Structural Health Monitoring Suitable for Airborne Components Using the Speckle Pattern in Plastic Optical Fibers

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***Abstract*— Structural health monitoring (SHM) is a key factor for the correct operation in large dimension structures. In this paper, we propose and demonstrate the application of a distributed optical sensor, suitable for SHM, based on the evaluation of the speckle pattern at the output of a polymer optical fibers, aiming to evaluate the damage imposed to airborne metallic and composite structures. We propose also several algorithms to analyze the speckle data and access the imposed mechanical perturbation. The maximum sampling frequency of this method is limited by the image acquisition devices, yielding to a value of 15 Hz in our case.**

***Index Terms*— Polymer optical fiber, speckle pattern, structural health monitoring.**

I. Introduction

A SAFE operation is the main goal of any aircraft operator. Since the structural failure may be catastrophic, it is important to monitor the structural health and to perform maintenance actions in order to maintain the operational performance [1], [2].

Structural health monitoring (SHM) has several definitions; however, it can be intuitively described as the diagnosis and prognosis of the structure capability to operate properly and maintain its structural integrity throughout its lifetime [2], [3].

For aircraft structures, it is known that structural degradation, induced by materials aging, due to the environment (fatigue, corrosion, etc.) or even due to unforeseen external events (impacts, etc.) is inevitable. Therefore, it is important to take special precautions for aircrafts operating close to or beyond the life cycle end, when a significant increase of structural defects may occur [4], [5]. For example, in 2000 more than 75% of the United States Air Force (USAF) aircrafts had more than 25 years [3].

Thus, to ensure a safe operation it is essential to conduct periodic inspections to the structure integrity, using external equipment's, and, if necessary, replace damaged components. Future tendency will be to replace completely the inspections by continuous structural health monitoring using on-board systems (implemented within the aircraft), increasing security and confidence in the systems and reducing the periodic inspection cycles, eliminating the costs of unplanned maintenance on new aircrafts and ensuring greater longevity of the components [6], [7]. For these SHM systems, the inspections will be conducted using non-destructive techniques, being the sensors and actuators permanently attached to the structure, collecting data continuously during the entire service life of the structure, without operator intervention, so that an integrity evaluation could be performed in real time and if necessary carrying out repairs in a timely manner [4].

A recent study on the requirements of a fighter aircraft inspection (in terms of metallic and composite structures) shows that more than 40% of inspection time could be saved if on-board intelligent monitoring systems had been used. Such systems may be composed by an assembly of sensors, actuators and signal processors that are able to respond and adapt to changes in their environment [7]. In addition, it is noticed that some authors assume that more than 20% of the cost of a transport aircraft maintenance/inspection (civil or military) may be saved, when using integrated damage monitoring systems.

As the damage position is not known a priori, the SHM implementation requires a sensor network, covering the whole structure. Recently, optical fibers have emerged as a sensor networks technology, getting the information all along the fiber length [8]. This economically attractive technology, namely if considering plastic optical fiber, has a great potential since it ensure continuous monitoring, do not require extensive maintenance, improve the performance and safety of the aircraft and extend the lifetime of structures [9]. For the particular case of aircraft structures, even though optical fiber sensors have demonstrated to be a promising technology, strain gauges still remain being the most used method to perform strain

Manuscript received May 9, 2017; revised June 9, 2017; accepted June 9, 2017. Date of publication June 13, 2017; date of current version July 10, 2017. This work was supported in the scope of UID/EEA/50008/2013 and IDMEC–LAETA, in part by the National Funds through the Fundação para a Ciência e a Tecnologia/Ministério da Educação e Ciência, and in part by the European Regional Development Fund under the PT2020 Partnership Agreement. The support from the Brazilian Ciência sem Fronteiras (PVE) Program is also appreciated. The work of P. Antunes was supported by FCT through the Postdoctoral Research Fellowship SFRH/BPD/76735/2011. The associate editor coordinating the review of this paper and approving it for publication was Dr. Minghong Yang. *(Corresponding author: Paulo Sérgio de Brito André.)*

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Digital Object Identifier 10.1109/JSEN.2017.2715258

measurements in operational aircraft structures [10], [11]. Furthermore, optical fiber sensors have important advantages over conventional strain sensors, including the reduced weight and the suitability (robustness, [12]) for being attached to metallic structures in operating aircrafts or embedded in the composite materials production for new generation planes [13].

In this paper we propose the use of an optical sensor, built in polymeric optical fibers and based on the analyses of the speckle pattern at the fiber output to monitor the structural health in aircrafts.

This work is organized as follows: after an introduction, the theory of the speckle pattern is presented in section II. Section III deals with the presentation of the developed sensor. In Sections IV and V the main experimental results for steady-state and for vibrational tests are presented. Finally, the main conclusions are drawn in section VI.

II. Polymer Optical Fibers and Speckle Pattern

The implementation of an SHM strategy requires the use of sensors to monitor several parameters, enabling the structural damage detection. Therefore, in order to make this monitoring possible, it is necessary to develop lightweight and compact sensors with a competitive cost (compared to conventional technologies well established in the market). A promising approach is the sensors based on polymer optical fibers (POF) development, which have electromagnetic interference immunity, are lightweight, robust, flexible and have no risk to produce electric sparks [14].

The POF are flexible waveguides generally produced in a rigid and transparent thermoplastic polymer, PMMA (polymethylmethacrylate). However, these fibers present some disadvantages like greater attenuation coefficients, limited production, lack of standardization, few suppliers and the inability to operate at high temperatures (above 80-100°C) [8]. Offering most of the same intrinsic advantages as any optical fiber, POF add some important benefits, like the handling simplicity, impacts and vibrations resistance, lower density ($\sim$1200 kg m^{-3}), higher elastic deformation limit ($\sim$10%), higher fracture toughness and a large diameter (0.25 mm-1.00 mm). These characteristics facilitate the light coupling with rough accuracy connectors and consequently reduce the total cost associated with the system.

Considering a coherent electromagnetic signal beam, focuses on a rough surface (with roughness greater than the radiation wavelength), the components scattered by independent areas of the surface get different phases relative to the incident wave phase. The phase shift of those components (still coherent) results in the interference (constructively or destructively) along space, generating a statistical distributed interference pattern, known as the granular speckle pattern. Therefore, this granular pattern observable in an area consists of a set of bright spots where the interference is constructive and black spots where the interference is destructive [15], [16].

The speckle patterns can also be obtained at the output of a multimode optical fiber, as proposed initially for multimode silica fibers [17], [18] and later for POF [19]. The speckle pattern in this fibers occurs due to interference among the different coherent modes propagating in the waveguide, with different phase velocities [20].

Fig. 1. Image of a speckel pattern obtained at the output of a POF.

Consequently, if the fiber is disturbed by external factors, the intensity distribution pattern in the fiber output, which reflects the aggregation of all individual propagating modes, changes. In Fig. 1 it is possible to observe a typical speckle pattern obtained at the output of a POF.

The total intensity of the speckle pattern, measured at the optical fiber output, when the fiber is exposed to a disruption is given by [11]:

$$I_i = A_i \left\{1 + B_i \left[cos\delta_i - F(t)\phi_i sen\delta_i\right]\right\} \tag{1}$$

where A_i depends on the modes self-interaction, B_i accounts for the steady-state mode-to-mode interaction, $F(t)$ is the external disruption, and ϕ_i is the phase of the mode-to-mode interaction [11]. The parameters A_i, B_i and δ_i are constant values for any given i^{th} speckle pattern. Each speckle pattern, i^{th}, can be seen as an interference matrix under the same perturbation. Thus, analyzing the speckle patterns and their evolution, it is possible to find the disruption affecting the fiber and its characteristics. These changes can be detected by comparing a reference pattern with the resulting pattern after deformation. Therefore, the implementation of this method as a vibration/deformation sensor is possible by deploying multimode fibers at the desired location [11].

The correlation coefficient between the reference speckle pattern and the subsequent patterns is representative of the disruption. The intensity of the speckle patterns before the perturbation $I_i(x, y)$ and after the perturbation $I_j(x, y)$ can be compared by the correlation coefficient between these frames:

$$C_{i,j} = \frac{\langle I_1(x,y)I_2(x,y)\rangle - \langle I_1(x,y)\rangle\langle I_2(x,y)\rangle}{\sqrt{(\langle I_1^2(x,y)\rangle - \langle I_1(x,y)\rangle)^2 \times (\langle I_2^2(x,y)\rangle - \langle I_2(x,y)\rangle)^2}} \tag{2}$$

where $\langle\cdot\rangle$ denotes the mean averaging over the spatial coordinates (x and y). The correlation coefficient takes the value 1 if the intensity distribution of the speckle pattern between the two frames are equal to and it gradually decreases as the speckle pattern changes [11].

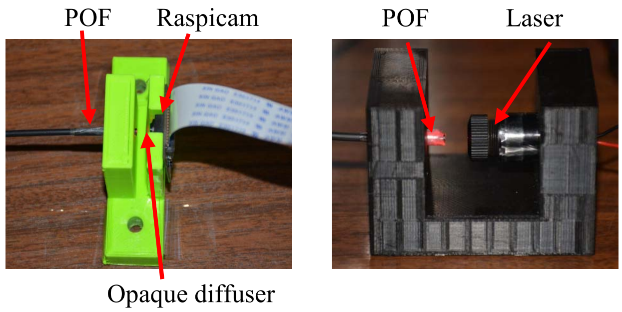

Fig. 2. Photography of the printed polymer structurers used to couple the POF to the Raspicam (left) and to the laser (right).

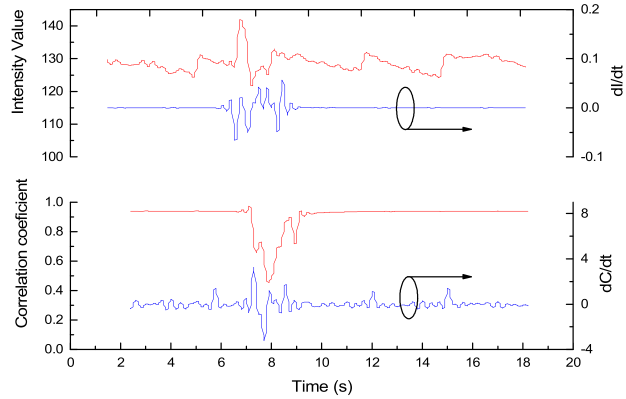

Fig. 3. Speckle pattern analyses as functions of time for a test sequence involving a disruption imposed at ~7 seconds: (top) frames average intensity value; (bottom) correlation coefficient between consecutive frames. The derivate values of the aforementioned parameters are shown on the right axis.

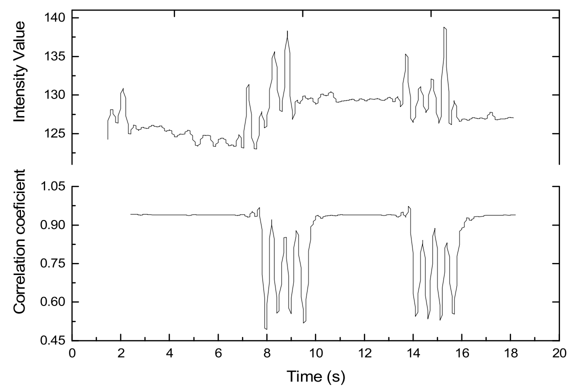

Fig. 4. Speckle pattern analyses as functions of time for a test sequence involving two sets of 4 disruptions imposed at ~8 and ~14 seconds: (top) frames average intensity value; (bottom) correlation coefficient between consecutive frames.

III. Optical Sensor Implementation

The propoused sensor comprises a semiconductor laser (Roithner - LDM650/3LJ), peaking at a wavelength of 650 nm with an optical power of 3 mW. The laser optical signal is injected in a POF (*Avago Technologies* – HFBR-RUS100Z), with a length of 2.25 m. After propagation, the output optical signal is projected onto a semi-opaque film and the speckle detection is achieved by a Raspberry Pi camera (Raspicam) with 1920 × 1080 pixel resolution, SNR of 36 dB and a frame rate of 30 Hz. The Raspicam is controlled by a Raspberry Pi 1 Model B (RPI), responsible for the digital signal processing, using Matlab®, performing the basic algorithms necessary for filtering, down sampling and correlation. Fig. 2 shows the supporting structures produced with PLA (Polylactic acid, which is a bio-degradable polymer) in a 3D printer (3D Systems, model Cube 3rd Generation), for coupling the POF ends to the camera and to the laser.

To get clearer and more perceptible speckle patterns, the camera acquisition settings must be changed, disabling all automatic effects. It is also necessary to increase the contrast, brightness, sharpness, shutter speed, ISO sensitivity and decrease the saturation. The increasing of the shutter speed and ISO sensitivity is a crucial step, improving the saturation limit and the detection of contours, increasing the sensitivity to mechanical vibration.

To ensure the continuous monitoring of structural health it is necessary to continuously acquire the speckle patterns and analyze them in real time. In this proof of concept the images where analyzed offline. However, the Raspberry Pi computational capacity is enough to process this analyses on real time.

IV. Steady State Results

To illustrate the sensor operation we present the results for a fiber lateral deformation of ~3.75 cm (for a fiber with a length of 45 cm), occurring at ~7 seconds (after the fiber was released and relaxed to the initial state). For the speckle patterns analyses several methods were applied, namely: *i*) consecutive frames correlation and *ii*) frame average intensity for an image area of 200 × 200 pixels centered with the speckle pattern. As an additional analysis tool it was also considered the local derivative for the described methods.

In Fig. 3 the perturbation results, using the described analysis methods, are presented. It can be realized that the correlation value is constant ~1 (the frames are highly correlated) when the POF is static. Then, the correlation coefficient value decreases during the perturbation (~7 seconds). After the perturbation the correlation value tends to re-stabilize around 1.

Moreover, the speckle pattern intensity also indicates the occurrence of the disruption. The occurrence of perturbations can also be detecting by analyzing the data time derivative values (for the intensity and correlation coefficient).

To analyze the ability to detect consecutive perturbations, two sets of four mechanical impacts were performed on the work table under which the optical sensor lays. The results are shown in Fig. 4, the first set began at ~7 seconds and the second repeated at ~13 seconds.

From the data of figure 4, it is possible to observe that each peak represents an impact, allowing to identify the two sets of 4 beats regardless of the algorithm used.

V. Vibration Tests

To analyze the vibration disruptions on a metal frame, representing an aircraft structure, a POF segment with 86 cm was fixed on the frame main diagonal (the total length was ~4 m). This aluminum sample has dimensions of 55.5 × 67.5 × 0.1 cm^3. The sensors used for the SHM system can be focused on the particular area of interest and the system can be designed to detect the expected types of damage. This proof of concept assumes the damage location within a typical wing inspection panel [6], [21].

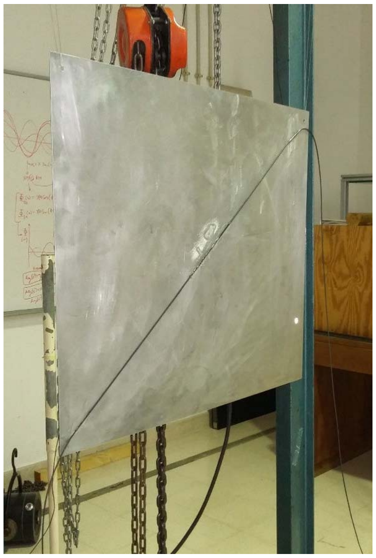

Fig. 5. Photography of the metal test frame with the POF fixed along the main diagonal.

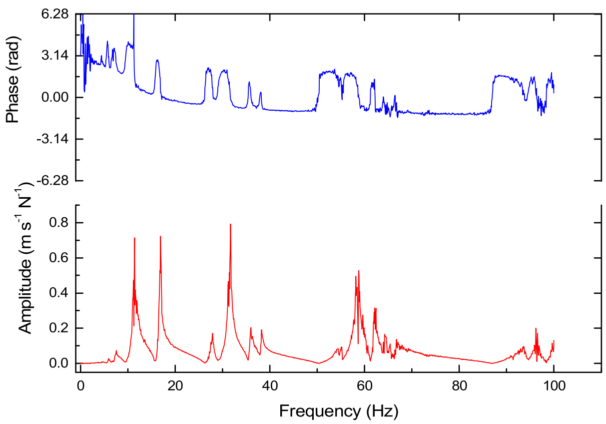

Fig. 6. Aluminum frame vibration spectral response. (top) phase, (bottom) amplitude.

The structure resonant frequencies, f_r, corresponds to the values for which the structure vibrates with higher amplitude under reduced excitation. Thus, performing the tests in the resonant frequencies values, higher vibration amplitudes are achieved and lower experimental errors are ensured.

To reproduce a free space disruption, the sample was suspended, as seen in Fig. 5, and excited by a vibration exciter (4809 Brüel & Kjær) near the metal structure corner, guarantying the excitation of a higher number of vibration modes.

Using the vibration shaker, was possible to estimate the experimental values for the resonant frequencies, through the Bode diagram analyses for the excitation force and vibration speed. Recurring to the Fast Fourier Transform (FFT) was possible to obtain the vibration amplitude and phase spectral response as displayed in Fig. 6. The resonance frequencies can then be identified by a peak-picking method in the amplitude spectrum and through an abrupt change in phase (7.6 Hz, 11.4 Hz, 16.9 Hz, 27.9 Hz and 36.0 Hz).

To evaluate the sensor response, the frame was subjected to a periodic sinusoidal mechanical disruption, with constant excitation amplitude and frequencies closer to the predefined resonant frequencies values. Furthermore, to verify the optical sensor outside the resonance the frequencies of 2 Hz, 50 Hz and 60 Hz were also used.

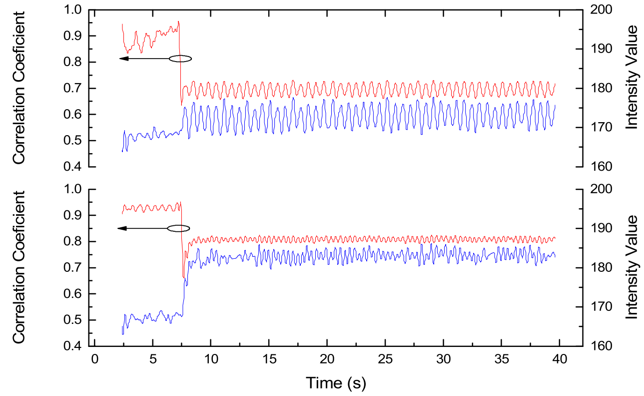

Fig. 7. Correlation coefficient and average intensity values (right axis) as functions of time for a periodic disruption started at ~7 second, with a frequency: (top) 16 Hz and (bottom) 28 Hz.

It is important to note that *Raspicam* operates with a 30 *fps* image transfer rate, i.e., through the Nyquist sampling theorem the optical sensor reliable operation is limited to a maximum frequency of 15 Hz. Consequently, above this frequency it is not possible to reproduce the perturbation signal from the speckle pattern analysis, due to the aliasing; however, a change in the correlation coefficient or intensity values can be used to identify the occurrence of the perturbation.

Fig. 7 shows the correlation coefficient between consecutive frames and the frame average intensity for two examples of disruption (16 Hz and 28 Hz).

Through an analysis of all the results of this test, it can be concluded that, regardless of the methods and the frequency used, it is possible to identify the mechanical perturbation.

To analyze the correlation coefficient and average intensity values for the different excitation frequencies, we consider the ratios of the correlation coefficient (ΔC) and frame average intensity (ΔI) during the perturbation to the steady state values (before the disruption). These results obtained with an integration window of 60 frames are shown in Fig. 8.

Through the previous results, it can be observed that a larger change in ratio value occurs in both methods, with large changes taking place for the frequency range [10 Hz, 50 Hz]. This range contains 3 resonant modes, that when excited result in vibrations with high amplitudes.

The sensitivity of ΔC and ΔI to the frame vibration amplitude depends on the frequency. This can be explained by the already referred aliasing due to the limitation of the camera refresh rate. However, both parameters show a complementary behavior, therefore a good trade-off will be to use both to assess the frame vibration in a wider frequency range.

Furthermore, it is also possible to use an additional parameter, the relationship between the observed normalized oscillating amplitude (Δr_i, where i designates correlation coefficient (C) or the intensity (I)) during disruption as a function of the working frequency, shown in Fig. 9.

Also in this analysis this procedure can be used if the disturbance frequency is bellow half the value of the video sapling rate to avoid the data alising.

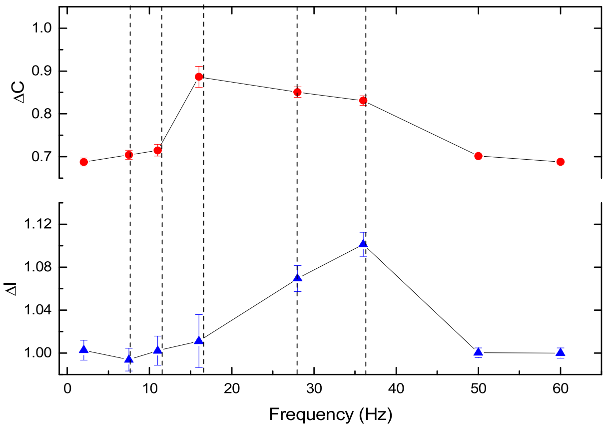

Fig. 8. Ratio of correlation coefficient (ΔC) and frame average intensity (ΔI) as functions of frequency. The lines are visual guides and the error bars represent the experimental uncertainty. The aluminum test frame resonant frequencies are indicated by the vertical dashed lines.

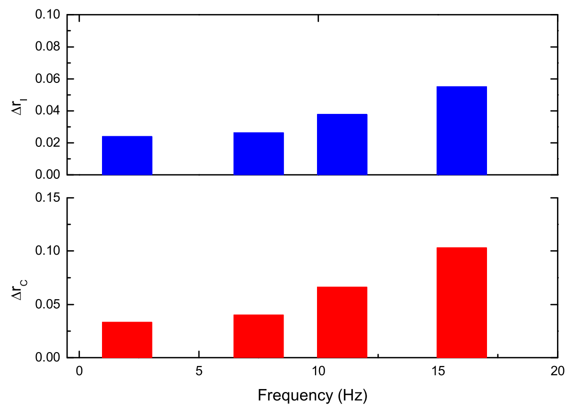

Fig. 9. Correlation coefficient (bottom) and intensity (top) normalized oscillating amplitude as a function of the excitation frequency.

The typical deformations in aircraft frames are imposed by tensile forces, for instance during take-off. To analyze this situation, the aluminum frame with the optical fiber sensor was tested in a Material Test System (MTS 810) and subjected to tensile disruptions, with a force ranging from 0 kN to 3 kN with a frequency of 6 Hz. The obtained results, of the correlation between consecutive frames during the tensile test are presented in Fig. 10.

Also from this test it is possible to conclude that the sensor could also identify the mechanical disruptions.

As a final remark we must point out that the speckle pattern is highly sensitive to the temperature. However, for the propose application the temperature fluctuations occur with a changing rate much smaller than the structural vibration, therefore both phenomena can be decoupled.

The attained results in terms of operation frequency and sensitivity are similar to other optical fiber sensors used for aircraft structural health monitoring [22], [23]. The operation coverage range of this sensor is limited by the plastic optical fiber attenuation (typically 0.2 dB/m for the operation wavelength), yielding to a value of ∼50 m by assuming a maximum attenuation of 10 dB. The accuracy to determine the vibration resonant frequency is defined by the bandwidth of the applied FFT (Bw_{FFT}), which depends on the camera sampling frequency (f_s) and on the signal length (N), $Bw_{FFT} = f_s/N$. Assuming a signal integration time of 10 s, the resolution can be estimated to be 0.1 Hz. These coverage range and resolution are adequate to cover the application here proposed.

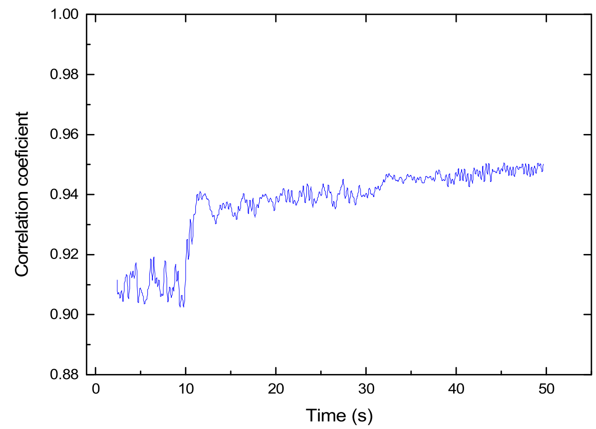

Fig. 10. Correlation coefficient for a tensile test with a frequency of 6 Hz and an average force of 1.5 kN.

VI. Conclusion

Aircraft structures, due to their operating conditions, require intense inspection operations, where optical sensors based SHM could play an important role. In this paper we presented the development of a polymer optical fibers sensor, using speckle patterns, for SHM purposes. In addition, the speckle patterns were studied and numerical algorithms for the images analysis were optimized.

It is noted that the isolated and vibration disruptions are more easily identified just comparing the frames average intensity (which has a faster image processing speed), whereas the consecutive speckle patterns correlation identify the tensile disruptions more easily. Therefore, the combination of these two algorithms allows the identification of any type of disruption. The maximum sampling frequency of this method is limited by the image acquisition devices, yielding to a value of 15 Hz in our case. However the typical resonant frequencies of these structures are bellow this limit.

Through all that has been presented above, it becomes clear that it is possible to create a structural aircraft health monitoring system using polymer optical fibers with reduced costs and enabling continuous monitoring with low electromagnetic interference ensuring safer, efficient and economically attractive aircrafts. Being feasible to integrate this sensor into critical areas of aircraft structure with minimal cost and weight penalty.

VII. Acknowledgment

The support from the Brazilian Ciência sem Fronteiras (PVE) Program is also appreciated. P. Antunes acknowledges the FCT support through the postdoctoral research fellowship sfrh/bpd/76735/2011.

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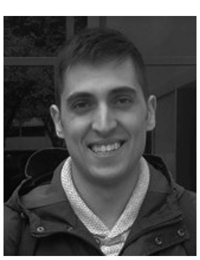

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