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Real time impact localization using modal superposition – Application to a composite aircraft fuselage

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Abstract

Aircraft ground operations involve multiple vehicles simultaneously approaching the fuselage with a potential risk of impact-induced damage to the airframe. In case of impact, quick and precise reporting of the event is key to select the appropriate maintenance procedure. This paper focuses on the localization of impacts applied on a cylindrical composite aircraft fuselage. An original and efficient vibration-based approach using a modal model of the aircraft on ground is described to localize impacts on the fuselage. The complexity of the structure is embedded in the vibration modes used in the identification procedure. Experimental tests on a A350-900 Airbus aircraft equipped with only 6 bi-axes accelerometers show very promising performances. The mean localization error is equal to 2m for an aircraft length of 65m.

Keywords: Impact localization, load reconstruction, composite fuselage, Structural Health Monitoring

1. Introduction

The localization of impact events is an important task of Structural Health Monitoring. For instance, aircraft "ground operations" involve multiple vehicles simultaneously approaching the fuselage with a potential risk of impact-induced damage to the airframe (see Figure 1). These damages are possibly invisible to a naked eye inspection for a composite fuselage (e.g. delamination, clip disbonding). Therefore, in case of impact, quick and precise reporting of the event is key to select the appropriate maintenance task. In order to optimize this procedure, there is an interest for a real-time impact detection system that could localize a ground impact within a limited zone, assess its severity and trigger the inspection. The goal is to use indirect measurements from sensors installed on the structure, such as accelerometers, to localize the impacts from the structure's vibrations.

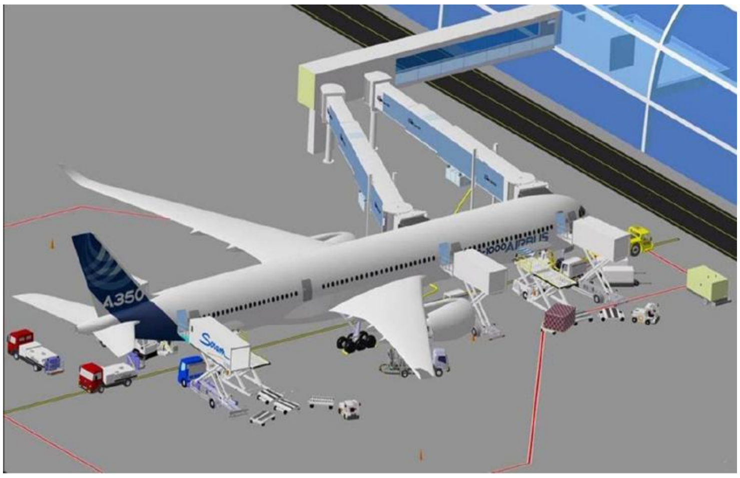

Figure 1: Ground operations at the gate

Many techniques have been experimentally validated under laboratory conditions on composite structures with the aim to prove their feasibility on larger structures. Most of the existing impact localization techniques are based on a wave propagation approach referred in the scientific literature as triangulation. The principle is to capture the Time of Arrival (ToA) of some traveling waves generated by the impact at different sensor locations. The ToA delays are then used to infer the impact location with a wave propagation model [1,2]. Instead of using a wave propagation model that may not correctly represent the actual behavior of the propagation medium, a reference database, or baseline, can be used. The first step is to record offline the sensor measurements due to impacts applied at various locations on the structure. Then, in the case of an online impact event, the sensor measurements are compared to the baseline to infer the impact location [3,4]. Methods based on artificial neural networks (ANNs) have also been developed to triangulate the impact location from the ToA delays without any assumption on the propagation medium. ANNs are mathematical models that can be trained with a reference data set to model a nonlinear relationship between inputs and outputs [5,6]. Many other techniques have been proposed to localize an impact from vibration measurements. The linear inverse problem of impact force reconstruction can be solved by moving the candidate impact location [7,8,9]; the time reversal approach can be employed [10,11]; the maximum of the power signal distribution can be computed [12]; and various statistical methods have been developed [13,14,15]. In the case of a ground support equipment impact on a composite fuselage, complex wave propagation phenomena are expected to occur such as wave scattering, reflection, and attenuation. With the above-mentioned wave-based approaches, it would be necessary to significantly increase the number of sensors so that such phenomena would be negligible within each cell of the refined sensor network.

The proposed impact localization methodology is an attempt to circumvent both the scientific and the technical obstacles of classical triangulation techniques. In particular, the proposed methodology works with a small number of low sampling frequency accelerometers (200 Hz). The concession is to lower the expectations regarding the localization accuracy, which approximately reaches a few percent of the aircraft length. Sections 2 and 3 summarize the main ideas of the proposed impact localization approach. The interested reader can refer to [16,17,18] for a more comprehensive description. Section 4 presents the procedure employed for the tested aircraft and section 5 presents the results of the impact test campaign. Only the main findings are presented herein, the interested reader may refer to [19] for a complete description of both the theoretical and practical aspects of the presented methodology.

2. Linear compression with the modal superposition technique

The proposed method is based on the well-known principle in Dynamics of modal superposition [20]. The idea is to describe the damped oscillations of the structure with a superposition of vibration modes, which correspond to specific deformations of the structure oscillating at particular frequencies (see Figure 2). From a mathematical standpoint, this technique describes a measured temporal signal $s(t;\boldsymbol{F})$, consecutive to an impact occurring at point F, with the relation [16]:

$$s(t;\boldsymbol{F}) \approx \boldsymbol{a}(t) \cdot \boldsymbol{z}(\boldsymbol{F}) = a_1(t)z_1(\boldsymbol{F}) + a_2(t)z_2(\boldsymbol{F}) + \cdots \tag{1}$$

where the coefficients in the vector $\boldsymbol{a}(t)$ depend on the sensor location, the impact load history, and the modal properties of the structure. These latter can be identified experimentally or numerically with modal analysis techniques. The measured signal may correspond to displacements, velocities, accelerations or strains. Only acceleration measurements are employed in the present study.

It is a remarkable property of relation (1) that it separates the contribution of the impact point $\boldsymbol{F}$ to the response. The response model is indeed linear with respect to its image $\boldsymbol{z}(\boldsymbol{F})$ called in our previous works [16-19] the Amplified Modal Participation Vector (AMPV). It is then a simple task to identify the AMPV from well-known model identification techniques based on least-squares minimization. Besides, it can be shown that the sensor location has a great influence on the robustness of this identification with respect to measurement noise or model errors. In fact, optimal sensor locations can be derived by avoiding the nodal lines of specific mode shapes [17].

In theory, the sum (1) goes to infinity but with smaller contributions as the natural frequencies of the associated modes increase. Therefore, the vibration response model can be compressed by truncating the sum up to a finite rank. This compression is furthermore linear in the sense that the impact point $\boldsymbol{F}$ only changes the proportions in which the vibration modes are excited through the coefficients $z_i(\boldsymbol{F})$. It can also be appreciated that the impact intensity only scales the AMPV but does not change the proportions in which the modes are excited due to the impact location. This observation is in fact a key feature for the robustness of the developed method which is insensitive to the impact intensity.

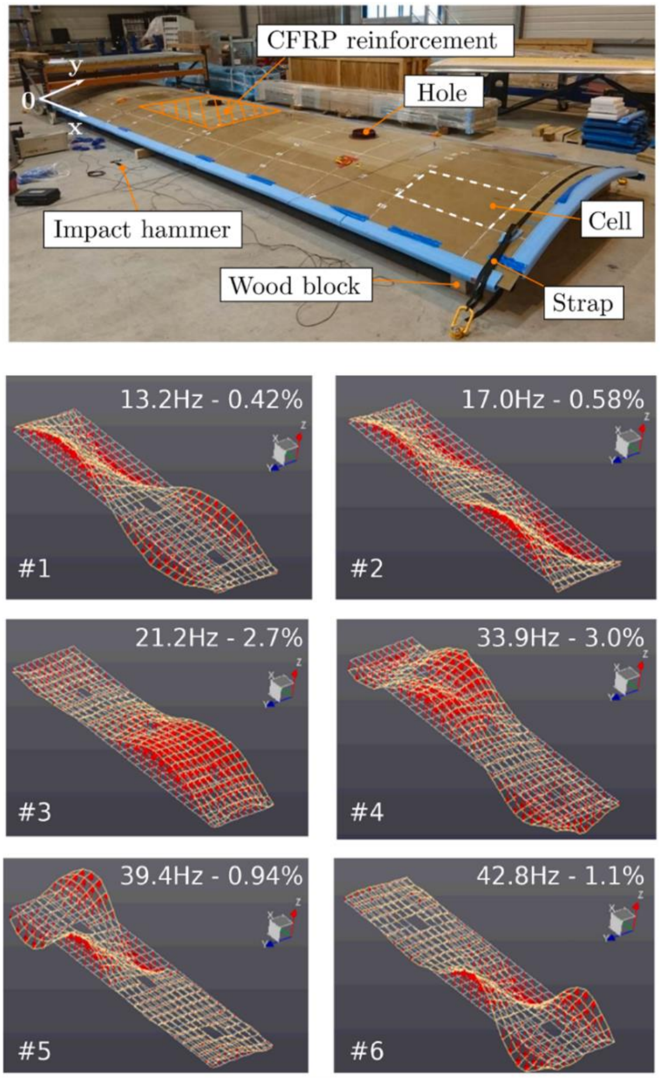

Figure 2: Mode shapes, natural frequencies and modal damping of a composite panel manufactured by Airbus [18]

3. Modal signature with a Discriminating Modes Family (DMF)

It is shown in [16] that the vector $\boldsymbol{z}(\boldsymbol{F})$ can be seen as a signature of the impact point $\boldsymbol{F}$ in the vibration response. Indeed, if specific vibration modes are selected in the analysis, then the proportions in which these modes are excited depending on the impact location are unique. This can be explained as follows with an analogy with the commonly used triangulation techniques.

Triangulation techniques consist in capturing the Time of Arrivals (ToAs) of the elastic waves at various sensors locations. The ToAs are then two-by-two subtracted to define time delays between each pair of sensors. A wave propagation model is used (or implicitly used if the procedure resorts to a database) to compute for each ToA delay a set of possible impact locations called iso-propagation line [3]. Geometrically, the impact point belongs to the intersection set of these iso-propagation lines. The challenge is to adequately mesh the structure with sensors so that this intersection set reduces to a unique point, for any impact location, in order to get a unique solution to the localization problem.

By analogy [18], the proposed technique consists in defining iso-proportion lines that intersect at a unique point if appropriate vibration modes are selected in the analysis. An iso-proportion line is defined as a set of points such that two vibration modes are excited in the same proportion for any impact occurring along this line. In fact, this unique intersection criterion precisely indicates what terms can be truncated in the response model (1). For instance, in the case of a simply supported plate, it is analytically shown in [16] that only three specific modes satisfy this unique intersection point property. In general, numerical techniques can be used to identify these families of modes called Discriminating Modes Families (DMFs).

However, this approach does not lead to uniform localization performances in general. In fact, some vibration modes families can only be used to localize impacts applied on specific areas of the structure. The challenge with this approach is then to identify DMFs that cover the structure at best. The so-called Angular Robustness Maps (ARMs) can be computed [18] from the mode shapes of the structure to identify these DMFs. Figure 3 shows for instance the ARM of a composite panel manufactured by Airbus. The red areas indicate the impact locations for which the proposed approach will provide accurate and robust results. An impact in a blue area, however, may not be correctly localized with the vibration modes family associated to this ARM.

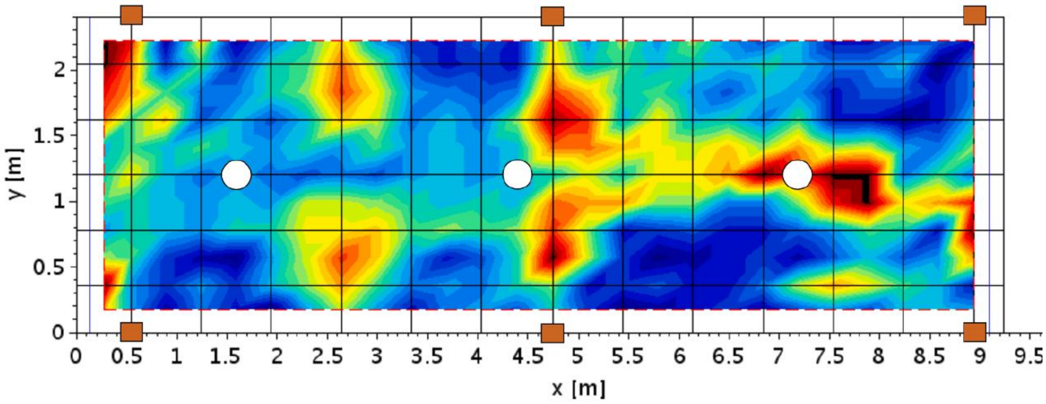

Figure 3: Angular Robustness Map associated to seven mode shapes of the composite panel. Areas in green/red indicate the impact locations that can be identified with robustness and accuracy with the proposed localization technique [18]

4. Procedure to localize impacts on a composite fuselage

4.1. Identification of the acceleration response model

Consider a cylindrical aircraft fuselage, initially at rest, subjected to an impact at time $t = 0$ on point $\boldsymbol{F} = (x, \theta)$, with a force vector normal to the surface (transverse impact). This situation is depicted on Figure 4. The impact energy is assumed high enough to produce a global vibration response of the complete aircraft so that the modal superposition principles applies.

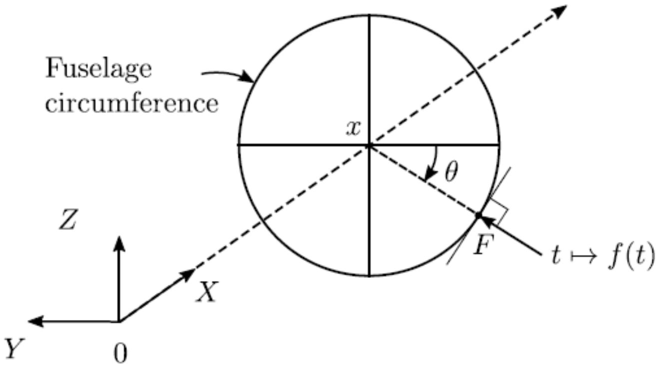

Figure 4: Transverse impact on a cylindrical fuselage (aircraft axis X is oriented from front to rear) [19]

In this study, only low-frequency vibration modes of the aircraft are considered (natural frequency lower than 15 Hz) so that the impact load history $t \mapsto f(t)$ is assumed to be a Dirac function with intensity f_δ. Let $\phi_i^{(d)}(\boldsymbol{M})$ be the i-th mass-normalized mode shape of the structure evaluated at some point $\boldsymbol{M}$ on the fuselage along direction d. The measurement direction is denoted as m (either along the Y-axis or the Z-axis in this study) and the impact direction is denoted as n (normal to the surface). In these conditions, the acceleration response model $s(t; \boldsymbol{F})$ at the sensor location $\boldsymbol{C}$ is given by [19]:

$$s^{(m)}(t; \boldsymbol{F}) \approx \sum_i \phi_i^{(m)}(\boldsymbol{C}) \phi_i^{(n)}(\boldsymbol{F}) f_\delta \ddot{g}_i(t) \tag{2}$$

where $\ddot{g}_i$ is the second time derivative of the i-th modal impulse response function defined by $g_i(t) = \omega_i^{-1} e^{-\eta_i \omega_{0i} t} \sin(\omega_i t)$, with ω_{0i} and η_i the natural frequency and the damping of the i-th mode, and $\omega_i^2 = \omega_{0i}^2 (1 - \eta_i^2)$. It is straightforward to reorder the terms in (2) to identify a model response as (1): $a_i(t) = \phi_i^{(m)}(\boldsymbol{C}) \ddot{g}_i(t)$ and $z_i(\boldsymbol{F}) = f_\delta \phi_i^{(n)}(\boldsymbol{F})$. The modal parameters in the coefficients $a_i(t)$ can be identified from an Experimental Modal Analysis (EMA) of the structure.

Note that relation (2) exhibits a direction coupling: an impact applied along the Y -axis may produce a vibration response along the Z-axis. This difficulty can be solved by considering a frequency band over which the vibration modes are purely planar. Fortunately, this is precisely the case in the range 3Hz-11Hz for the tested aircraft. In such a frequency band, the acceleration response in the Y-direction (respectively, in the Z-direction) is uniquely linked to the Y-component (respectively, the Z-component) of the impact force:

$$s^{(Y)}(t; \boldsymbol{F}) \approx \boldsymbol{a}^{(Y)}(t) \cdot \boldsymbol{z}^{(Y)}(\boldsymbol{F}) \tag{3}$$

$$s^{(Z)}(t; \boldsymbol{F}) \approx \boldsymbol{a}^{(Z)}(t) \cdot \boldsymbol{z}^{(Z)}(\boldsymbol{F}) \tag{4}$$

where $z_i^{(Y)}(\boldsymbol{F}) = f_Y \phi_i^{(Y)}(\boldsymbol{F})$ and $z_i^{(Z)}(\boldsymbol{F}) = f_Z \phi_i^{(Z)}(\boldsymbol{F})$ with $f_Y^2 + f_Z^2 = f_\delta^2$. The acceleration response models (3-4) are identified with a simple least-squares minimization from the measurements of 6 bi-axis accelerometers with a sampling frequency of 200Hz (see Figure 5). The complete model identification procedure that has been used in the experiments is in fact slightly more complicated since the impact energies were not sufficient to excite the whole aircraft, and also because the impact time is an additional unknown of the problem (see flowchart in Figure 7).

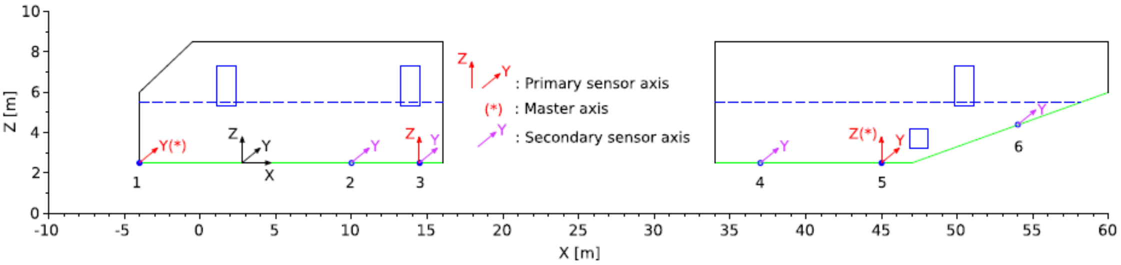

Figure 5: Positions of the 6 bi-axis accelerometers on the tested aircraft. The measurements of the secondary sensors are used to detect what half of the aircraft has been impacted (front or rear). The measurements of the primary sensors are used to identify the acceleration response models in directions Y and Z. [19]

4.2. Impact localization technique

With the proposed approach, the impact localization problem consists in identifying the two coordinates x (axial localization) and θ (angular localization) of the impact point from the AMPVs $\boldsymbol{z}^{(Y)}(\boldsymbol{F})$ and $\boldsymbol{z}^{(Y)}(\boldsymbol{F})$ previously identified from the acceleration measurements. The axial localization is performed with the collinearity research procedure presented in [18]. This technique consists in identifying the lines of the modal matrix that are roughly collinear to the AMPVs (see Figure 6). The outputs are the axial coordinate x and the two components f_Y and f_Z of the impact force vector. The angular coordinate is identified from the simple geometrical relation $\tan\theta = f_Z/f_Y$ (see Figure 4).

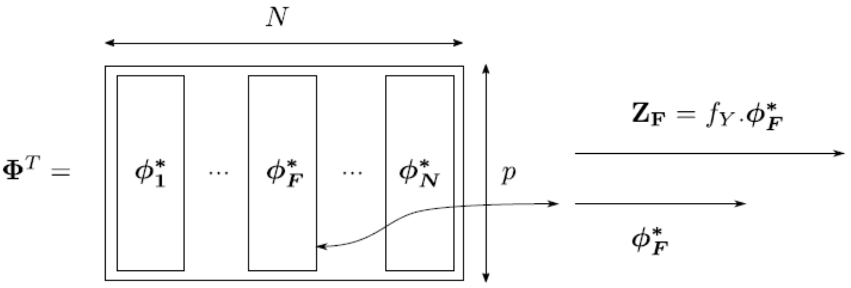

Figure 6: Illustration of the collinearity research procedure employed to perform the reverse link $\boldsymbol{z}(\boldsymbol{F}) \to \boldsymbol{F}$ [19]

4.3. Flowchart

Figure 7 summarizes the complete impact identification procedure. An Experimental Modal Analysis (EMA) of the aircraft has been performed prior the impact tests to identify the vibration modes within the frequency band 1Hz-15Hz. The localization procedure resorts to three distinct DMFs: modes 7-9,11 to identify $\boldsymbol{z}^{(Y)}(\boldsymbol{F})$ for an impact applied on the front half of the aircraft and modes 3-5-11 for the rear half ; modes 6-8-10 to identify $\boldsymbol{z}^{(Z)}(\boldsymbol{F})$ for an impact applied on either half of the aircraft. Recall that this uncoupling between directions Y and Z is a simplification made possible by the fact that the mode shapes of the tested aircraft are purely planar within the frequency band of interest.

Figure 8 illustrates the different steps of a single impact localization for an impact applied on the bottom/right of the rear passenger door. As described in the flowchart presented in Figure 7, all the measurements of the secondary sensors are used to determine the sensor responding first. In the present case, the latter is the rear sensor 6Y (see Figure 5) and hence the detected half is the rear. The measurements of the rear primary sensors (5Y and 5Z) are then used for the model identification step. The spectrum reconstruction of the measured acceleration signal 5Z is presented to illustrate that the contributions of the DMF modes in the (OXZ)-plane have been correctly captured (reconstruction of the blue curve within the DMF bandwidth).

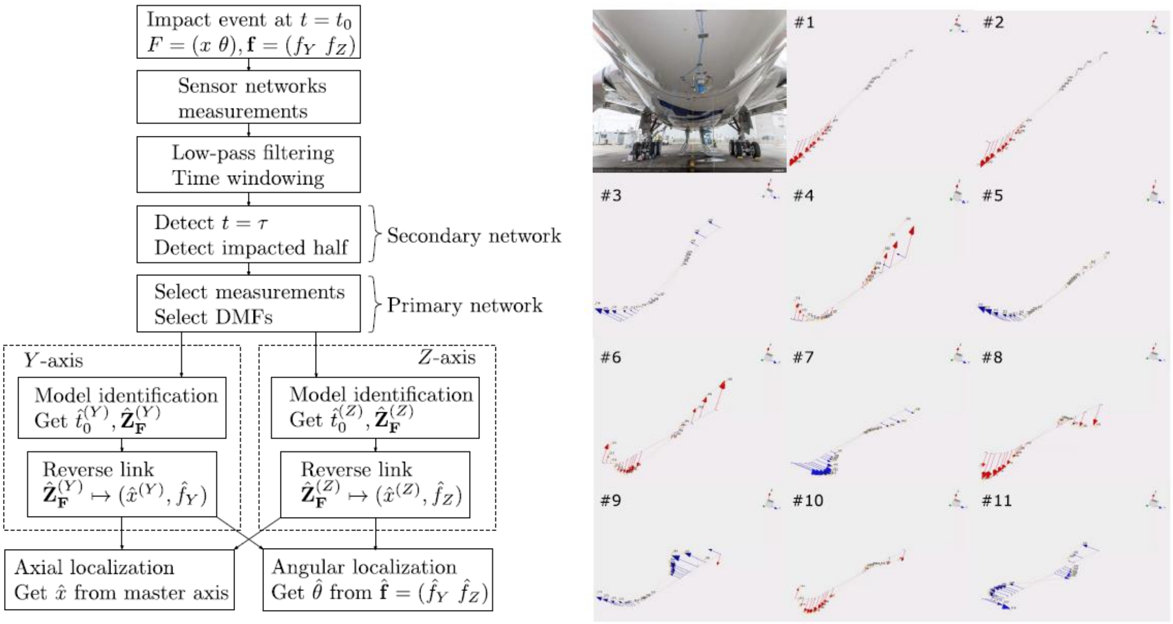

Figure 7: Flowchart of the impact identification procedure (left) and mode shapes extracted within the range 1Hz-15Hz with an EMA of the tested aircraft (right) [19]

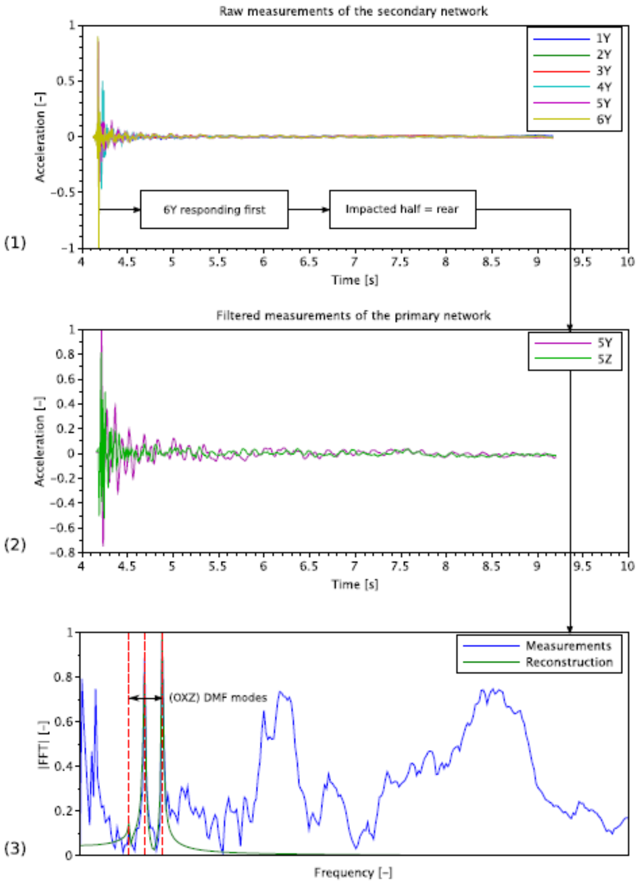

Figure 8: Illustration of the program flowchart for the impact applied at $x = 52$m and $z = 5$m (bottom right of the rear PAX door). (1) Detection of the impacted half. (2) Selection of rear primary sensor measurements. (3) Spectrum reconstruction of 5Z measurements with (OXZ) DMF modes. [19]

5. Experimental results on the aircraft Airbus A350-900 MSN003

5.1. Set up

The aircraft is an Airbus A350-900 on ground without engines (see Figure 9). The fuselage skin and the main components of the structure (stringers in the axial direction and frames in the radial direction) are made of composite materials. The aircraft has been impacted on the external skin of the fuselage by a 5.5 kg hand-held impact hammer from PCB Piezotronics, 086D50. Therefore, the applied impacts during these tests have a much lower energy than the impacts that may occur during the operational life of an aircraft [21]. In addition, it has been observed that the vibrations induced by the impact hammer did not propagate well from one end of the aircraft to the other end (strong signal attenuation). This is why a secondary network is dedicated to the detection of which half has been impacted (front or rear). The primary sensor measurements for the model identification step are then selected in accordance with the impacted half. Table 1 summarizes the parameters of the set up and the selected DMFs for the impact identifications.

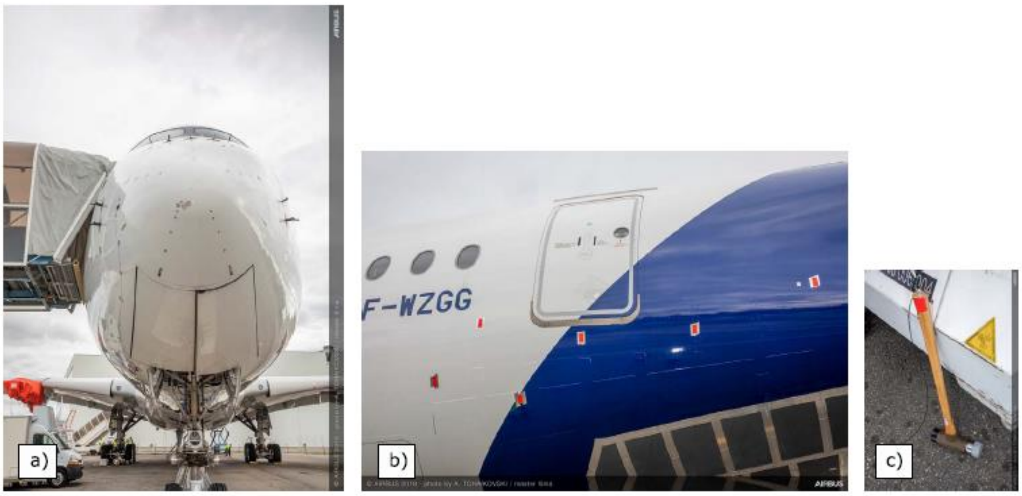

Figure 9: (a) Tested aircraft (A350-900 MSN003). (b) Impact locations around the rear passenger door. (c) Impact hammer. [19]

Aircraft	Length: 65 m Fuselage: composite skin, composite stiffeners
Sensors	Six bi-axis accelerometers from PCB Piezotronics, 356A14 distributed along a line of the aircraft belly Measurement axes: Y and Z Sampling frequency: 200 Hz Acquisition duration: 5 s
Acquisition system	Data Physics ABACUS LMS Test Lab 15A
Methodology parameters	DMF (OXY) front half: $\phi_7, \phi_9, \phi_{11}$ DMF (OXY) rear half: $\phi_3, \phi_5, \phi_{11}$ DMF (OXZ) front and rear: $\phi_6, \phi_8, \phi_{10}$ Dispersion factor: $\gamma = 2$

Table 1: Parameters of the set up and selected DMFs from the Experimental Modal Analysis [19]

5.2. Localization results

The impacts have been applied at 23 different locations according to a typical distribution of impacts on a fuselage during its operational life. The impact locations are mainly concentrated around the passenger and cargo doors on the lower half of the fuselage. For simplicity during the tests, all the impacts have been applied on the left side of the aircraft. No impact has been applied on the central section of the fuselage (between 16m and 34 m), which is obstructed by the wings of the aircraft. In addition, all the impacts have been applied thrice per location to test both the accuracy and the robustness of the proposed impact localization method.

Figure 10 presents the localization maps of the three series of impacts. A red cross represents an actual impact location and a black cross represents an estimated location. The mean localization error for all the impacts is equal to 2m, which roughly corresponds to a few percent of the aircraft length. This performance, in terms of mean localization error compared to a characteristic dimension of the structure, is consistent with other experimental validations on a metallic plate in [16,17] and a stiffened composite panel in [18]. In this case, it can be appreciated that 100% of the applied impacts are detected with only six accelerometers (no stand-alone red crosses) and a simple modal model of the aircraft. It reveals that the contributions of the DMF modes are correctly extracted from the measured vibration responses, even if the reconstructed frequency band is small with respect to the actual frequency content of the measured signal (see Figure 8). Besides, it is observed that the localization error in the Z-direction is lower (0.7 m) than the mean localization error in the X-direction (1.6 m). This is because the axial localization is achieved with a technique using low-frequency mode shapes of the aircraft that slowly vary along the X-axis (see Figure 7). The Z-coordinate of the impact point is estimated by another approach based on the estimation of the impact force direction.

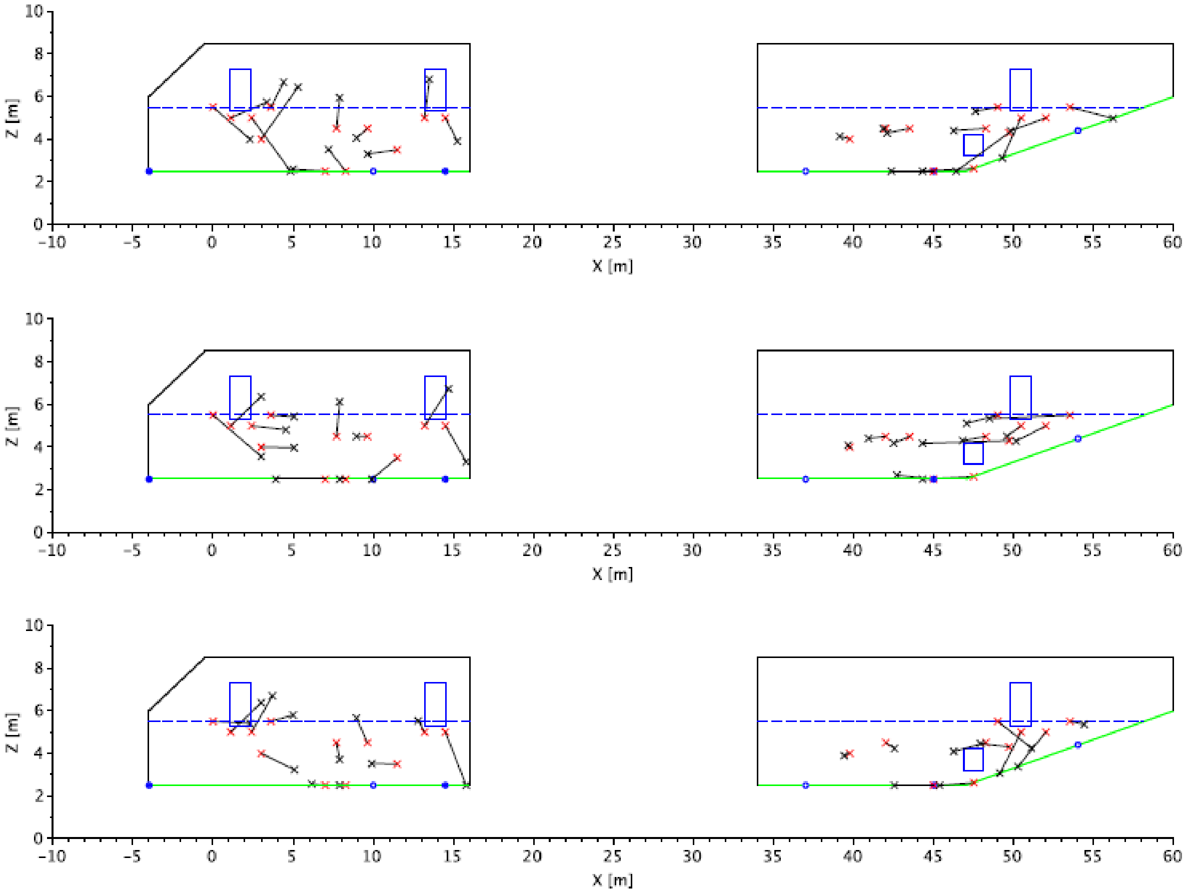

Figure 10: Localization maps for the three series of impacts. Red cross: actual impact location. Black cross: estimated impact location. [19]

6. Conclusion

This paper presents an original and efficient methodology for localizing impacts and reconstructing the applied load history on a composite fuselage from the vibration measurements of a small number of accelerometers. The proposed technique consists in extracting specific modal participations as a signature of the axial coordinate of the impact point. The angular coordinate is estimated from the identification of the impact force vector assumed normal to the fuselage surface. An impact test campaign has been performed in outdoor conditions on a complete A350 aircraft at scale 1:1. The methodology, initially carried out on a simply supported 40cm x 40cm metallic slab (with help of one sensor only), then on a complete piece of composite structure 9m x 3m, is performing successfully on the aircraft, with help of six sensors only. We observed the same mean localization error with respect to a characteristic length of the impacted structure (~4%). The localization results show that the applied impacts are identified with satisfactory accuracy with respect to the complexity and the dimension of the studied structure. These results are promising to develop in future works a more advanced impact identification system.

7. Copyright Statement

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