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Title: **Impact Source Localization on a Helicopter Tail Rotor Blade**

Authors: Francesco Ciampa[1]
Michele Meo[1*]

[1]Department of Mechanical Engineering, University of Bath, Bath BA2 7AY, UK
[*]Corresponding author: m.meo@bath.ac.uk

ABSTRACT

This paper illustrates an in-situ Structural Health Monitoring System for the localization of the impact source on a helicopter composite tail rotor blade. This technique, based on the Inverse Filtering process, is applied to a number of waveforms recorded by a number of passive piezoelectric transducers containing the impulse response of the medium. Unlike other ultrasonic impact localization methods, the present technique allows obtaining the optimal focalization of the impact point by taking advantage of multiple linear scattering and a small number of receiver sensors. The impact localization results shows that the location of the impact point could be achieved with a high level of accuracy in any point of the structure as long as a high number of information from the signal spectrum was contained in the recorded waveforms.

INTRODUCTION

Impact localization based on ultrasonic guided waves (GW) has become an important tool for Structural Health Monitoring (SHM) systems [[1], [2], [3], [4]]. A number of algorithm-based methods have been developed in the past for the localization of the acoustic emission (AE) source in isotropic and anisotropic plate-like structures. Most of these techniques rely on time of arrival (TOA) identification and the group velocity determination of the coherent part of the wave field (ballistic wave) reaching a network of transducers bonded on the structures. Usually, advanced signal processing technique such as peak detection, cross-correlation, Hilbert and wavelet transformation can be employed to extract physical parameters from measured data, and then to use them to detect the impact location [[5], [6]]. However, the dispersive nature of GW and the presence of multiple scattering, mode conversion and reflection from the boundaries (*diffuse wave field*) can lead to waveforms recorded from the sensors dissimilar from the original elastic source. To overcome these limitations, Inverse Filtering (IF) process has been used as a tool for the imaging of the impact source in solid media [7]. Indeed, in an IF experiment, due to the time invariance and spatial reciprocity of linear wave equation, an input signal can be focused back on the original source if the output received by a set of transducers is time reversed and emitted onto the excitation point. The first improvement of IF process is to compensate the dispersive behaviour of GW. Indeed, depending on the propagation frequency, dispersive GW have a number of wave packets that travel at higher and lower speeds toward the receiver sensor. After an IF process, the slower modes are emitted first, so that all the waveforms can converge at the original source point at the same time, thus compensating dispersion [8].

The objective of the research work is to report, both theoretically and experimentally, an *in-situ* SHM system able to identify the occurrence and location of low velocity impacts on a helicopter tail rotor blade. Indeed, unlike conventional plate-like panels, this composite structure presents a strong anisotropy and inhomogeneous elastic nature due to the presence of a double material (CFRP and GFRP), a geometrically complex shape due to the curvature of the blade airfoil section and rivets, and variations of the mechanical behaviour due to local changes of the thickness. The proposed imaging technique is based on the IF approach applied to the waveform originated from a point of the structure of unknown location (impact source), and a number of signals stored into a database containing the experimental Green's function of the medium.

INVERSE FILTERING FOCUSING PROCESS

If the time reversal invariance and spatial reciprocity of the elastodynamic wave equation are satisfied, the IF imaging process can be used to focus ultrasonic waves in diffuse wave fields and anisotropic media. This technique allows compensating some detrimental effects such as the limited transducer bandwidth and the material absorptions, in order to recover the optimal focusing at the impact source. In addition, according to Huygens's principle in diffraction theory, the reconstruction of the wave function in a generic volume at any time can be obtained by the knowledge of its sources located on a 2D surface [[9], [10]]. The reciprocal time reversal experiment is usually split in two steps.

In the first step a number of signals representing a library of impulse responses from *M* points ("excitation points") along the plane of the structure is recorded by one receiver transducer and stored (Fig. 1).

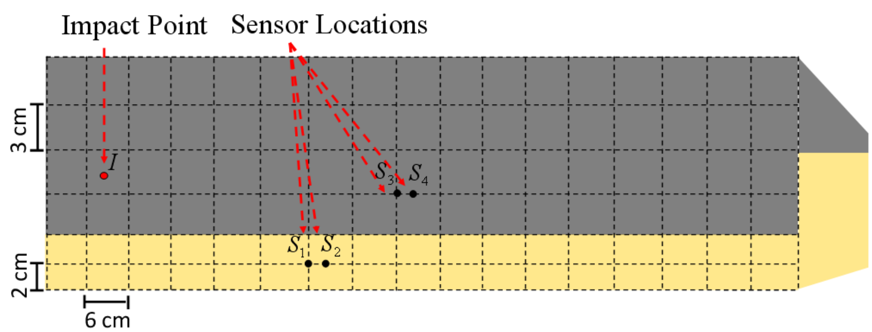


Figure 1 Architecture of the imaging method

The second step consists of the recognition of the optimal refocusing procedure at the source location. The basic idea is to correlate the impulsive transfer function associated to each excitation point with that of the new impact of unknown location. In this manner, the information on the AE source location is accomplished as the maximum of the correlation at the focus point (referred as "virtual IF experiment"). Moreover, by taking advantage of a fully diffuse wave field, only one sensor can be used for the imaging process [11]. Fully diffuse wave field are characterized by a superposition of different fields with uncorrelated amplitude and random direction of propagation and phase [12]. Furthermore, in complex structures such as the tail rotor blade tested, the measured signals are typically non-stationary and feature an exponentially decaying "coda" which is dominated by multiple scattering (Fig. 2).

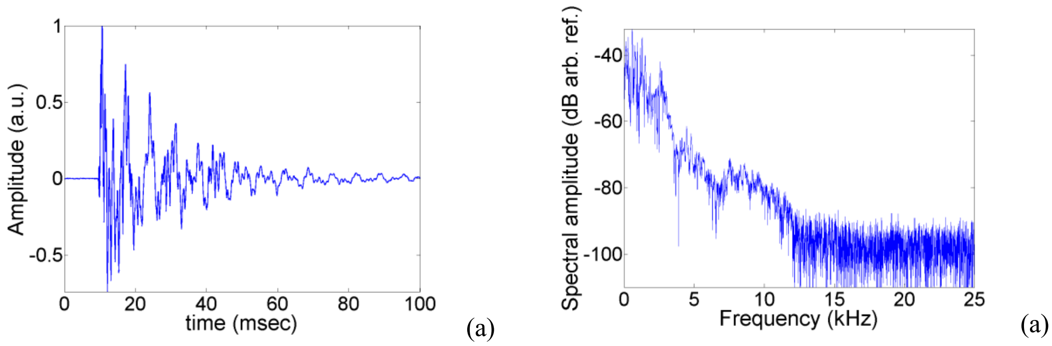


Figure 2 Normalized time history in one of the excitation points (a) and its frequency content (b)

In particular, the presence of heterogeneities such as a composite double material (CFRP and GFRP), local variations of the thickness and the curvature of the rotor blade airfoil influence the acoustic properties of the structure, generating reverberations within the medium.

EXPERIMENTAL SET-UP

The experiments were carried out on a composite tail rotor blade (125 cm x 20 cm x 2 cm) provided by Agusta-Westland (Fig. 3).

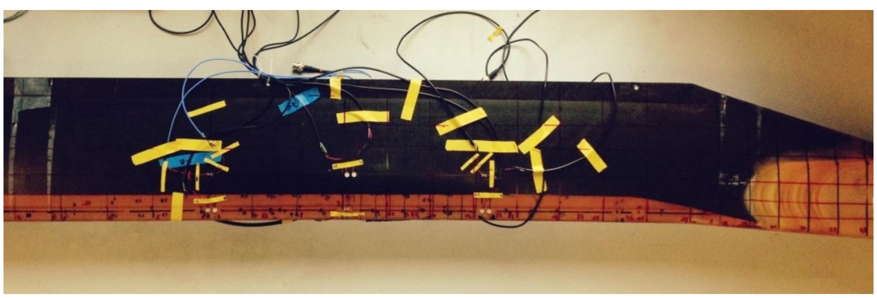


Figure 3 Image of the composite tail rotor blade tested

The structural make-up is the following (Fig. 4).

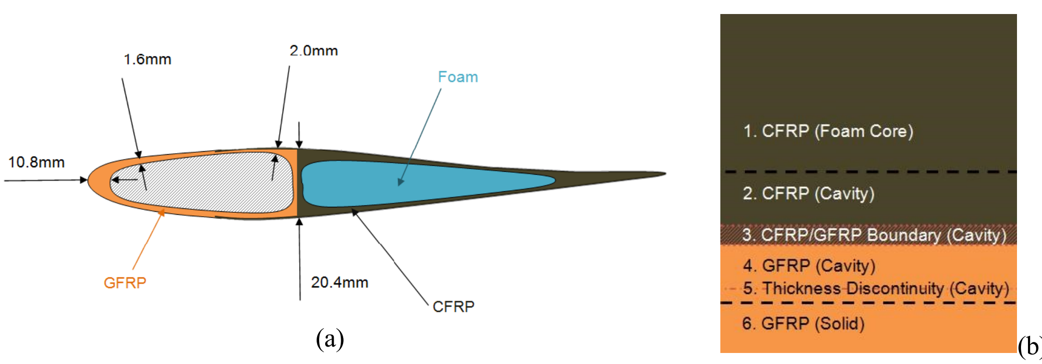


Figure 4 Composite rotor blade schematic (a) and region of interest on the surface (b)

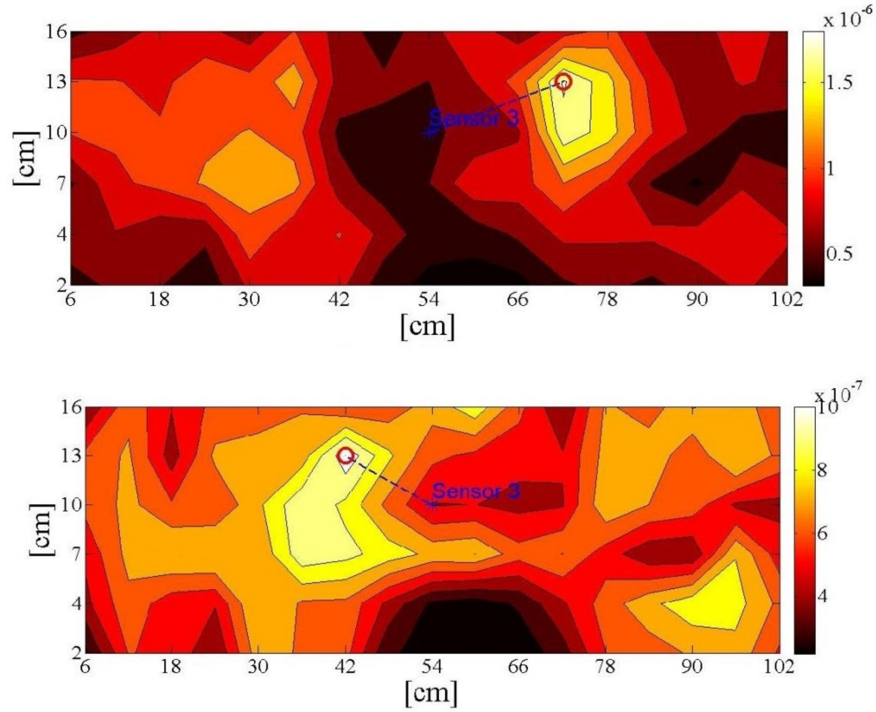
In particular, the leading edge of the blade is made of GFRP for impact damage tolerance, whilst CFRP has been used for the rest of the blade to increase the structural strength and stiffness. The section of the blade is split into two parts by a CFRP spar web. The leading edge section is a cavity and the trailing edge section is filled with foam. In addition, the surface of the blade was divided into six distinct regions, as shown in Fig. 4b, based on the expected behaviour of the propagating GW. The dashed black lines mark the boundaries of the leading edge cavity space into which sensors could be placed in practical applications. The greatest complications were expected in region 3, the CFRP/GFRP boundary region, where the number of CFRP plies was reduced incrementally until GFRP made up the surface. It was not known what effect this would have on GW propagating through it. The passive sensors employed were four piezoelectric transducers (APC sensors) with diameter of 6.35 mm, thickness of 2.5 mm and central frequency of 100 kHz (broadband spectrum), mainly used for ultrasonic applications. The waveforms were acquired using an oscilloscope (Picoscope 4224) with a sampling rate of 99.5 kHz. From the time histories and the associated spectra (Fig. 2), the main energy of the amplitude spectrum of the waves induced by an uncontrolled system (modal hammer) was confined below 12 kHz. All the impacts were carried out manually in order to avoid damaging the structure, and as a result, negligible energy in the spectrum at frequencies higher than 25 kHz was found. Moreover, the dispersion diagrams were not successful because of the unknown mechanical properties and layout of the composite blade. Hence, it was difficult to discriminate vibration modes with fundamental GW modes in this particular spectrum range. Moreover, the duration time window *T* of the signals acquired must be higher than the Heisenberg time τ_w or break time, which is equal to the modal density of the structure. However, since is impossible to estimate τ_w due to the lack of knowledge of the mechanical properties of the blade, according to the Nyquist theorem and the long reverberation present in the waveforms recorded, a 100 ms duration time window *T* was chosen (Fig. 2a). Sensor positions are reported in Table 1.

Table 1 Sensors coordinates

	x-coordinate (cm)	y-coordinate (cm)
Sensor 1	36	4
Sensor 2	40	4
Sensor 3	54	10
Sensor 4	58	10

IMAGING RESULTS

According to second section, the structural surface was divided in M=17 x 6 excitation points, distributed along a grid of rectangular cells (Fig. 1). The size of the single cell is not constant, but varies from smaller cells of dimensions 6 cm x 2 cm on the GFRP region, to greater cells of dimensions 6 cm x 3 cm on the CFRP section. Such a configuration was designed to improve the resolution at the leading edge of the blade, as that is the area mostly subjected to impacts. The refocusing wave fields at the impact source location are represented as a 2D map and the impact points are deduced from highest values of the correlation coefficients (Fig. 5).



(a)

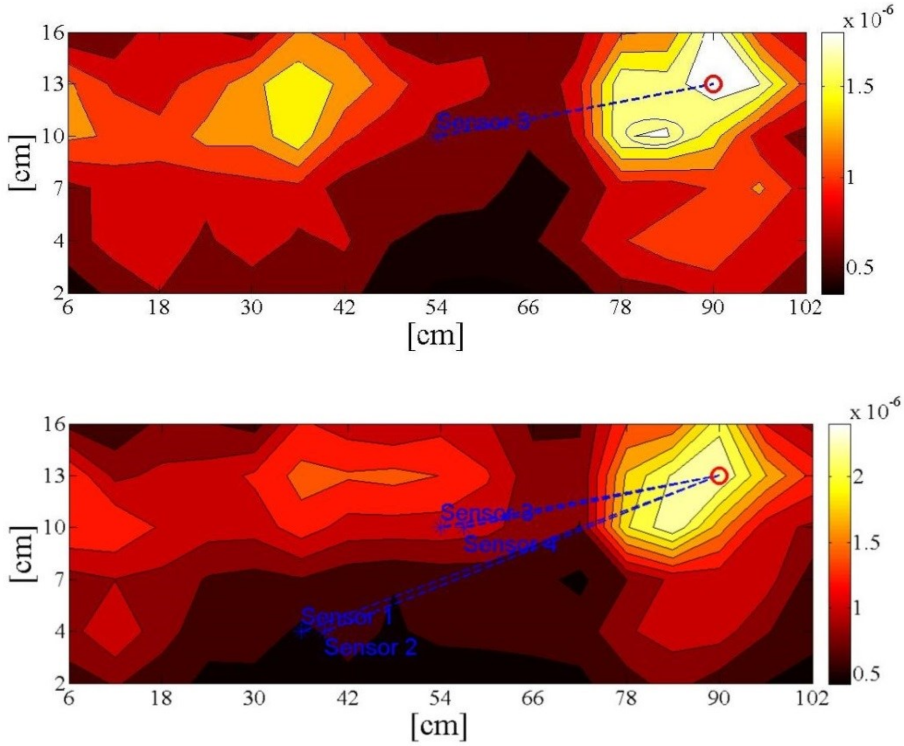
(b)

Figure 5 2D imaging of the impact location using only sensor 3 for two different impacts located at x_1=72 cm, y_1=13 cm (a) and x_2=42 cm, y_2=13 cm (b)

In the above figure, the asterisk symbol corresponds to the position of sensor 3, the red circle to the real impact location and the dashed blue line to the distance between the sensor and the impact point. However, it was found that for some excitation points, the incoherent measurement noise (e.g. sensor noise, electronic noise, etc…) could negatively influence the library of signals acquired in the first step, leading to ambiguities in the focusing at the source. This further effect was eliminated by acquiring simultaneously the wave fields in both steps with additional transducers, and then averaging the maxima of the correlation coefficients. In our tests, four sensors were used as they provided satisfactory results for the impact location in each excitation point (Fig. 6).

Indeed, it can be seen from Fig. 6 that small ambiguities (highlighted by a blue circle) in the imaging of the impact source using only one sensor, were clearly resolved using the averaged values of the correlation coefficients from four receivers.

Hence compared to other ultrasonic impact localization techniques based on TOA evaluation, this methodology not only needs a simple signal processing to locate the source (with computational time less than 1 sec), but also it does not require any numerical routines as well as a priori knowledge of the mechanical properties and the GW dispersion behaviour.



(a)

(b)

Figure 6 2D imaging of the impact location using only sensor 1 (a) and four sensors (b) for the impact located at x_1=90 cm, y_1=13 cm

CONCLUSIONS

This paper presented an *in-situ* Structural Health Monitoring (SHM) imaging system for the localization of impacts on a composite complex structure such as a tail rotor blade. Unlike conventional plate-like panels, this composite structure presents a strong anisotropy and inhomogeneous elastic nature due to the presence of both glass fibre and carbon fibre, a geometrically complex shape due to the curvature of the blade's airfoil section, and variations of the mechanical behaviour due to local changes of the thickness. The proposed imaging technique is based on the inverse filtering or reciprocal time reversal approach applied to the waveforms originated from a point of the structure of unknown location (impact source), and a number of signals stored into a database containing the experimental Green's function of the medium. Unlike other ultrasonic impact localization methods, the present technique allows achieving the optimal focalization of the impact point in the spatial and time domain, by taking advantage of multiple linear scattering and a small number of receiver sensors.

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