On line Implementation of a Structural Health Monitoring System

Massimo Viscardi, Romeo Di Leo

Abstract— The concept of predictive maintenance, whose application became every day more and more diffused was born some years ago. The fundamental idea on which the predictive maintenance is based on is the monitoring of specific parameters that can supply useful information on the system state of health. In the presented application, vibrational levels represent one of these parameters and relative continuous monitoring is proposed. In the specific FRF functions have been indicated as monitoring functions. The presented application will show an on-line implementaion of the proposed approach, with experimental results related to a laboratory test article whose results have demonstrated the validity of the proposed idea.

Keywords— Structural Health Monitoring, Frequency Response Function, Piezoelectric materials, Train.

I. Introduction

STRUCTURAL Health Monitoring SHM or continuous on-line monitoring of structural integrity is today a relevant topic in many engineering fields as industrial applications, automotive, aerospace, and large civil structures. The current inspection techniques can be progressively replaced with new more advanced health monitoring systems. Current health monitoring presents many limitations. In fact it requires structures to be temporarily withdrawn from service, besides some of the present techniques require using bulky and expensive equipment as well as access to the areas to be checked [1].

The SHM systems have the aim of being more sensitive and to allow an automatic on-line monitoring of the structural health. SHM systems would carry to a substantial reduction of the maintenance and the related life-cycle costs of structures.

Much of structural health monitoring research is incited by the reason that damage tolerant and fail-safe design of aircrafts, civil and aerospace structures requires an important amount of inspection and defects- monitoring at regular intervals [2]–[4]. With the risk of failure and the cost of scheduled but unneeded maintenance ever increasing, intelligent real-time monitoring is imperative to guarantee safe and affordable structures.

Besides the expected enhancement of safety and maintenance performance, also economic aspects play an important role. This regards on the one hand the reduction of unnecessary inspection and repair costs and on the other hand, the possible weight reduction for example of aircraft parts at the designing phase.

The SHM systems can be applied to new or aging structures.

At the present, two main general approaches are being investigated in an effort to develop an effective structural health monitoring system.

The first one is the global approach, which measures and analyzes damage-induced changes in the vibrating properties. The second one is a local approach whereby changes in the characteristics of ultrasonic waves propagating across existing defects or created by emerging defects are measured and analyzed. For both approaches important research efforts have been made in research centers, universities and industries [5].

SHM technologies use permanently attached actuators and/or sensor networks to enable the continuous inspection of the reliability of structures.

Sensors (accelerometers, temperature probe, flowmeter, etc.) are used to follow the behavior of the component monitoring some particular parameters of the structure. From that parameters the health status of all components can be investigated. In this way it is possible to check the component in an automatic and real time way, giving a warning when one or more investigated parameters are out of the normal range [6]. This is the circumstance of something, that is damaged inside and a maintenance operation is required. The maintenance is done when and if necessary reducing costs.

The SHM systems falls clearly in the type of Maintenance Strategy defined in the literature as Predictive [7].

The present work presents a proposal of a specific SHM methodology. The proposal falls inside the field of the first approach, global approach, which measures and analyzes damage-induced changes in the vibrating properties. In a specific way, the proposal methodology doesn't consider explicit variations in modal frequency and mode shapes of the structure but it is centered on Frequency Response Function FRF.

II. Methodology for the SHM System

If damage occurs in a structure, it most always produces changes in stiffness, damping and sometimes in the mass of the structure. The dynamic behavior of a system depends by its mass, damping and stiffness properties. For this reason it is possible to measure the aforementioned changes through vibration measurements.

To evaluate variations in dynamic response due to changes in stiffness, damping and sometimes mass, produced by the damage, it is possible to use techniques based on the analysis of dynamic characteristic of the structure as natural frequencies

and modal shapes. This approach would need of performing modal analysis of the structure and unfortunately it isn't suitable for the aim of an online health monitoring system of a complex structure.
Moreover variations in natural frequencies and modal shapes, produced by damage, can be very reduced [9], [10].
For this reason it is proposed the adoption of a methodology based on the analysis of experimentally evaluated Frequency Response Functions FRFs of the structure.
This complex function of the frequency is defined as

$$H(f) = \frac{S_{yx}(f)}{S_{xx}(f)} \quad (1)$$

where S_{yx} and S_{xx} are respectively the cross-spectrum between the output and input signals and the auto-spectrum of the input signal. FRF contains all the information related to the dynamic behavior of the structure.
A new damage in a structure will produce a change in the path of energy transmission from a source of vibration to the sensors, in a particular way to the more near sensors to the fault position, so that Frequency Response Function FRF variations will be revealed by these sensors, without any influence on the acquisition signal from the other sensors of the structure.
In particular, the algorithm proposed compares the amplitude of the on-line acquired FRF with a reference stored FRF, obtained in the condition of healthy structure.
The present work proposes this methodology of changes in FRFs amplitude in conjunction with a Damage Index (DI), finalizing the activity to the study of health status of the mechanical connection between electro-mechanical systems and their supports as it will be explained in the next section.
Following the previous considerations, the general procedure consist of a set of action that can be resumed in the next steps

- one or more actuators are used as a source of a vibrational field on the structure;
- at some points on the structure, where sensors are positioned, the FRFs of the health structure are acquired. These functions are saved and utilized as reference since they characterize the structural integrity of the monitored structure;
- in subsequent instants at the same points, the acquisition of the FRFs is repeated;
- these new FRFs are compared with the referred ones. A Damage Index based on the measured differences is calculated;
- if the DI exceed s a threshold value, this indicates that a damage has occurred close to the sensor that provide the highest index.

In this approach the calculated DIs are the averages of differences between integer an damaged structure's FRFs. The assumed DI expression is:

$$\frac{\sum_{i=1}^{n} |FI_i - FD_i|}{\sum_{i=1}^{n} |FI_i|} \quad (2)$$

Where FI_i and FD_i are respectively the n values of the health and damaged structure's FRFs. The value of n depends from the sampling frequency and frequency bandwidth of acquisition.
DI gives values greater than zero if any variation in the structural dynamic behavior occurs and it returns zero if a complete repetitiveness of the experimental measure is obtained.
Since the procedure is mostly based on a good reliability of the FRFs acquisition phase, its control plays a very important role:

- each FRF can be averaged N times in order to cut off all the noise due to factors characterized by a characteristic time lower than the acquisition one;
- during every acquisition the Coherence Function between the input and the response signal can be evaluated. This function represents an index of the frequency correlation between them. This approach permits to fix the frequency bandwidth limits to analyze the acquired FRFs.

Obviously the analysis frequency bandwidth will depend on the excitation device and on the sensors operative maximum frequency when applied in the monitored structure.
Next pictures show a WBS of the proposed method:

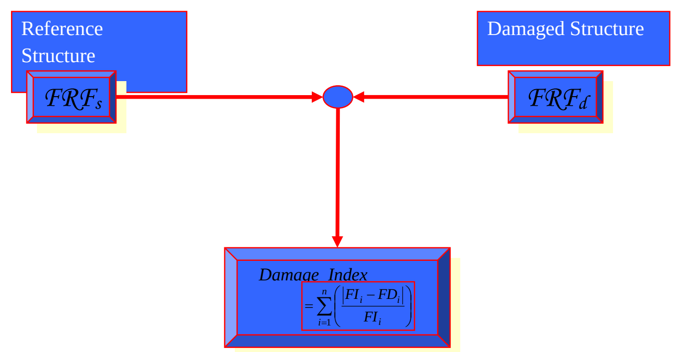

Figure 1: WBS of the SHM system

III. IMPLEMENTATION OF THE METHOD

The health monitoring tool has been created within Simulink, a block diagram environment for multidomain simulation and Model-Based Design. It supports simulation, automatic code generation, and continuous test and verification of embedded systems. Simulink provides a graphical editor, customizable block libraries, and solvers for modeling and simulating dynamic systems. It is integrated with Matlab, enabling to incorporate Matlab algorithms into models and export simulation results to Matlab for further analysis.
For real time implementation , the DSpace system has been used; it is composed by a PX-10 Expansion Box. Inside there are a DS 1005 single processor board, a high speed A/D, 16 channels board DS 2004 and a D/A, 16 channels board DS 2103. As user interface the real time system there is a laptop where Control Desk software was installed. The laptop is interfaced with PX-10 thanks to the link board DS 817.

Figure 2: DSpace Control System A/D board

The global architecture of the SHM system is reported in the next figure 3.

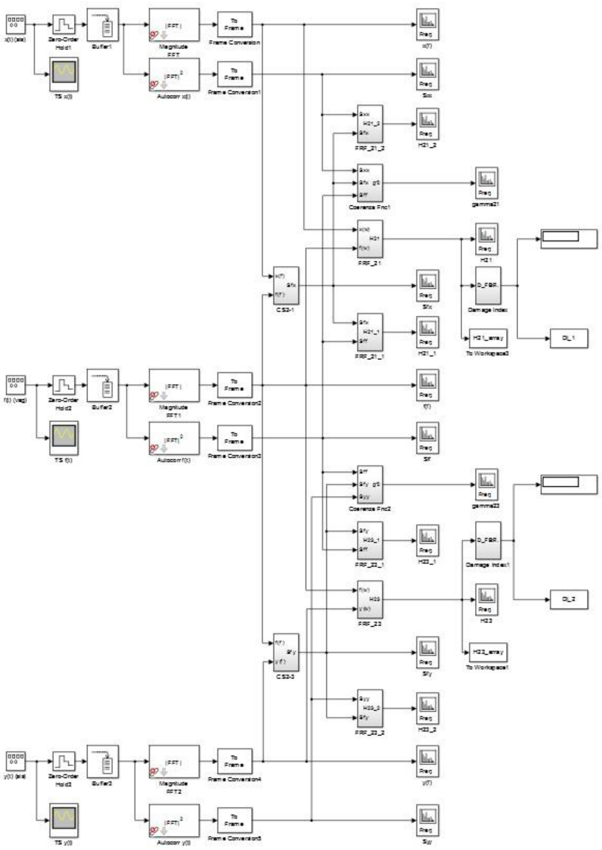

Figure 3: Global architecture of the SHM system

IV. TEST ARTICLE

The real test article to which the present study has been oriented is represented by the traction converter of a passenger train. The traction converter is mounted under the train floor and fixed by bolts. The whole component is composed by four power unit and a control panel. The control panel is centered in the traction converter (fig. 4).

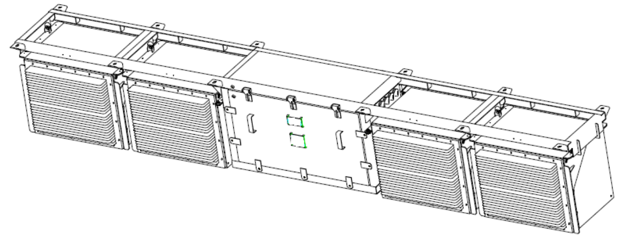

Figure 1: Traction Converter

Each of four modules can work independently from others and it is the same for engine and chopper.

Each power unit is composed by three inverters, a Traction Unit Control TCU and a breaking chopper. The system is governed by a control signal from the cab hood to the TCU (fig.5).

Figure 5: TCU

Its dimensions are 1.2x0.68x0.65 meters for a whole mass of 89 kg. The whole system is encapsulated to prevent the contact with water and dust. The hot flow generated by the inverters is dissipated by a static fan and the air flow is guaranteed by the train movement. No rotating fan is mounted on board.

For each component is present a datasheet with maximum level of acceleration allowable but also with other technical requirements as for example maximum operative temperature and so on.

If vibrations overcome the project levels, they can be damaged. One of the cause that can produce an increment of the components vibrations is a possible fault in the bolts of the connection system between the frame of the control panel and the chassis of the train.

In fact, in the upper face of frame of the control panel are collocated the attachment points with the chassis of the train. The connections are realized by bolts and no anti-vibration systems are mounted on board. Next pictures 6 sketch of the TCU main structure.

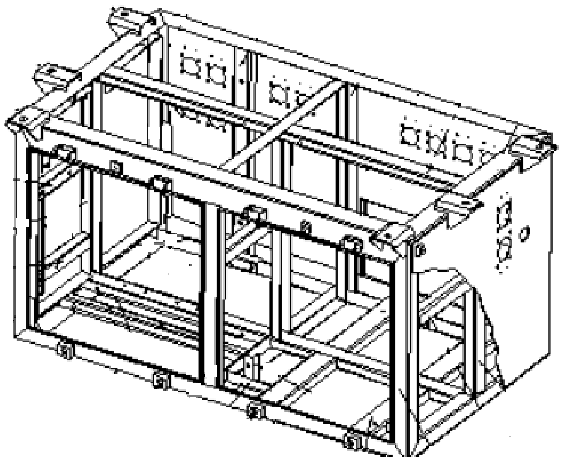

Figure 6: TCU mechanical box drawing

Fault of every bolt can be complete with the total break of the single connection element or partial when there is a loosening of the bolt. Six is the total number of aforementioned connections between control unit and the chassis of the train.

V. IMPLEMENTATION OF THE PROPOSED METHOD

The proposed methodology, as above described, has been decided to be applied for the predictive maintenance of this electro-mechanical components.

The physical set-up would require the installation of a group of sensors for the measure of the acceleration levels of primarily components or specific target point. For this aim standard piezoelectric accelerometers can be used (or alternatively MEMS sensor).

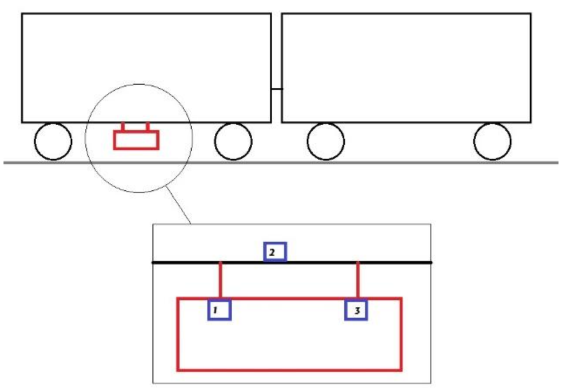

Figure 7 - Hypothetic situation to test the SHM tool

The method use the Frequency Response Functions, as this function, is self-containing the mass-stiffness-damping properties of the mechanical system. But this means that at least one reference signal is necessary for the computation of the FRF. So, as a general scheme, it has been defined that one or more siganls (output signal) have to be measured by the accelerometer sensors installed on the component of the control unit while the reference one (input signal) has to be acquired by an accelerometer, directly installed on the chassis of the train (whose dynamic properties are invariant by the neglectable behavior of the TCU frame) .

The calculated FRF should change if a fault in the constraint conditions between control unit and chassis changes during the operative life of the train as consequence for example of a fault of one or more bolts.

The use of FRF between signal acceleration of components and chassis allows distinguish when variation of vibrating behavior of electro mechanical components is due to a totally or partial fault of one or more bolts from the case in which the variation is produced by a modification of vibrating conditions for the chassis of the train in presence of healthy connections.

In a specific manner the operative calculated FRF will be compared with the same FRF calculated in a controlled condition in which the healthy status of the structure (in our case of the connections) is sure.

A general WBS of the method is here illustrated.

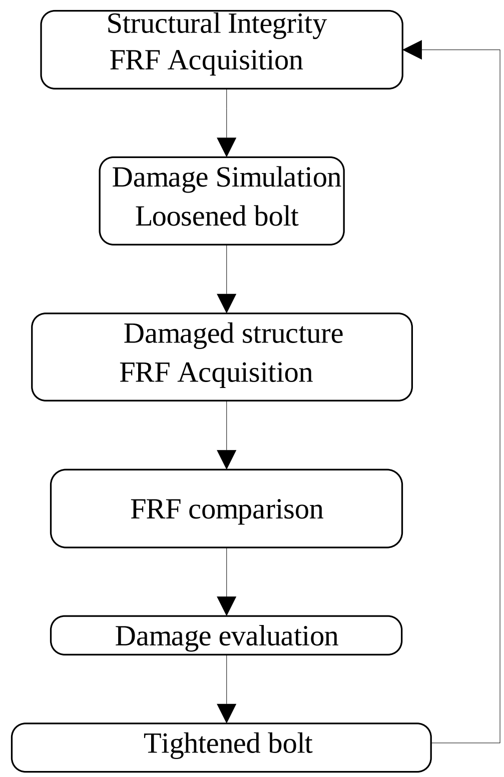

Figure 8 - Hypothetic situation to test the SHM tool

VI. FIRST TEST ON SIMULATED MOCK-UP

For the experimental test, it has been recreated in laboratory the hypothetical situation described in Chapter 5. It has been fixed a small metallic box under a beam with 4 bolts and a foil in the box to represent an electronic board. To generate the exiting strain, a shaker has been placed near the structure, but not so far from the box.

Figure 9 – Laboratory test structure

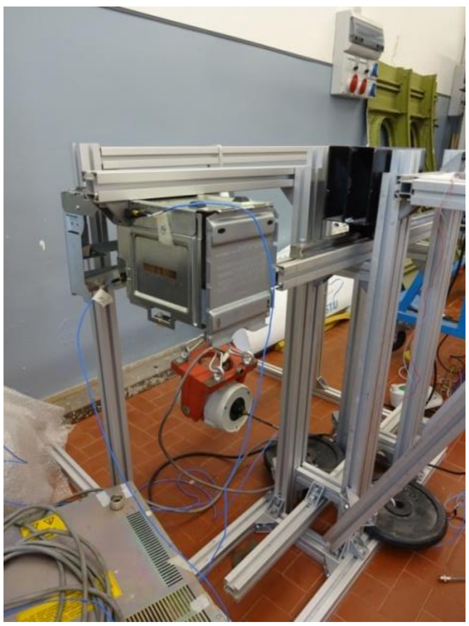

Figure 10 – Laboratory test set-up

To acquire the structure's responses, three accelerometers have been placed in three specific points (fig 11-13): the first is next to the shaker to acquire the reference signal, the second is on the box near the bolts for the acquisition of the responses, and the third is on the electronic board to supervise the board's behavior and any possible damages.

Figure 11 – Reference accelerometer

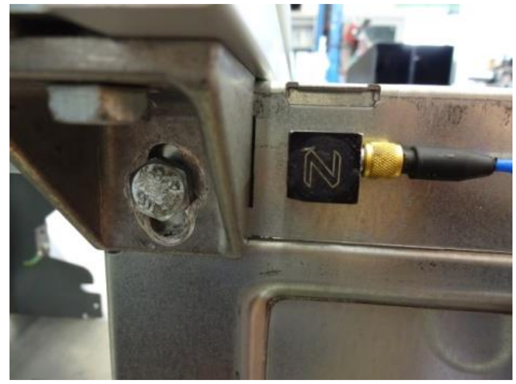

Figure 12 – Accelerometer positioned near one bolt

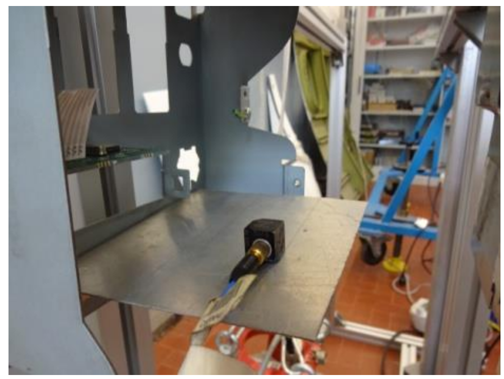

Figure 13 – Accelerometer positioned on the clamped board

The two accelerometers, those ones on the box and on the board, acquire the signals in the three directions, while the accelerometer next to the shaker acquires the signal only in the z direction.

The Simulink code (as described in figure 3) has been changed to adapt itself to the acquisition. During the simulation, the real number of the acquired signals is seven; 3 signals for the accelerometer on the box, 3 signals for the accelerometer on the board, 1 signal for the accelerometer next to the shaker. For this reason, the Simulink code has to calculate 6 FRFs, so that it can be possible to compare the Damage Indexes and to recognize the direction in which there is the maximum excitation.

Seven acquisitions have been done:

- RUN 1: signal acquisition for a healthy structure; these signals will be used for the "healthy" FRF.
- RUN 2: signal acquisition for a healthy structure with a mass of 20g on the electronic board.
- RUN 3: signal acquisition for a structure without the mass on the board and with the bolt 1 unscrewed.
- RUN 4: signal acquisition for a structure with the bolts 1 and 2 unscrewed.
- RUN 5: signal acquisition for a structure with the bolts 1, 2 and 3 unscrewed.
- RUN 6: signal acquisition for a structure with all the bolts unscrewed.

- RUN 7: signal acquisition for a structure with all the bolts well screwed.

Each RUN returns three "damaged" FRFs and each FRF has been compare with the "healthy" FRF of RUN 1 to get a Damage Index which has to monitor the structure along a particular direction. For this reason, the Simulink code has been run for a total of 12 times, in particular 6 times to monitor the box and 6 times to monitor the electronic board.
All the Damage Index values have been stored and compared. The Damage Indexes' behavior as computed for the acquisition positioned on the clamped board is reported in next figure 14 .

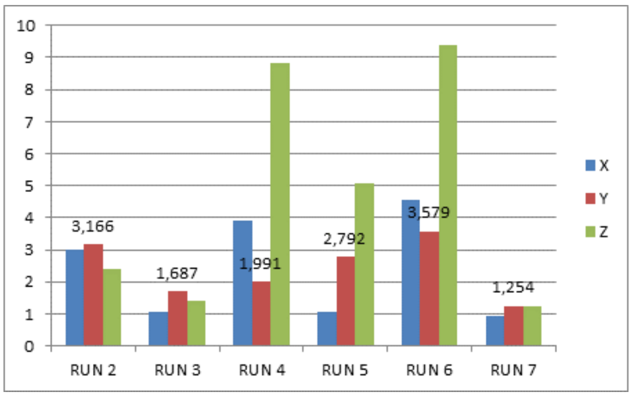

Figure 14 - Damage Index graphic for the ELECTRONIC BOARD

It appear evident that DI behavior (refer to y and z direction) has well monitored the structure with a DI well proportional ti the extension of the damage.

VII. CONCLUSIONS AND FUTURE DEVELOPMENTS

The present paper has presented a proposal of a specific SHM methodology. It doesn't consider variations in modal frequency and mode shapes of the structure but it is centered on Frequency Response Function FRF and relative Damage Index DI .
The match is made through the calculation of a damage index DI, as defined in the second section of the present work.
When DI would overcome a threshold value, this means that something in the system is changing and a check is required .
In this manner electro-mechanical components in the control unit will be protected against a long exposition to excessive accelerations, due to the connection's fault, which will lead to the damage of the components.
The prompt maintenance activity will reduce over-costs, linked to the substitution of broken electro-mechanical components and to a possible sudden interruption of the service with great disappointment of clients and bad publicity for the company.
With the realization of the Simulink code, it has been reached a first prototype of program which is able to monitor a structure through the FRF analysis and the evaluation of the Damage Index. Even though the elaboration of DI values does not describe in a perfect way a structure subjected to non-destructive damages, the program can be improved adding other blocks.
For example, to improve the FRFs calculation, it could be necessary to do more than one signal acquisition for the same structure condition, so that the Simulink code can estimate a mean value of the acquired signals and reduce the error caused by the real-time acquisitions.
Thanks to the dSpace hardware, it could be possible to get a real-time monitoring process which, during the acquisition, returns the Damage Indexes values and alerts the user in case of a serious damage in the structure. Furthermore, there is the possibility to improve the Simulink code with new blocks which can be created by some strings written in Matlab and get the program more efficient and with an elegant interface design too.
This SHM tool has the peculiarity of versatility because it can be applied in every structure which needs a continuous structural health monitoring to avoid any maintenance works for destructive damages which provide an excessive costs. It can be applied on simple or complex structures; it is enough to build a good neural network, so that, with a low number of sensors and, consequently, a low cost of the applied instruments, all the structure will be monitored with a particular attention on the mainly stressed parts.

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