A Fast Integrated Device for Detection of Connections and Interns Defects in Aeronautical Structures.

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Résumé :

L'objectif concerne la détection rapide, en temps réel, du début d'endommagement des liaisons entre des éléments de structures et aussi des débuts d'endommagements internes ; il s'agit d'obtenir des informations concernant l'importance et la localisation de tels endommagements. Ceci préalablement à des investigations approfondies.
Le principe : Cette méthode est basée sur le fait que le comportement dynamique d'une structure durant sa phase d'excitation, et ensuite de relaxation, fournit des informations importantes quant à l'état des liaisons des éléments, et des dommages internes de ces éléments.
La technique consiste en l'analyse de la réponse dynamique de la structure ; elle ne nécessite qu'un nombre réduit d'actuateurs et de capteurs intégrés à la structure. Il n'est pas nécessaire d'effectuer des mesures en des points très proches (Comme c'est le cas usuellement en CND).
Notre but est de déduire certains critères concernant la sensibilité de la méthode aux endommagements, et de proposer une méthode d'exploitation originale.

Abstract:

The objectives: Fast detection, in real time, of beginning of connection defects between structures elements and internal elements defects, obtaining some quantitative information with importance and position of defects. It is aimed to provide information preliminary to thorough examinations.
The Principle of the diagnosis: This method is based on the fact that structure behaviours during its phase of excitation, and afterwards, constitute powerful indicators of the quality of the limiting conditions or internal damage.
The technique consists in examining the dynamic response of the structures, and it requires a small number of sensors integrated into the structure; It is not necessary to take measurements in very close points (as it is usually the case in NDT).
Our study aimed deducing some form of criteria concerning these conditions and proposing an original exploitation.

Key words: wavelet analysis, smart structures, failure detection.

1 Proposed method.

Aeronautical structures work under extreme conditions; consequently, it is important to know well their health, this because of their sensitivity to the damage by shocks and also by tiredness. If important damages are easily detectable, it is not the same for the limited damage of material or connections which can result only in one limited failure of material or a deterioration of the connections (joining, welding, bolts or rivets). These effects can remain completely undetectable at the time of a visual inspection of the structure.
Such a local failure may (in certain conditions) evolve quickly, and to have for consequence a loss of local rigidity, even the break of the material or of the connections.
It is not possible (for questions of time and cost) to multiply deepened examinations on the ground by classic techniques of NDT; so the method aims concern the fast detection (in real time) of early beginning of defects

of connection between elements of structures and internal defects of these elements, and to obtain quantitative information with the importance of the defects, and their position. It must provide information preliminary to thorough examinations.
The method we present concerns the detection of the evolution of the mechanical properties of materials and connections by vibratory analysis, with transducers integrated into the structure (which constitutes the object of this presentation).

The tests for the validation were initially carried out on an aluminium alloy beam, and then on composite structures (carbon-epoxy).

1.1 Our Works.

A first theoretical access of the problem was made with an analytical model intended to characterize the vibratory behaviour of a beam subjected to sinusoidal trains of finished duration.

In order to test the feasibility of the proposed method, a simple slender beam subject to piezoelectric actuator excitations was used. Transverse vibrations response was measured with a piezoelectric sensor. A not conformist assembly (asymmetrical) of actuator and sensor inducing simultaneously bending and stretching, allows obtaining an increase of the sensibilities to the sliding of frequencies and variations of damping.

The first tries allowed seeing certain interesting aspects, namely at the beginning of excitation and at the end of excitation, but secondary phenomena appeared, especially at these times.

An analysis with numerical method FEM of the vibratory behaviour of the structure was then developed; it allows the revealing, in particular of points which we considered before as secondary, but which are actually extremely important.

1.2 The stages of the work.

The following points are presented:
- Symmetrical and asymmetrical excitation,
- The received signals,
- Wavelets analysis, interpretation and the observed "abnormalities",
- Numerical modelling of the transitory behaviour of elements of structures subjected to transient harmonious excitements,
- Application in the case of structures in composite materials, the tries concern composite plates,
- Treatment of the signal, and obtaining significant information.

2 Excitation with two actuators (sensor in another abscissa), and case of a single actuator with sensor placed on the opposite face of the beam.

Two configurations of assembly of the piezoelectric transducers were tested:
- Symmetric assembly: two actuators stuck on opposite sides of the beam (excitation with a phase shift of π); the sensor being situated in another abscissa,
- Asymmetrical assembly (figure 1): a single piezoelectric actuator is stuck on the structure, and the sensor is just stuck on the opposite face of the beam.

We notice that the asymmetrical assembly presents (for the envisaged utilization) several advantages:

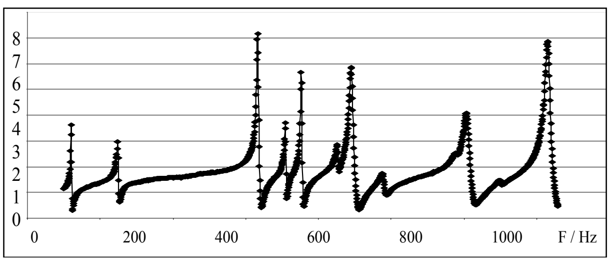

FIG. 1 – Asymmetrical excitation

In particular, the variation of amplitude is much rougher in this case, because of the extremely fast evolution of the phase at the time of the passage of the natural frequency.

This sensibility of the answer to the variation frequency of the signal relatively to the natural frequency of the mode, made that we shall work mainly with the asymmetrical configuration.

3 The obtained signals and their interpretations.

Excitation frequency was chosen to be a resonant frequency of the clamped–clamped beam. A mode of vibration, which was not too close to other adjacent modes of vibration, was chosen. The reason is the requirement that the slide of natural frequency from clamped-clamped to clamped-imperfectly clamped beam will not pass another clamped-clamped natural frequency.
The excitation was applied for a finite time; and, on the typical measurement results, the following domains would be observed:
- Excitation domain, with the duration chosen such that the initial transient is followed by a long enough steady state part (with or without modulations),
- Relaxation domain, which starts after the excitation source is turned off and is characterised by duration and amplitude variation strongly dependent of the boundary conditions, excitation type and position of actuator.
The method is extremely sensitive for the detection of the variations of natural frequencies of a structure, where from as a result of the damages; so a scanning of the frequency of excitement allows bringing to light important variations of the shape of the received signal, this in the neighbourhood of the natural frequency (figure 2). In particular we notice:

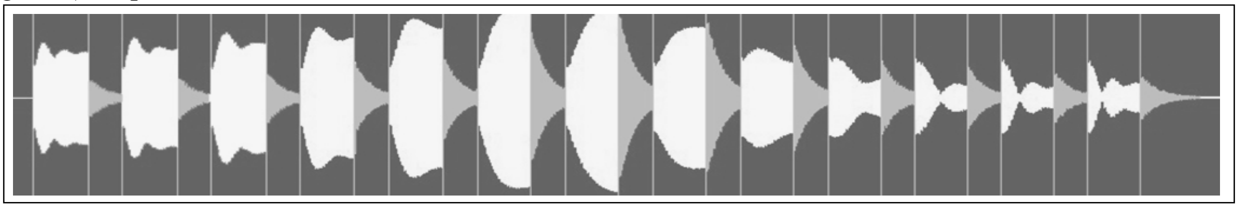

FIG. 2 - Temporal signals with scanning of the frequency, from 590 to 625 Hz

- Below the natural frequency :
  - o Response during excitation is slightly modulated; modulation frequency rises when one moves away the natural frequency (by an inferior value).
  - o Amplitude discontinuity (decreasing).
- At the natural frequency:
  - o During excitation the amplitude is increasing.
  - o Low amplitude discontinuity.
- Upper the natural frequency:
  - o During excitation the response is strongly modulated, the frequency of the modulation increase when one move away from the natural frequency (by a superior value).
  - o High amplitude discontinuity (increasing).

In the practical application, the natural frequency of the system with damage of the connections is always lower than the undamaged system's one.

4 Increase of the signal received at the beginning of relaxation

In the case of a symmetrical excitation, only the mode of pure flexion is induce, and then we do not observe discontinuity of amplitude and phase during the passage from forced oscillations to free oscillations,
For an asymmetrical excitation, the action induced simultaneously a local stretching and a local bending. The effects will be more complex as regards the indications of the sensor of deformation.

We so determined for the place of the sensor the expressions of the relative elongations concerning the pure stretching e_l and the pure bending e_b.
It is to note that the natural modes corresponding to the longitudinal vibrations are very higher than those corresponding in the natural modes of bending; so if it does not seem useful to correct of this fact the expressions of e_l. It is not the same for the modes of bending, which are strongly influenced by the resonance which can amplify the deformations e_b by important factors (x10), this by the introduction of a complex function of the frequency $f(\Omega/\omega_n)$ which leads to $e^*_b = e_b.f(\Omega/\omega_n)$.
The total relative elongation $e_l + e^*_b$ is then (because of phase shifts) of weaker absolute value than the one corresponding to the pure bending.

During the cessation of the excitation, there would be so passage for the stretching deformation e_l from the value defined by the previous expression to a zero value, and, because of the continuity of the vibrations of bending, the value of the elongation e^*_b would be temporarily kept, that would induced an increase of the elongation. For the resonance this effect is practically not observable because $|e_l| << |e^*_b|$.

As a consequence, this method is extremely sensitive for the detection of the variations of natural frequencies of a structure, where from as a result of the damages.

5 Application for the detection of the damage of the structures.

5.1 Experimental set-up.

For testing the feasibility of the proposed method, a simple slender beam subject to piezoelectric actuator excitations was used. Transverse vibrations response was measured with a piezoelectric sensor.
The diagram of the experimental set-up used in this study is shown (figure 3).

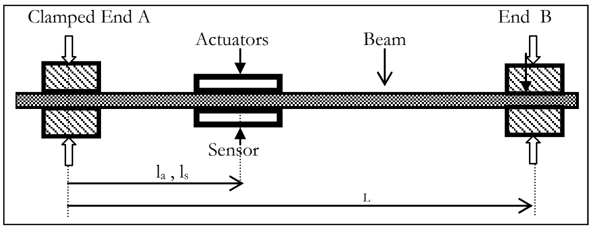

FIG 3 - Experimental set-up diagram.

End A of the beam was maintained clamped, with two tight bolts, while end B of the beam was modified gradually from clamped (representing a healthy state, level 1), to free (representing a totally damaged state, level 0). End B in healthy state was achieved by tightening the two bolts against Belleville washers. The degradation of the end B connection was achieved by reducing gradually the clamping force applied.

The measures were made by equipping the structures of piezoelectric transducers, which were chosen for their capacity to create and to measure the deformations. Their integration in the structure needs however several precautions, indeed the thickness of the film of glue as well as its mechanical properties influence largely the answer of the system sensor and glue [1]. We did not make systematic study concerning the sticking of the transducers; although for the experimental observations, the natural frequencies of transducers are much superior to those of the beam.

5.2 Data acquisition and treatment of the measures.

Excitation by DSP: the piezoelectric actuator was directly ordered by a DSP. This last one programmed in C.
The frequency parameter of excitation is fundamental. To facilitate the observation and the detection of the degradations we wish that the structure deforms a lot; the choice of the frequency of excitation will be made for a natural frequency of a healthy structure.
The duration of excitation; it seems that the duration of the transient regime is different from a mode to another mode. The tries were realized below the permanent regime, some tries were realized with longer time, but did not bring more significant results.
The signal acquisition device: it is classical.

Treatment of the measures: we made a treatment using a software of frequency analysis developed before [1, 2], which allows an using fine analysis with wavelets transform, which by its duality time/frequency allows to follow an accurate frequency evolution, where from as a consequence the process of degradation of the material.

5.3 Experimental results.

As indicated, excitation frequency was chosen to be a resonant frequency of the clamped – clamped beam. A mode of vibration, not too close to other adjacent modes of vibration,

The conditions of connection vary gradually, and are characterized by values of clamping.

The excitation was applied for a finite time; figure 4 shows typical measurement results of the excitation and the relaxation response for the experimental set-up used in this study:

1. Connexions A clamped and B Clamped,
2. Connexions A clamped and B lightly damaged,
3. Connexions A clamped and B strongly damaged.

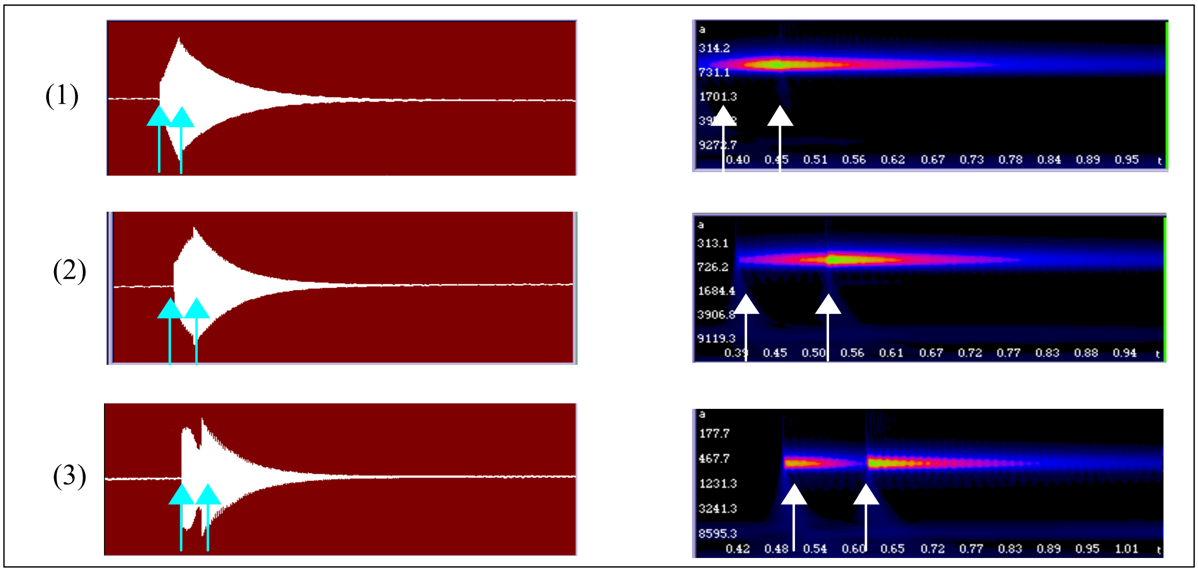

FIG. 4 – Experimental results: (Time signal & Wavelets transform).

Besides the important variations of amplitude, the wavelets transform brings to light the appearance of low frequencies signals, in particular at the beginning of the period of excitation, and at the beginning of the phase of relaxation.
This could not be explained by the analytical model used before, and required a modelling of the dynamical behaviour by a numerical method.

6 Modelling the dynamical response of the beam.

We consider the equation (1) for transverse vibrations of a slender beam of length L, with no external force or bending moment except locally $f_{(x,t)}$ toward application of the actuator:

$$\frac{\partial^2 y_{(x,t)}}{\partial t^2}+a^2\frac{\partial^4 y_{(x,t)}}{\partial x^4}=\frac{f_{(x,t)}}{\rho A} \qquad \text{with : } a=\sqrt{\frac{EI}{\rho A}} \qquad (1)$$

- y(x,t) is the deflection, function of beam longitudinal axis x and time,
- E is Young's elastic modulus,
- I is the cross-sectional area moment of inertia about the beam longitudinal axis,
- A is the cross section, and ρ is mass density,

In a first time [1], the separation of variables approach with a solution of the form: y(x,t) = p(t)·r(x) transform the above partial differential equation in two ordinary differential equations, one for p(t) and the other for r(x). But this method does not agree with transient response of the structure; the analytical methods of the type "separation of variables" are unsuitable for the study of the transitory behaviour.

6.1 Calculations by a method of finished differences.

The understanding of the frequency evolution of the signal was obtained from a modelling of the dynamic behaviour of the structure by finished differences (explicit, before, centred) [2].

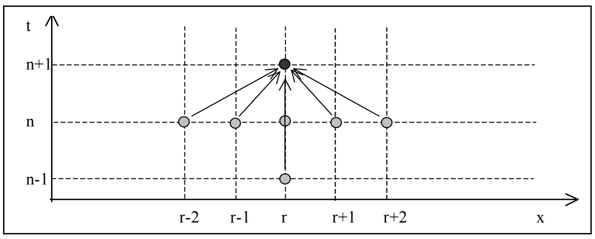

FIG. 5 – Calculation scheme

The deformations are calculated at a time for all the points of the beam (x, where space step marked r), then a new calculation is made for an increment of time (t, where time step marked n)
The excitation, which is local, is considered in the following way: entered on a domain r characterized by a function of time

The development of the model required:

- The introduction of a term of damping (for reasons of stability),
- The optimization of the steps of calculation (for reasons of stability and accuracy).

6.2 Results of the calculation.

The obtained results are presented under the shape of a "topographic" representation with in abscissa the variable of space, and in-depth the variable of time, and associated with curves functions of space and parameterized by time.

From these results, another representation (figure 6) shows the temporal evolution of the local deflection of the beam, with illustration of the evolution in the time of the longitudinal profiles of deformation.

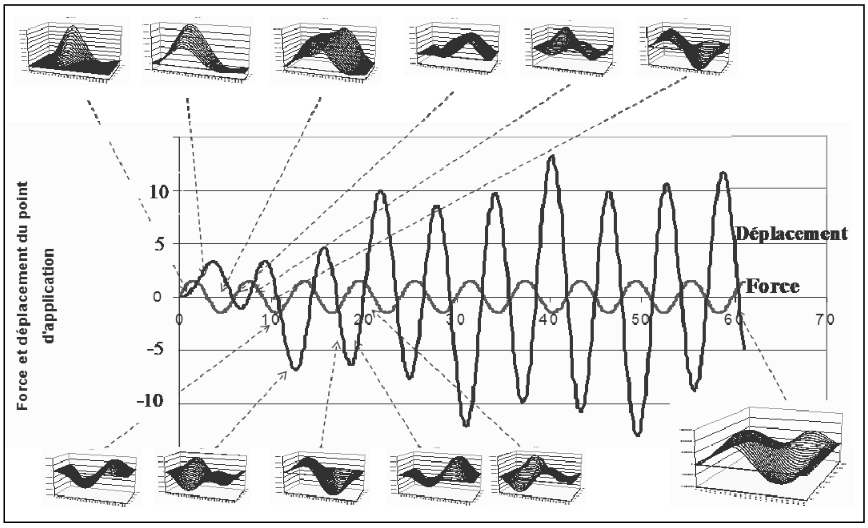

FIG. 6 – Modelling of the response at the beginning of excitation.

It appears in particular, that before arriving on the aimed mode, it is necessary to go through all the lower modes.

So, apparently, the temporal signal shows at the beginning longer periods than excitation signal, what we interpreted.

We also tested various conditions of connection and changes internal damages of the structure.

7. Conclusion.

The contribution of the analysis by a time-frequency method by means of the wavelets transform gives accurate information on the evolution of the connection; a degradation of the connection is characterized at once by an amplitude modulation during excitation and also a very clear increase of amplitude discontinuity.

Furthermore, it was noticed that the sinusoidal regime (modulated or not) was not obtained at once, and that there was before a passage by the lower modes.

The works also concerned the sensibility of the method in the detection of the internal damage.

One can thus say that we have a significant indicator of the weakness of the basic structure.

The cases of composite beams and then plates in composite materials were approached, both on the aspect connections and internal defects.

We thank the "Conference des Grande Ecoles" for having supported this project.

8. Perspectives of continuation

What remains is to quantify the defects, on the whole, of more complex structures. This is concerned with the bonding of elementary structures as well as the damage to the materials themselves.

Afterwards the optimization operations will be directed toward finding and localizing the minimum number of sensors needed to acquire information on the state of health of the structure.

At least measurement and data processing automation.

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