Signal Processing Strategies Using Micro-Systems for In Situ Health Monitoring of Aircraft

Patrice Masson, Philippe Micheau, Thomas Delaunay and Jérôme Pinsonnault
GAUS, Department of Mechanical Engineering, Université de Sherbrooke, Sherbrooke, Quebec, J1K 2R1, Canada

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ABSTRACT

This paper provides an overview of a recently started project aimed at reducing the high costs associated with periodic prescribed inspections of aircraft structures by the development of an in situ structural health monitoring (SHM) system. The development of the in situ monitoring system is based on the use of advanced sensing and actuating devices such as MEMS and functional materials. This paper highlights candidate signal processing strategies for health monitoring of aircraft structures. In this preliminary work, one of the candidate time-frequency approaches is presented: subband filtering or signal envelope processing. This strategy is implemented on a real-time rapid prototyping system and validated on a simplified aircraft component. Experimental results are presented and provide some indications on the appropriateness of this approach for health monitoring of structures.

INTRODUCTION

MEMS (Micro Electro Mechanical Systems) devices potentially offer improved reliability at a fraction of cost compared to the classic technologies. These potentials, which have been, long time ago, recognized by the automotive sector, specifically in the areas of engine and fuel control, active safety devices, intelligent transportation systems, etc. The proven benefits of the MEMS devices in the automotive industry have generated considerable momentum within the aerospace sector to explore developments and applications of various MEMS devices. More specifically, the industry has shown significant desire for MEMS devices for more efficient and reliable engine control and monitoring, better evaluations of stresses induced in the aircraft structure, and enhanced aerodynamics of the airfoil and flight safety, to name only few. The small size and weight along with the reduced power consumption of such devices is the key feature that has prompted the interests in the aerospace sector.

A new aerospace consortium, Consortium de Recherche et d’Innovation en Aérospatiale du Québec – CRIAQ, was created in the province of Quebec, Canada in 2002, where 65% of the Canadian aerospace sector is concentrated [1]. The objective of CRIAQ is to carry out collaborative industry driven pre-competitive research at the various Quebec Universities. Six technology areas were identified: manufacturing and composites, modeling and simulation, vibration, acoustics and icing, design optimization and integration, avionics and MEMS. This paper presents an overview one of the project related to the use of MEMS for structural health monitoring.

Aircraft are subjected to many loading cycles, which results in fatigue cracks emanating from regions of stress concentrations in the structure. In order to reduce the high costs associated with periodic prescribed inspections of the structure, the development of an in situ aircraft structural integrity device is of great interest to the industry. This device would avoid the need to dismantle some parts of the aircraft for the periodic inspections and would therefore translate into tremendous economic benefits. This device would also propose a solution in agreement with a current tendency in the aerospace industry where some components are not anymore systematically replaced at given intervals, unless a problem is detected.

Thus, the sensing system developed within this project will assist in evaluating the damage in the structure, either passively or actively. During normal operation, the intelligent monitoring system will provide real-time in situ structure load transfer profiles, identifying the efficiency and health of the structure, to an on-board controller or data acquisition system.

The novelty of the proposed approach for the development of an in situ monitoring system is the employment of advanced sensing and actuating devices such as MEMS and functional materials, like piezoelectric materials (Polyvinylidene polymers (PVDF) and piezoelectric ceramics (PZT)). Moreover, the complexity of signal acquisition, analysis, and presentation is user specified. For instance, the system can be used in two modes off-line and on-line mode. In the off-line mode data is collected at regularly scheduled interval; whereas in the on-line mode the data is acquired and analyzed on flight.
OVERVIEW OF CURRENT SHM TECHNOLOGIES

Studies aimed at addressing some of these issues have been reported by several researchers [2,3]. However, the issue of real-time in situ monitoring of the structure has received little attention. Traditionally, the health monitoring of aircraft structures is conducted off-line and at prescribed flight hours during regularly scheduled maintenance. These inspections are thereby limiting the availability of the aircraft as well as imposing risks on the use of the aircraft. Techniques such as ultrasonic inspection, acoustic emission, scans, and X-rays are commonly used. They provide qualitative assessment of the health of the structures. These techniques along with visual inspection cannot detect any crack growth in the structure and provide no early warning for preventive maintenance of the structures. All of these lead to increased operation and maintenance costs. It is highly desirable to have a means of continuously monitoring the integrity of the structure in order to improve performance and reduce costs. The Table 1 presents an overview of SHM technologies of interest for continuous monitoring.

SENSING STRATEGIES

Recently-developed technology for structure monitoring focused on the use of conventional sensor technology such as strain gages. Because of their maturity and simple data acquisition, these sensors come at a lower cost and extensive data base history. In spite of these advantages, these conventional sensors carry the excess weight penalty associated with their protection and shielding from electromagnetic interference as well as their electrical insulation. Further problems associated with bonding strain gage sensors to the structure include: premature gage debonding, premature connectors and soldered tab fatigue failure, complexity of multipoint sensing and multiplexing.

Advanced sensor technologies provide the potential for eliminating or at least reducing problems associated with conventional sensors. Sensors such as optical fibers provide immunity to electromagnetic interference caused by electrical systems in close proximity to the sensor elements, reduction of weight, increased geometric flexibility and enhanced multiplexing capability, improved sensitivity, and greater dynamic range. Dual function piezoelectric film sensors/actuators can further be integrated into the structure to provide in situ process monitoring as well as health monitoring during normal operation of the structures. Piezoelectric sensors/actuators can also be used for structural vibration sensing and control. This will render the passive structure adaptive and hence provides the structure with the capability of reducing structural damage and prolonged life cycle. Other sensors that are of potential use for structural health monitoring include shape memory alloys and MEMS sensors. The Table 2 illustrates the advanced sensor characteristics for structural health monitoring.

<table>
<thead>
<tr>
<th>Material</th>
<th>Damage</th>
<th>Detection technique</th>
</tr>
</thead>
<tbody>
<tr>
<td>Metallic structure</td>
<td>Crack</td>
<td>Modal analysis, Modal damping, Electro-mechanical impedance, Time-frequency, Reduced-rank stiffness, Lamb wave, Structural transmissibility</td>
</tr>
<tr>
<td></td>
<td>Corrosion</td>
<td>Electro-mechanical impedance, Structural transmissibility, Lamb wave, Eddy current</td>
</tr>
<tr>
<td></td>
<td>Dents, holes</td>
<td>Modal analysis, Modal damping, Structural transmissibility</td>
</tr>
<tr>
<td></td>
<td>Broken fastener</td>
<td>Modal analysis, Modal damping, Structural transmissibility</td>
</tr>
<tr>
<td></td>
<td>Debonding of the adhesive layer</td>
<td>Electro-mechanical impedance</td>
</tr>
<tr>
<td>Composite structure</td>
<td>Delamination</td>
<td>Modal analysis, Modal damping, Lamb wave, Electrical conduction</td>
</tr>
<tr>
<td></td>
<td>Crack</td>
<td>Modal analysis, Modal damping, Time-frequency, Lamb wave, Electrical conduction</td>
</tr>
<tr>
<td></td>
<td>Separation from metallic structure</td>
<td>Electrical conduction, Electro-mechanical impedance</td>
</tr>
<tr>
<td></td>
<td>Dents, holes</td>
<td>Modal analysis, Modal damping, Lamb wave</td>
</tr>
<tr>
<td></td>
<td>Buckling</td>
<td>Electrical conduction</td>
</tr>
</tbody>
</table>

Table 1: Overview of SHM technologies of interest for continuous monitoring.

<table>
<thead>
<tr>
<th>Sensor Characteristics</th>
<th>Fiber Optic Sensors</th>
<th>Shape Memory Alloys</th>
<th>Piezoelectrics</th>
<th>Strain Gauges</th>
</tr>
</thead>
<tbody>
<tr>
<td>Embeddability</td>
<td>Excellent</td>
<td>Excellent</td>
<td>Very Good</td>
<td>Good</td>
</tr>
<tr>
<td>Frequency response</td>
<td>1-200 kHz</td>
<td>1-10 kHz</td>
<td>1-20 kHz</td>
<td>1-500 kHz</td>
</tr>
<tr>
<td>Sensitivity</td>
<td>0.11µε</td>
<td>0.1-1.0µε</td>
<td>0.001-0.01µε</td>
<td>2µε</td>
</tr>
<tr>
<td>Cost</td>
<td>Moderate</td>
<td>Low</td>
<td>Moderate</td>
<td>Low</td>
</tr>
<tr>
<td>Maximum Strain</td>
<td>10000µε</td>
<td>5000µε</td>
<td>550µε</td>
<td>10000µε</td>
</tr>
</tbody>
</table>

Table 2: Advanced sensing strategies for health monitoring [4].
SIGNAL PROCESSING STRATEGIES

It is well known that damage will cause local stiffness loss, damping increase or introduce non-linearities in the structure [5]. It is the purpose of the intelligent data processing to detect one of these using a reliable approach. For damage to be detected by any approach, it has to affect noticeably the dynamics of the structure. In this respect, the nature of the signal exciting the damaged area is of primary importance for proper detection, including frequency and amplitude.

First, two general approaches can be distinguished. In the first approach, the signals provided by the sensors are passively processed to extract a useful indicator related to structural degradation. The signal measured by the sensor is thus obtained from the excitation of the component by external sources such as aerodynamic load, engine vibration, etc. In the second approach, an actuator is used to provide an excitation signal and the sensors measure the response of the component to the excitation. This approach can be called an active strategy. In this strategy, by controlling the excitation, frequency or amplitude, ranges can be chosen to optimally measure the relevant information correlated with damage. Generally, a signal from a damaged part is compared to a healthy initial signal (frequency and amplitude).

Another distinction can be made based on the rate of measurements taken by the sensors. An off-line system will be able to provide an assessment of the integrity of the components at specified inspection intervals on the ground. In this case, the external disturbances are limited and the signal to noise ratio at the sensors is increased. On the other hand, an on-line or in situ monitoring system will allow real-time monitoring of the component in flight conditions and can continuously issue an alarm if a critical condition has been reached. In this case, the excitation signal will be superimposed with the external disturbances and a strategy will have to be used to decorrelate the two signals.

The monitoring of the structural integrity can be conducted either at low frequencies by analysing the modal behaviour of the structure or at higher frequencies using ultrasonic techniques by studying the wave propagation in the structure. Among the available strategies for damage detection, ultrasonic and acoustic inspections are well-known techniques. Frequencies involved are in the order of $10^5$ to $10^6$ Hz. Other approaches working at lower frequencies are based on the monitoring of the non-linearities associated with the evolution of damage in the structure [6]. The concept of non-linearity contrast can be used to quantify the energy content of a non-linearity arising from a damage to the structure. It has been demonstrated that a non-linear system can be characterised by time-frequency variations of the response of a structure under sinusoidal excitation [7].

IMPLEMENTATION OF IN SITU MONITORING

SYSTEM CONFIGURATION

The Fig. 1 illustrates the instrumented structure in the first phase of the development, where piezoelectric sensors and actuators will be used and where the detection algorithm will be implemented on a rapid prototyping dSPACE system. This first phase will aim at defining the specifications for the sensors and actuators to be designed for integration into the structure, based on the selected detection algorithm. Such specifications will include the type of measurement (force, acceleration, strain, …), required sensitivity, spatial resolution,… In its most advanced form at the end of the second phase of the development, the envisioned active monitoring system will consist of embedded components such as MEMS sensors and actuators, with integrated electronics for signal processing and data transmission to an on-board data logging and interface system.

Figure 1: System configuration for the first phase of development of an in situ structural health monitoring system.

Experimental and numerical investigations will first be conducted to study the impact of several types of damages (corrosion, impact, debonding,…) on the dynamic and/or static response of the multilayer structure formed by the embedded/bonded sensor/actuator and the structure underneath. Typical military or commercial aircraft component damage scenarios will be used for the study. The numerical model will be based on the finite element method and assessment with experimental results will be conducted. This numerical tool will be used to identify a model of the complete structure both for dynamic and static behavior and should allow characterizing the loading of the structure in order to design the sensing and actuating configuration for the signal processing and experimental investigations in the study.

The model should allow establishing a correlation between the parameters of the model and the type and extent of the damage on the structure. The model will therefore allow obtaining some indications on the optimal location of the sensors and the actuators as well as on the relevant frequency ranges. Two levels of development are considered for the signal processing and analysis. A first proof-of-concept prototype will consist of a signal processing system designed in a prototyping environment. This part of the work might thus use typical configurations
such as plates with bonded piezoelectric ceramic (PZTs) in order to simply demonstrate the concept of the signal processing strategy. Moreover, even if the proposed strategies are oriented towards continuous or on-line monitoring of the multilayered structure, as a first step in this work, the strategies will be applied to structures where the only excitation will be provided by the actuators. The full potential of the approach will be demonstrated in configurations where other disturbances (aerodynamic load, engine vibration) will be superimposed with the actuator signals.

The signal processing strategies will first be prototyped using two dSPACE rapid prototyping and hardware-in-the-loop systems. These systems have 6 GFlops computational power and 32 channels each. One of the dSPACE systems will be used to develop the data processing strategies while the other one will be used as a simulator to emulate the complete hardware system, from the signal sent to the actuators to the signals received from the sensors and including the possible damage modes. A second level of development will be achieved when the signal processing strategy will be ready for implementation into a compact and affordable control unit, in order to be easily integrated in the aircraft. DSP-based processors will be considered as candidates for implementing the dedicated controller/monitoring unit.

SUBBAND FILTERING TECHNIQUES

Subband filtering techniques have been applied in active control [8] and in numerical simulation [9]. For application to the health monitoring of structures, it is proposed to measure the envelope of the signal and to use it as a metric for the condition of the structure.

Lee and Park [10] have shown that the signal envelope technique allows for a good estimation of the modal parameters, even when the impulse signal of a closely spaced mode system is severely truncated and the data length is less than the time constant. A similar approach consists in using a wavelet representation in the time-scale domain [11]. Because this tool can provide a representation of the envelope decay as a function of time for each mode, Lamarque et al [12] used a wavelet-based formula to estimate damping in multiple degrees-of-freedom systems from time-domain responses. However, the validity of this decoupling procedure is linked with the wavelet frequency resolution. Ruzzene et al [13] performed a continuous wavelet analysis of the free response of dynamic systems to extract modal features: both natural frequencies and damping ratios which are difficult to identify. They concluded that the wavelet analysis represents a good improvement of the technique based on the Hilbert Transform. Moreover, it has been demonstrated that time-frequency tools are useful to analyze non-linear system [7].

Formulation of the problem

Single degree-of-freedom systems

Let first consider the simple case of a viscously damped single degree-of-freedom system. The measured output of the system (displacement or acceleration) is \( y(t) \) and the input control force on the system is \( u(t) \). The system is characterized by its impulse response as:

\[
y(t) = A \exp\left(-\zeta \omega_n t\right) \cos(\omega_d t + \Phi) \Gamma(t)
\]

where \( A = F / \omega_d \) with \( F \) the time integral of an applied impulse force, \( \omega_n \) is the undamped angular frequency, \( \omega_d = \omega_n \sqrt{1-\zeta^2} \) is the damped angular frequency, \( \zeta \) is the damping ratio, and \( \Gamma(t) \) denotes the Heaviside function. The envelope of the response signal is given by the term \( A \exp(-\zeta \omega_n t) \) which modulates the oscillating term \( \cos(\omega_d t + \Phi) \).

A well-established technique for the measurement of the envelope of the signal consists in computing the following analytic signal:

\[
y_a(t) = y(t) + jH\left[y(t)\right]
\]

where \( j^2 = -1 \), and \( H\left[y(t)\right] \) is the Hilbert Transform of \( y(t) \) [14]. For real single-degree-of-freedom structures with damping, the analytic signal \( y_a(t) \) can be approximated by a rotating vector \( R(t) = \exp(j\omega_d t) \) modulated by a slowly-varying complex envelope \( Y(t) = A \exp\left(-\omega_n \zeta t + j\Phi\right) \):

\[
y_a(t) \equiv Y(t)R(t)
\]

The main interest of this approach is to separate the analytic signal into two components: a slowly-varying signal, i.e. the complex envelope \( Y(t) \), and a fast signal, the oscillating term \( R(t) \). It should be noticed that the modulus of the complex envelope is the envelope of the real signal: \( |Y(t)| = A \exp(-\zeta \omega_n t) \).

Multiple degrees-of-freedom systems

For multiple degrees-of-freedom structures usually found in real applications, the system is damped and several modes are excited. In this case, the impulse response can be expressed as the sum of the \( L \) most relevant modes of the structure:
where \( i \) is the modal index. One method to obtain the complex envelope \( Y_i(t) \) for each mode would be to filter the signal using a band-pass filter in order to pick out each mode of interest and to reject all the others.

**Implementation of the strategy**

**Modeling tools**

The original proposed approach is to monitor each envelope of modes at a specific scale (rate). The block diagram shown in Fig. 2 presents the monitoring strategy. To approximate the signal envelope for each mode, the authors used filter bank analysis to implement this decoupling procedure and filter bank synthesis to implement the construction procedure. For each frequency subband, the complex envelope is monitored with one subcontroller. In other words, filter banks allow to divide the whole frequency domain into \( L \) frequency subbands, each of them being considered as a structural health monitoring system.

![Figure 2: Principle of the subband adaptive controller.](image)

A practical implementation of the synthesis consists to use filter banks.

\[
u(t) = \sum_{i=1}^{L} A_i \exp(-\zeta_i \omega_{ni} t) \sin(\omega_{di} t) \Gamma(t) \tag{4}\]

where \( i \) is the modal index. One method to obtain the complex envelope \( Y_i(t) \) for each mode would be to filter the signal using a band-pass filter in order to pick out each mode of interest and to reject all the others.

The complex envelope of each mode can be obtained with the inverse operation:

\[
Y_i[k] = [\downarrow M] \left[ G_i(t) \ast (y(t) \exp(-j\omega_i t)) \right] \tag{6}
\]

where \( \downarrow \) is the downsampling operator. The output signal is demodulated both in amplitude and phase at the frequency \( \omega_i \). A low-pass filter of causal impulse response \( G_i(t) \) is applied to limit its frequency support into a low-frequency domain \([- \Delta \omega_i / 2; + \Delta \omega_i / 2]\). The result from this operation is the complex envelop of the mode \( i \).

**Subband time-frequency model**

The system can be represented by the following model with input \( u(t) \) and output \( y(t) \):

\[
y(t) = h(t) \ast u(t) \tag{7}
\]

where \( \ast \) denotes the convolution operator. The impulse response \( h(t) \) is defined by Eq. (4) when \( y(t) = h(t) \) and the input is an impulse signal, \( u(t) = \delta(t) \).

Then, in the scale domain, the discrete transmittance can be simply represented by an IIR filter:

\[
Y_i[k] = \frac{B_i(q^{-1})}{A_i(q^{-1})} U_i[k] \tag{8}
\]

where \( A_i(q^{-1}) = 1 - a_i q^{-1} \) (if there is only one observable mode in the subband) and \( B_i(q^{-1}) = FG(q^{-1}) \left( b_{\omega_i} + b_{\omega_i} q^{-1} + \ldots \right) \), where \( FG(q^{-1}) \) is the decimated response of the two low-pass filters.

**Mechanical interpretation of the model**

The numerical pole \( a_i \) of the denominator in Eq. (8) is the complex pole \( \lambda_p \) observed in the \( \ell^p \) subband. The relation between the numerical pole in the subband and the \( \ell^p \) complex pole of the flexible structure is given by:

\[
a_i = -\exp(-\zeta_i \omega_{ni} T_i) \exp\left(j(\omega_{di} - \omega_i) T_i \right) \tag{9}
\]
The modulus of the pole depends on the time constant \( \tau_i = \frac{1}{\zeta_i \omega_{ni}} \) of the complex pole and the downsampling rate \( T_i \). The phase of the pole depends on the distance in the frequency domain between the resonance frequency and the center of the subband.

As the discrete transmittance represents the physical process model, its parameters are time-varying. Thus, it must be continually identified on-line. This is the main interest of the approach for the active monitoring.

**On-line identification**

The application of the monitoring system in the \( i^{th} \) subband, requires the knowledge of the parameters \( a_i \) and \( b_i \) of the subsampled model of the system. To track the time variation of the parameters, it is necessary to implement an on-line identification of \( a_i \) and \( b_i \).

The predictor for the model (Eq. 8) is described by a linear regression of the form:

\[
\hat{Y}_i[k] = \hat{\theta}_i \varphi_i[k]
\]

(12)

where \( \hat{\theta}_i = [\hat{a}_i, \hat{b}_{0,i}, \hat{b}_{1,i}, \ldots] \) is the vector used to parametrize the model and \( \varphi_i[k] = [Y_i[k - 1], U'_i[k], U'_i[k - 1], \ldots] \) is the regression vector of known data at the undersampled time \( k \), and \( U'[k] = FG(q^{-1})U[k] \) is the filtered excitation.

Identification is done by using complex recursive least squares with a forgetting factor: CRLS-\( \lambda \). Forgetting factor \( 0 < \lambda < 1 \) is mainly used to track time-varying parameters. This factor must be chosen as a trade-off between tracking capability and noise sensitivity. Based on the theory of recursive identification of L. Ljung and T. Soderström [15], the CRLS-\( \lambda \) is used to identify the ARX model parameters as follows:

\[
R_i[k] = \lambda R_i[k - 1] + \overline{\varphi_i[k]} \varphi_i'[k]
\]

(13)

\[
q_i[k] = \lambda q_i[k - 1] + \overline{\varphi_i[k]} Y'_i[k]
\]

(14)

\[
\hat{\theta}_i[k] = R^{-1}[k]q_i[k]
\]

(15)

**EXPERIMENTAL VALIDATION**

**Experimental setup**

The Fig. 3 presents the measurement setup that was used for the preliminary measurements using the signal envelope approach. One frame of a fuselage is excited by a piezoelectric using a wavelet in the frequency range 1133 Hz ± 200 Hz (signal \( u(t) \), see Fig. 4). This frequency range will allow to excite the structure on its (1,9) mode located at 1133 Hz. The transverse velocity response of the structure is measured at three points with a laser vibrometer (signal \( y(t) \)).

**Preliminary results**

This section presents some preliminary results that were obtained for the three measurement points. The Fig. 5 presents the time response of the structure measured at point 1, in the upper part of the section. A point mass (30g) was added to the structure in the vicinity of point 1 to investigate its effect on the structure and the measurement was taken again. Eqs. (12)-(15) were then used to estimate the \( a_i \) for this subband and Eq. (9) was used to evaluate the corresponding \( \zeta_i \) and \( \omega_{ni} \). Table 3 summarizes the results obtained for both cases.
Figure 5: Time response $y(t)$ at point 1

Table 3: Model parameter $a_i$ with and without an added mass.

<table>
<thead>
<tr>
<th>Added mass</th>
<th>Parameter $\hat{a}_i$</th>
<th>$\zeta_i$</th>
<th>$\omega_{ni}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 g</td>
<td>$\hat{a}_i = 0.873 - 0.07i$</td>
<td>1%</td>
<td>1126 Hz</td>
</tr>
<tr>
<td>30 g</td>
<td>$\hat{a}_i = 0.565 - 0.565i$</td>
<td>1.6%</td>
<td>1070 Hz</td>
</tr>
</tbody>
</table>

These first results show that both the frequency and the damping are affected by a slight modification of the structure, i.e. with the added mass. The CRLS algorithm used with the subband approach has thus the potential to allow for on-line detection of such modification of the structure by identification of the parameter $\hat{a}_i$.

As an indication of the impact of a missing rivet on the localized measurement of the transverse velocity, Figs. 6-9 present the measurement results at points 2 (close to the missing rivet) and 3, in both the time and frequency domains. The results are presented within the subband frequency (scale) domain, where the center of the subband, shown at 0 Hz in Figs. 7 and 9, corresponds to 1133 Hz.

These results show that both the time and frequency responses of the structure are severely modified in the vicinity of a damage, i.e. a missing rivet. This effect is apparent even if the measurement points are very close to each other. However, in this case, the evaluation of the
modal parameters $\zeta$, and $\omega_n$, will require further investigation.

**CONCLUSION**

In this paper, an overview of structural health monitoring technologies applicable to continuous health monitoring was presented. The subband filtering technique was presented as a candidate technology for the detection algorithm to be developed. The implementation of the approach has been described and preliminary results were presented to assess the effect of a damage on the signal processing algorithm. Future algorithm development will investigate modal parameters estimation for complex damaged structures.

The expected outcome of the structural health monitoring project is a well-defined approach for monitoring the integrity of structures using advanced sensors and actuators, such as piezoelectric materials or MEMS. The use of MEMS could allow for distributed sensing with a large number of low-cost units, communicating between each other to provide a global information related to the integrity of the structure. An experimental assessment of the approach will be conducted on a laboratory prototype consisting of selected aircraft structures configurations.

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**REFERENCES**


**CONTACT**

Patrice Masson: Patrice.Masson@gme.usher.ca

Philippe Micheau : Philippe.Micheau@gme.usher.ca