Ground Tests on a wing of an aircraft model using fiber optic sensors

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ABSTRACT

This paper concerns the use of fiber optic sensors for performing an experimental modal analysis in a wing of an aircraft model. Modal analysis can be used as a tool for checking the structural integrity of structures, in other words it can be used in a new branch of non destructing testing called Structural Health Monitoring (SHM). The objective of this paper is preliminary to the design of an SHM system for aeronautical structures. An SHM system is typically constituted by: integrated sensors, a system for data acquisition and an expert system for damage assessment. In this work the last part is not treated. The sensors used are the Fiber Bragg Gratings that have been embedded in the skins of the wing. Time domain response of the fiber optic sensors induced by impact hammer are acquired and transformed into the frequency domain. Using classical modal analysis techniques the first two strain mode shapes of the wing are determined from the Strain Frequency Response Functions. Also an accelerometer has been used to retrieve the mode shapes. Finally the results from a finite element model have been compared with the experimental results.

INTRODUCTION

The idea of using optical fibers as part of a nervous system on a structure has been applied for the first time in the eighties [1]. At that time fiber optic sensors were not mature and consequently plain optical fibers were used. That approach was limited only to on-off information. In other words only the failure of an optical fiber could be associated to structural damage since that failure resulted in loss, or dramatic intensity reduction, of optical signal. Nowadays due to a fall out from the telecommunication market, some devices, developed for optical signal filtering or processing, can be used as very small and integrated sensing devices. Particular relevance for structural application is covered by the Fiber Bragg Gratings (FBGs) that are basically strain optic sensors but offer several advantages over the conventional ones. FBGs can be multiplexed along the same fiber since they have the property of reflecting a specific "color" that allow the identification of the sensor. In fact usually the sensors are interrogated by injecting into the fiber a broad band infrared signal 40 nm wide. Each sensor properly manufactured, reflect a specific wavelength, called Bragg wavelength, that carries the strain information. Also, due to the small diameter of the optical fibers (from 150 to 250 μm) they can be embedded quite easily into composite materials [2-7] and with more difficulties into metallic materials [8-12]. These sensors can be used not only for performing direct Structural Health Monitoring (SHM) [13-14] but also for impact assessment [15] and for position monitoring [16,17]. One way of performing SHM is through modal analysis. Modal parameters can be acquired using sensorless optical fibers embedded into the component and inserted into an interferometer. In Ref. [6] that has been done on a Glass Fiber Reinforced Plastics

(GFRP) beam while in Refs. [18,19] on a zinc-aluminum alloy slender bar. In order to perform a real modal analysis, point measurements are required as opposed to the global (i.e., the total strain integrated over the embedded length) measurements that one can obtain with an interferometer. The first dynamic point strain measurement from embedded FBGs have been obtained in Refs. [20-22]. In particular in Ref. 22 the Strain Frequency Response Functions (SFRFs) of a Carbon Fiber Reinforced Plastic (CFRP) beam with an embedded FBG have been obtained while in Ref. 23 the first and second strain mode shape of the same bar have been retrieved from the SFRF. From now on the mode shapes retrieved from SFRF, will be referred to as strain mode shapes. In this paper the same procedure will be applied on a more complex structure but using also an FBG interrogation system with high acquisition rate. That will allow the retrieval of strain mode shapes other than the first one. The SFRFs are similar to the conventional FRFs obtained by impact hammer and accelerometers. For the retrieval of strain modes, the same rules and algorithms used for the conventional mode shapes are followed.

WING MANUFACTURING

Four Fiber Bragg Gratings (FBGs) have been embedded in one wing (1.3 m long) of a model of an unmanned aircraft (shown in Fig. 1). The sensors will provide real time strain measurements. Each wing of the aircraft has been manufactured as a sandwich with polystirene core and one ply of Glass Fabric (GF) (0/90) characterized by a density of 80 g/m^2. An epoxy resin with the relevant curing agent has been applied manually. The two parts of the polystirene core have been cut using a hot wire machine. The first layer of GF has been put on the two separate sections of the core. Then the I section spar of the wing was prepared connecting two C section of GF (0/90) and two slender plates of Carbon Fabric (CF) on each side characterized by a density of 200 g/m^2 (see Fig. 2). Also here the epoxy resin and the curing agent has been applied manually with a proper tool. Four fibers (two on the top and two on the bottom of the I spar) with one FBG each were positioned on the I spar. Finally one layer of GF with epoxy resin has been used to cover the whole assembled wing. Due to the presence of the polystirene it was not possible to cure the composite into an autoclave. Therefore external loads have been applied on the wing surface and 24 hours were required to completely cure the resin at room temperature. In Fig. 3 is reported a picture of the wing mounted on a fixture for dynamic test.

Figure 1. Photograph of the aircraft model.

The Glass Fiber Reinforced Plastic (GFRP) is transparent and consequently allows to see the spar as well as the polystirene body of the wing. The white dots on the spar are removable tags used to label the experimental grid used in the subsequent modal analysis test. In Fig. 2 two fibers are visible (see the two lines on top of the CFRP rectangular slender plate). The other two sensors have been embedded symmetrically with respect to the wing body and are not visible in the picture.

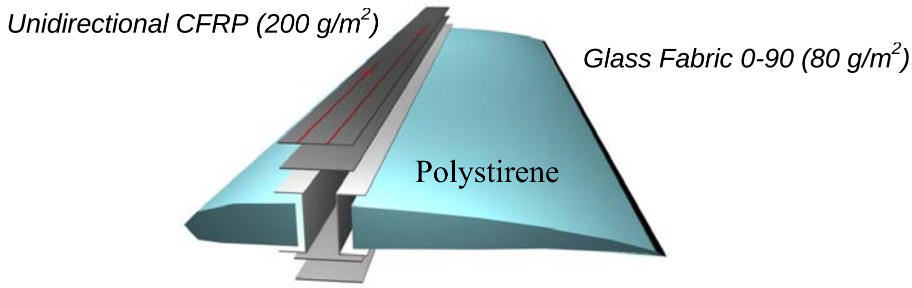

Figure 2. exploded view of the CFRP spar and the polystirene body of the wing.

Figure 3a. Photograph of the wing. In white is the body of the wing, in black is the spar.

Figure 3b. Photograph of a detail of the clamped end of the wing.

NUMERICAL MODAL ANALYSIS

The aim of this paper is not the validation of a Finite Element model, however since the experimental grid was positioned only along the spar (because elsewhere the strength of the wing was quite low and was not possible to use impact excitation) a numerical modal analysis could help in determining the type of modes to be expected. The Finite Element (FE) model has been prepared using the pre-post processor FEMAP. The analysis has been performed with MSC/NASTRAN. 3484 elements (2359 nodes) have been used throughout the model. In particular QUAD elements have been used for the wing spar and the wing panels, BRICK elements for the polystirene body of the wing and spring elements for an improved simulation of the clamped end of the wing. The stiffness of the springs has been chosen to tune the first numerical natural frequencies of the model with the experimental ones. In Fig. 4 is reported the Finite Element Model of the wing. In Fig. 5 are shown the numerical mode shapes while in Tab. 1 are reported the results of the numerical modal analysis.

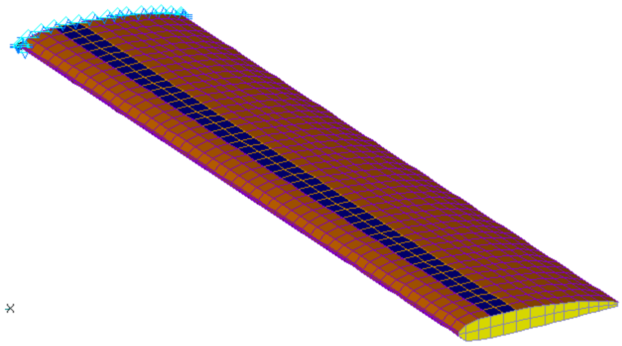

Figure 4a. FE model of the wing

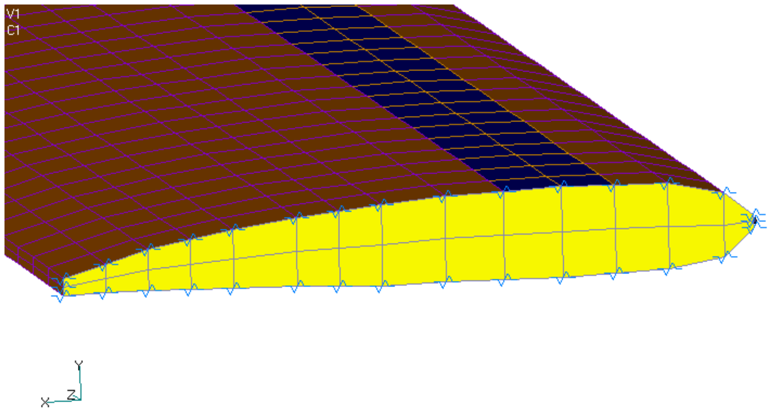

Fig. 4b. Detail showing the spring elements

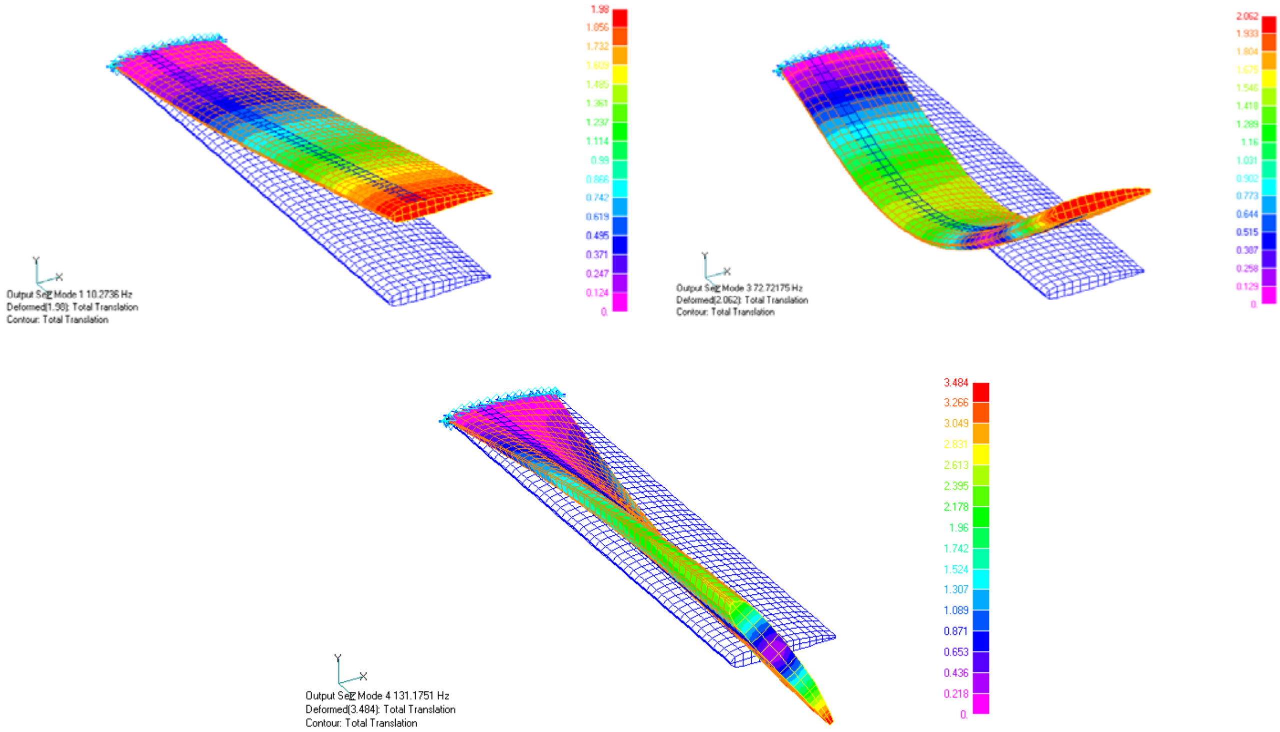

Figure 5. Mode shapes of the numerical model of the wing

Table 1. Natural frequencies of FE model

Frequency	Mode type
10.27	First bending
72.72	Second bending
131.17	First torsional

EXPERIMENTAL TEST

The wing has been clamped in one end (see detail in Fig. 3b). The constraint has been manufactured with the same procedure used for the wing, and the same materials, i.e., polystirene, Glass Fabric (GF) and an epoxy resin system (resin + curing agent). The curing cycle was 24 hours at room temperature. To reinforce the constraint, two aluminum plates have been glued on the GF. An experimental modal analysis has been performed using for the excitation either an instrumented impact hammer or an electromagnetic shaker. The responses have been measured both with an accelerometer and with the four FBGs embedded in the wing. The electromagnetic shaker has been driven using a stepped sine signal from a signal generator. This type of excitation provides an increased amount of energy to each mode of vibration.

In Fig. 6 is reported as an example the Frequency Response Function (FRF) obtained with the impact hammer and accelerometer, and in Fig. 7 the SFRF relevant to the impact hammer excitation and the fiber optic strain sensor. The response has been obtained using the commercially available Micron Optics Interrogation System. This system has the limitation in the sampling frequency which is about 50 Hz. Consequently it is not possible to capture mode shapes with natural frequencies above 20Hz. The natural frequencies and the damping coefficients of the FRFs shown in Figs. 6 and 7 are reported in Tab. 2.

Table 2. Experimental modal parameters of First mode shape.
Interrogation of FBGs with Micron Optics Instrument.

Frequency	Damping coefficient	Curve fitting	Sensor
$f_1 = 10.47$	$\zeta_1 = 0.024$	YES	Accelerometer
$f_1 = 10.44$	$\zeta_1 = 0.021$	YES	FBG

In Fig. 8a is reported the first strain mode shape as retrieved extracting the modal parameters from the row data of the SFRFs obtained from one of the embedded FBG and in Fig. 8b the corresponding one using the fitted SFRFs . In Fig. 9 are reported the first three mode shapes as retrieved from the FRFs obtained from the accelerometer response and in Tab. 3 the corresponding frequencies and damping coefficients. It can be clearly seen from Fig. 8 and 9a that with both methods the first bending mode of the cantilevered wing does not look exactly as expected. In fact this mode resemble a rigid body motion about the clamped end. Due to the lightweight type of material used it was not possible to tighten the wing end too much. An attempt to model this fact has been performed as mentioned by introducing the spring elements at the constrained end. This also allowed to make a rough adjustment of the first resonant frequencies. The comparison can be performed only on the first two frequencies because with the type of experimental grid chosen (Fig. 3a) only bending modes in the wing span direction could be detected.

Table 3. Experimental modal parameters obtained from accelerometer response.

Frequency	Damping coefficient	Curve fitting	Sensor	Mode type
f_1= 10.47	$\zeta_1 = 0.024$	YES	Accelerometer	First bending
f_2= 64.73	$\zeta_2 = 0.027$	YES	Accelerometer	Second bending
f_3 = 163.89	$\zeta_3 =0.023$	YES	Accelerometer	Third bending

To overcome the limitation imposed by the interrogation system we have also used a home made unit developed at the university of Sannio [24,25]: passive configuration involving broadband interrogation and optical filtering have been used to demodulate returned Bragg signals. Due to the passive nature of the interrogation unit, system bandwidth is only limited by the electronic circuitry involved in the detection unit, actually limited to 400KHz. Consequently with this unit, there were practically no limitations on the interrogation rate. In Fig. 10 are reported the imaginary and the real parts of the SFRFs obtained in the range 0-400 Hz. In Figs. 11 and 12 are reported the first and second strain mode shapes obtained from the SFRFs acquired with the high frequency interrogation system. In Tab. 4 are reported the natural frequencies of the first six modes.

In order to have a fully integrated system also the exciting devices should be embedded or surface attached into the structure. The most reliable health monitoring system based on modal parameter estimation is a Multi Input Multi Output (MIMO) system. In an application such as the one at hand, one can think of using two to four piezoelectric patches embedded in different locations on the wing and a much higher number of FBG sensors multiplexed in few optical fibers. To go in this direction, besides the tests described, we have also used a Single Input Multi Output test in which the excitation was given by a shaker B&K 4809 powered by the amplifier B&K 2712 that was driven by a signal generator HP Universal Source 3245. The shaker was connected to the wing tip by a wire. Several stepped sine excitation were applied to the structure, the most accurate being that one centered around the first resonance, i.e., in the range 9-11 Hz with a step of 0.001 Hz every 20 seconds. In Fig. 13 are reported the FFT of the responses of three sensors. The fourth sensor was no longer accessible because the connector broke by accident. This last aspect is not as critical as the commonly known problem of the ingress-egress of the fiber from the component. Being aware of this aspect, to prevent breakage of the fiber at the ingress-egress, we left the plastic jacket (900 μm in diameter, being 125 μm the actual diameter of the optical fiber that reaches 250 μm with the coating) starting from just before the egress outwards.

Table 4. Experimental natural frequencies obtained with high frequency interrogation system.

Frequency	Curve fitting	Sensor	Mode type
f_1= 9.8	NO	FBG	First bending
f_2= 64.0	NO	FBG	Second bending
f_3 = 45.2	NO	FBG	First torsional
f_4 = 120.0	NO	FBG	Second torsional
f_5= 166.6	NO	FBG	Third bending
f_6=333.3	NO	FBG	Unidentified

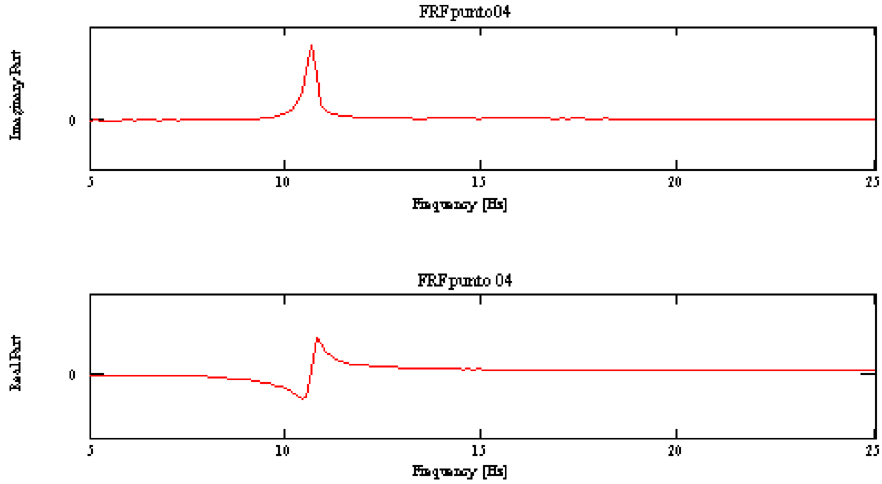

Figure 6. FRF obtained with impact hammer and accelerometer.

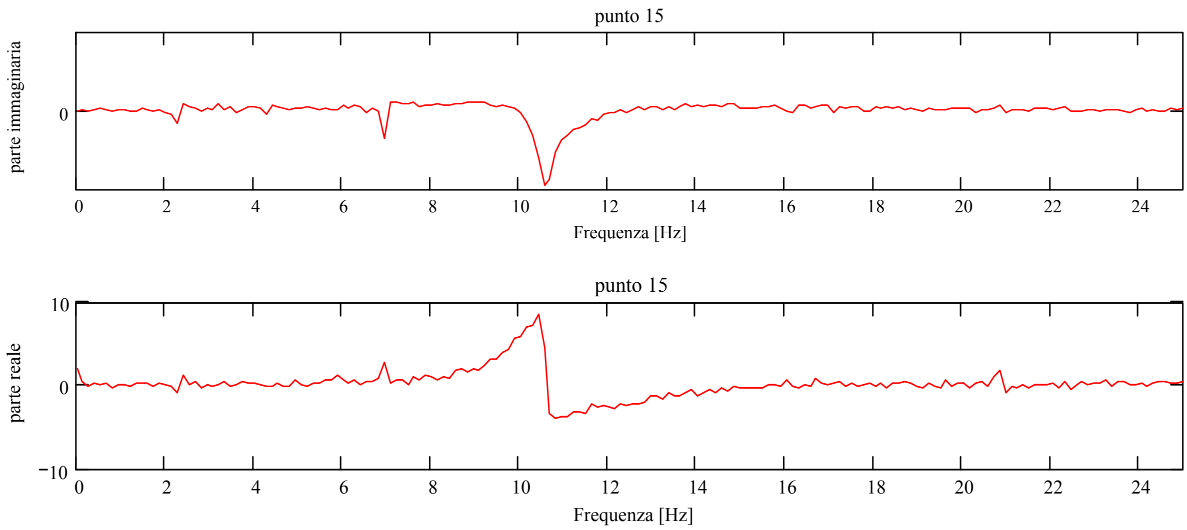

Figure 7. SFRF obtained with impact hammer and Fiber optic strain sensor.

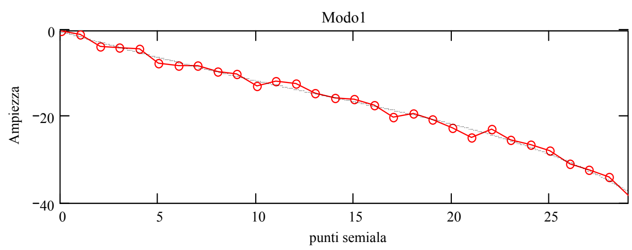

Fig. 8a. First strain mode obtained with unfitted SFRFs of the FBG.

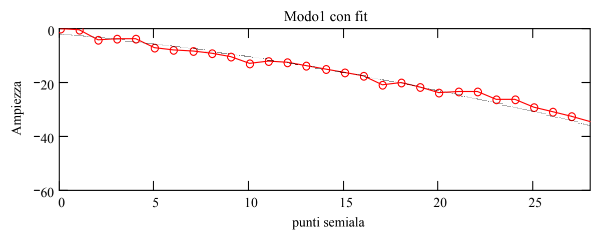

Fig. 8b. First strain mode obtained with fitted SFRFs of the FBG.

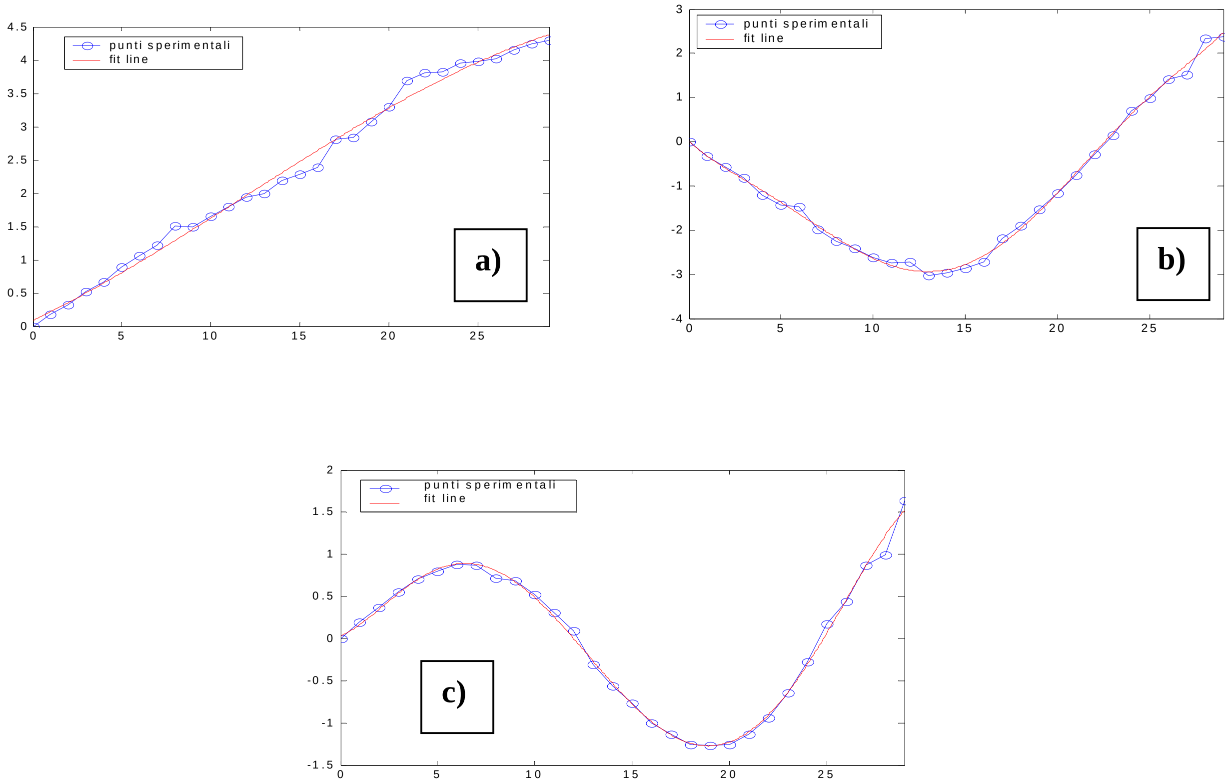

Fig. 9. Mode shapes obtained from the accelerometer response.

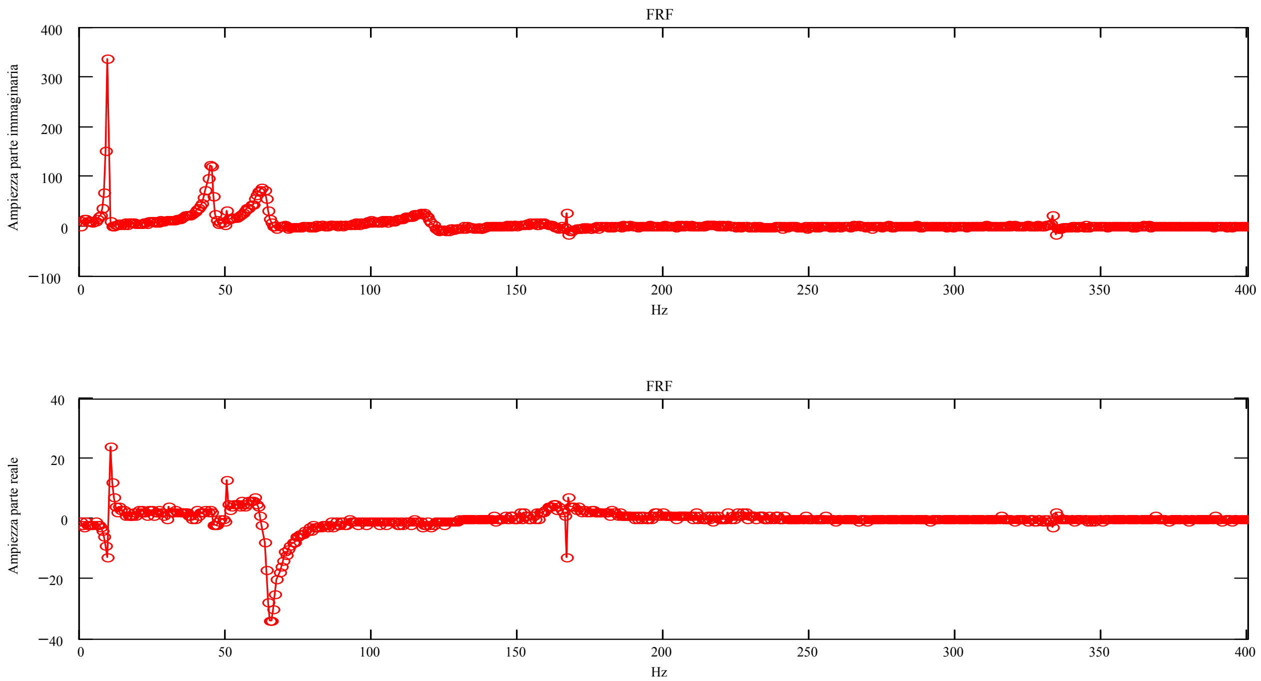

Fig. 10. Imaginary and real part of one SFRF relevant to one FBG, obtained with high frequency interrogation system.

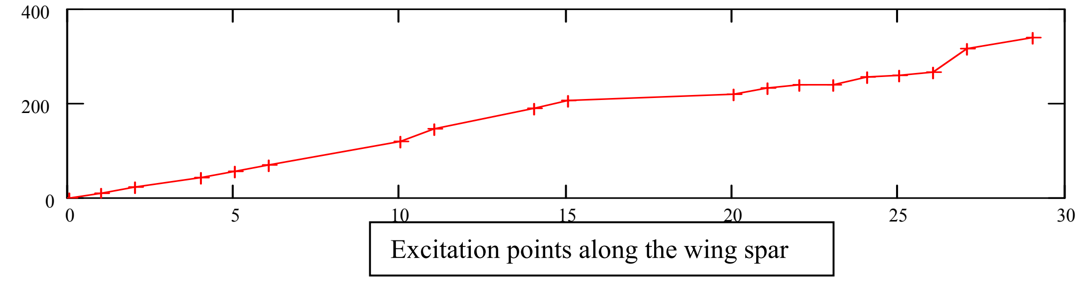

Fig. 11. First strain mode obtained from the FBG FRFs acquired with the high frequency interrogation system.

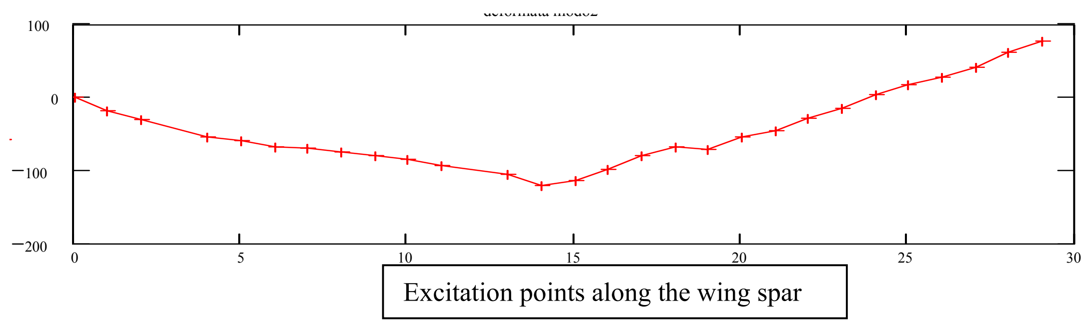

Fig. 12. Second strain mode obtained from the FBG FRFs acquired with the high frequency interrogation system.

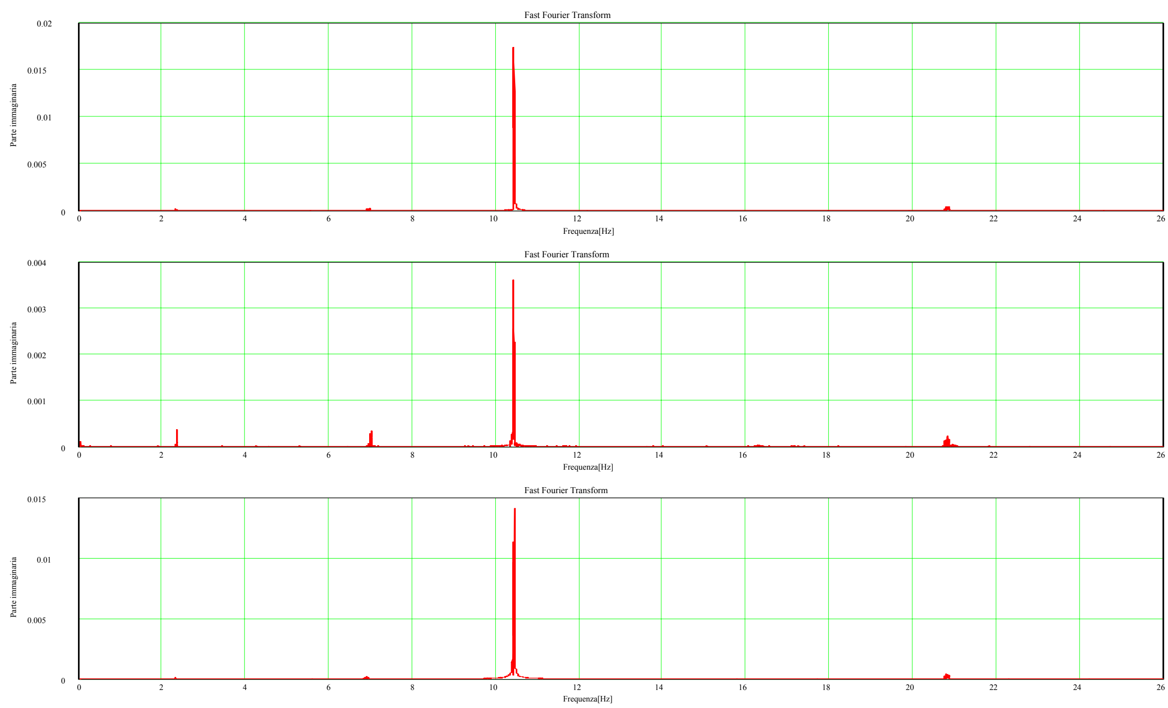

Fig. 13. Imaginary part of the FFT of the response of three different FBGs when excited with stepped sine excitation.

CONCLUSIONS

As a first step for the development of a health monitoring system for an aircraft component, based on fiber optic sensors and on modal parameter acquisition, four Fiber Bragg Gratings have been embedded into a model of an aircraft wing. Several tests have been performed using both one accelerometer and the FBGs for sensing the dynamic response of the wing. For the excitation both an impact hammer and an electrodynamic shaker have been used. Two different interrogation systems have been connected to the optical fibers for the acquisition of the dynamic strain measured by the FBGs. The two interrogation systems are based on two different demodulation approaches. In particular the commercial interrogation system is limited on the acquisition rate. Also the tests performed with the stepped sine excitation were limited to the acquisition of the first mode shape only. Consequently the comparison with the other tests were confined only to the first mode. The comparison of the experimental results obtained with all the techniques described was very satisfactory considering that some frequencies have been obtained without fitting the data. Also the first two mode shapes obtained with the FE model of the wing compares well with the experimental data. Of course a better tuning of the second mode shape could have been obtained, but this was out of the scope of the present work that in conclusion has demonstrated that SFRF can be obtained from FBGs and used to determine the modal parameters of a structure.

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