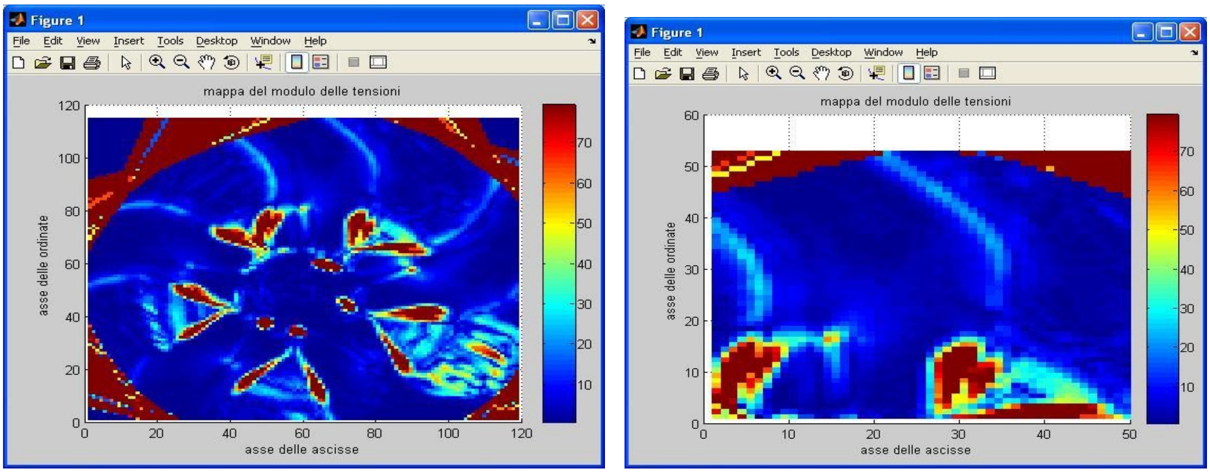

Figure 15. Stress maps of the fan (on the left), and the blade (on the right) relative to test 2.

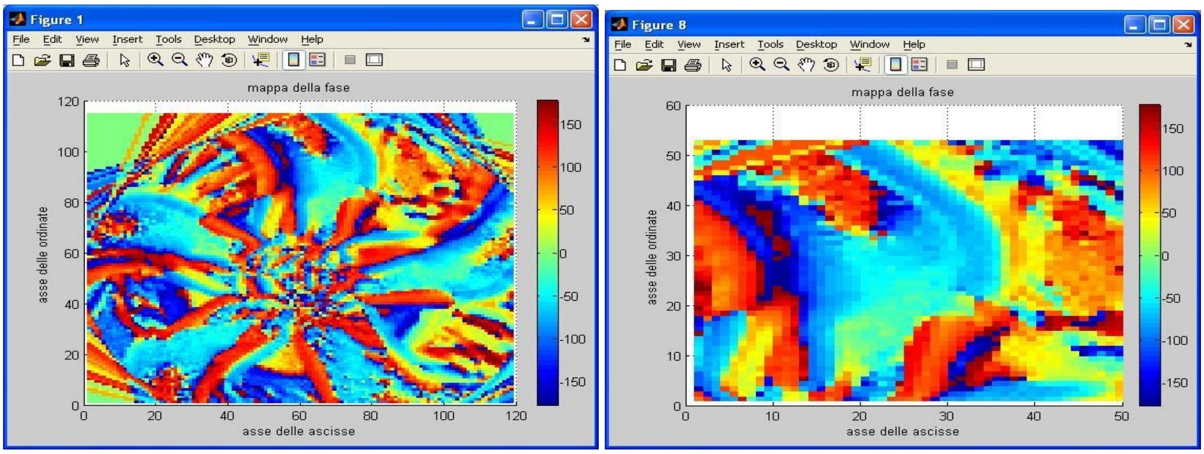

Figure 16. Phase maps of the fan (on the left), and the blade (on the right) relative to test 2.

These maps confirm the previous results and their stress distributions, but it is lost the stress gradient (Fig. 13, 15). To validate the developed methodology, the stress maps in Fig. 9, 11, 13, 15 were compared with those (Fig. 8) of the fan joined to the shaker.
The qualitative comparison of those maps gives good results; in fact, the stress concentration is localized in the same area.

Moreover, this technique has been applied also on plastic tab of a washing machine and the goal of these tests consists in obtaining the stress of maps of this component in its typical working condition.
The area of the plastic tab was very large, and then was divided into parts to be studied; thermal films were acquired during normal washing operation and centrifugation at the rotational speeds of 900 and 1600 rpm. The thermal markers have been applied on each area examined of the component. Thermoelastic maps are displayed in fig. 17, and gives confirmation of FEM modelling. Therefore, using the developed measurement techniques, it was possible to validate the numerical model of the washing machine component analysed, in terms of predicted stress concentration factors.

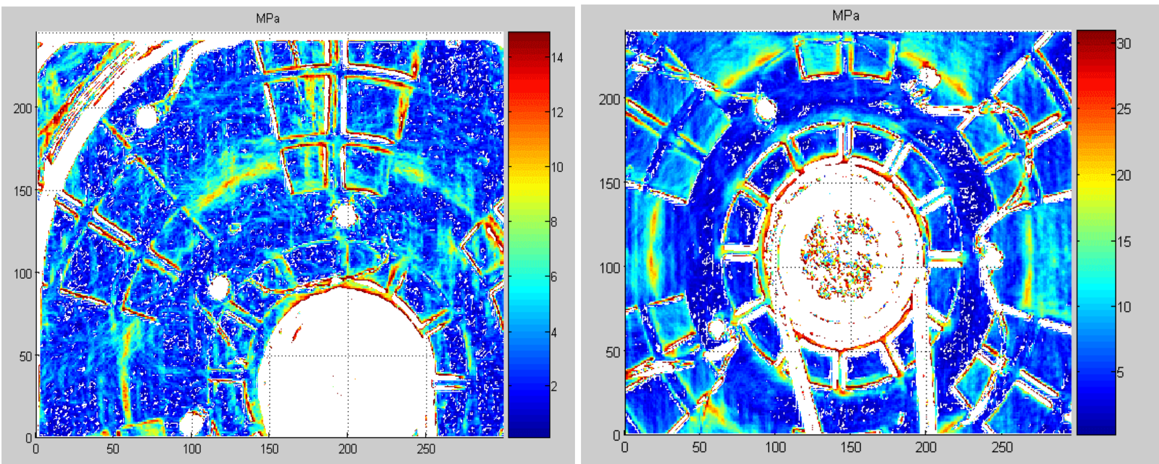

Figure 17. The stress maps of the shell in its working condition.

IV. CONCLUSION

A methodology was developed and tested to measure by thermoelasticity stress fields on moving mechanical components, rotating and oscillating; this technique requires only to record a thermal film of the component surface during its motion.
The second step was performed by means of Termoimage, software developed homemade, and it compensates the movement and rotation of the fan.
The files, containing the frames realigned, were processed to filter the thermal signal to carry out the only contribution of the thermoelastic effect; to this purpose it was developed two routines in Matlab code based on DFT and digital lock-in.
Overall, the methodology permits to perform the TSA on mechanical component in movement, and this allow us to analyse the stress pattern in normal working condition.

REFERENCES

[1]. Thomson, W. (Lord Kelvin), "On the Dynamical Theory of Heat", Transaction of the Royal Society of Edinburg 20: 261-283 (1853).
[2]. Harwood N. and Cummings W.M., "Thermoelastic stress analysis" Hadam Hilger, Bristol, Philadelphia and New York.1991
[3]. M. Moretti et al., Measurement on rotating mechanical component by Thermoelasticity. Congresso BSSN, 2005.
[4]. R. Montanini, G. Rossi, A. Quattrocchi, D. Alizzio, L. Capponi, R Marsili, T. Tocci, Structural Characterization of Complex Lattice Parts by Means of Optical Non-Contact Measurements
[5]. G. Allevi et al. Investigating additive manufactured lattice structures: a multi-instrument approach. IEEE Transactions on Instrumentation and Measurement (2019)
[6]. G. Morettini et al. Collection of experimental data for multiaxial fatigue criteria verification. Fatigue & Fracture of Engineering Materials & Structures 43 (1), 162-174 (2020)
[7]. J. Slavič et al. Non-stationarity and non-Gaussianity in Vibration Fatigue. Sensors and Instrumentation, Aircraft/Aerospace, Energy Harvesting & Dynamic (2020)
[8]. L. Capponi, J. Slavič, G. Rossi, M. Boltežar. Thermoelasticity-based modal damage identification International Journal of Fatigue, 105661 (2020)
[9]. Stress Photonics, www.stressphotonics.com
[10]. Alan O. Schafer: "Discrete - time signal processing", Prentice Hall International Inc.
[11]. John H. Scofield, A Frequency-Domain Description of a Lock-in Amplifier", American Journal of Physics, 1994.
[12]. A. Di Renzo, R. Marsili, M. Martarelli, M. Moretti, G. Rosati, G. L. Rossi, "Simultaneous Application of Scanning Laser Vibrometry and Thermoelasticity for Measurement of Stress-Strain Fields on Mechanical Components" Int Conf. on Vibration Measurements by laser techniques, Ancona, June, Proc of SPIE - vol 6345, 2006.
[13]. R. Marsili, G.L. Rossi, M. Becchetti, R. Flori, "Measurement of stress and strain by a thermocamera", SEM Annual conference & Exposition on Experimental and Applied Mechanics, June 1-4, 2009, Albuquerque, New Mexico, U.S. ISBN: 978-1-61567-189-2.
[14]. Allevi, G., Cibeca, M., Fioretti, R., Marsili, R., Montanini, R., Rossi, G., Qualification of additively manufactured aerospace brackets: A comparison between thermoelastic stress analysis and theoretical results, (2018) Measurement: Journal of the International Measurement Confederation, 126, pp. 252-258. DOI: 10.1016/j.measurement.2018.05.068
[15]. E. Cardelli, M. Cibeca, A. Faba, R. Marsili, M. Pompei, G. Rossi, "Magnetic sensors for motion measurement of avionic ballscrews" (2017) AIP Advances, 7 (5), art. n° 056639, American Institute of Physics Inc. DOI: 10.1063/1.4975047

L. Capponi, R. Marsili." Thermoelastic stress analysis on rotating and oscillating mechanical components." *International Journal of Computational Engineering Research (IJCER*), vol. 10, no.6, 2020, pp 17-25.