ISSN 2176-5480

22nd International Congress of Mechanical Engineering (COBEM 2013)
November 3-7, 2013, Ribeirão Preto, SP, Brazil

VIBRATION-BASED DAMAGE IDENTIFICATION APPLIED FOR COMPOSITE PLATE: EXPERIMENTAL ANALYSES

Ricardo de Medeiros
Murilo Sartorato
Flávio Donizeti Marques
Volnei Tita
University of São Paulo, São Carlos School of Engineering, Department of Aeronautical Engineering
Av. João Dagnone, 1100 São Carlos, SP, Brazil
medeiros@sc.usp.br, murilosart@gmail.com, fmarques@sc.usp.br, voltita@sc.usp.br

Dirk Vandepitte
KU Leuven, Department of Mechanical Engineering – PMA Division
Celestijnenlaan 300 B, B-3001, Heverlee, Belgium
Dirk.Vandepitte@mech.kuleuven.be

Abstract. *Detection of damage on aircraft composite structures has been one of the major concerns of operators during the last two decades. Vibration-based methods using piezoelectric sensors and/or actuators incorporated into composite structures offer a promising option to fulfill such requirements and needs. These methods can use finite element analysis combined to experimental results in order to detect damage. Thus, it is possible to identify, to locate and, also, to estimate the damage events, comparing dynamic responses between damaged and undamaged structures. The basic idea of the vibration-based damage detection method consists on assuming that damage is a combination of different failure modes, which affect the local stiffness of the structure, and this changes the dynamic characteristics of the structure, i.e. the modal frequencies, mode shapes and modal damping values. In this paper, there is an investigation in order to develop a vibration-based damage identification method for composite structures. This investigation consists of analyzing experimentally the mode shapes and Frequency Response Functions (FRFs) from undamaged and damaged composite plates in order to evaluate different types of metrics for damage identification. Thus, rectangular plates made of composite material, resin epoxy and carbon fiber, were submitted to a vibration tests. The experimental tests were carried out by using an impact hammer, which excited the structure with pulse signal, and accelerometers, which measured the output data. Firstly, experimental dynamic analyses in undamaged composite plates were carried out in order to obtain the Frequency Response Functions. Secondly, one plate was damaged by impact loading ("non-controlled damage") and other plate was damaged by manufacturing (controlled damage). Furthermore, experimental dynamics analyses were performed in order to obtain the Frequency Response Functions for both damaged plates. Experimental results were analyzed by using different metrics, which were compared in terms of their capability for identifying damage. Finally, it was discussed the advantages and limitations to use vibration-based damage detection method into the context of SHM (Structural Health Monitoring).*

Keywords: *structural health monitoring, damage metrics, vibration experimental data, vibration based method*

1. INTRODUCTION

Structural damage can be defined as a permanent change in the mechanical state of a material medium and it may affect the structural performance. Common sources of damage in structural components include micro-structural defects (dislocations, voids, inclusions), corrosion (loss of material), residual stress, cracking (fatigue, matrix, ply), fastening fault (weld crack, bold preload, broken rivet), adhesive fault (de-bonding, delamination, separation) and instabilities (e.g. thermomechanical buckling) (Adams, 2007). This set of damage induces different behaviors of the material thereby increasing the risk of unpredicted structural failure causing catastrophic, economic, and human life loss. Hence, in order to maintain the safety and reliability of the product, it is necessary to inspect periodically the structure. This is the reason that it is possible to find several non-destructive techniques (NDT) for the identification of damage in a structure (Fan and Qiao, 2011) before showing catastrophic failure.

Successful damage detection and localization in structures is essential for health monitoring and maintenance. NDT, which can identify damage, may be used for this purpose. However, most of the non-destructive methods, such as ultrasonic methods, require the location of the damage and that location must be accessible. The methods, which are based on vibration responses, usually do not show these limitations. The basis of vibration response methods is that damage changes the dynamic behavior of the structure. A number of model-free damage identification techniques have been developed and successfully investigated because of they are computationally simple and also offer the potential to be used as real–time health monitoring systems. Most notable among these techniques are based on natural frequencies, mode shape curvatures, modal flexibility and its derivatives, modal stiffness, modal strain energy, frequency response function (FRF) and its curvature, and power spectral density (PSD).

Vibration-based structural health monitoring (SHM) and damage detection techniques have received much attention recently in the aeronautic engineering field (Liu and Nayak, 2012). A good SHM system can greatly increase the efficacy of structural maintenance, reduce maintenance cost and enhance the reliability of structures as well. In addition, experimental methods for establishing dynamic characteristics of linear vibrating structures, such as, matrix of impulse response functions, complex frequency response functions or modal characteristics (natural frequencies, modal damping, and mode shapes) are currently well established (McConnell and Varoto, 1995; Ewins, 2000). These characteristics depend upon some parameters: elastic constants; mass density; boundary conditions and geometric dimensions. Any change related to these parameters modifies the structural dynamic properties, such as natural frequencies, modal damping and/or mode shapes, i.e. these modifications produce global changes in the structure response. Therefore, the approaches for structural health monitoring (SHM) can be classified as local and global monitoring. For example, non-destructive techniques are the most widely used methods for local health monitoring and, normally, methods, which are vibration-based schemes, are used for global structural monitoring.

Due to the simple instrumentation and development of new powerful system identification techniques, SHM systems based on the changes in the vibration characteristics of the structure has gained an increasing worldwide attention in the last years. Important advances in this field have been discussed by Doebling *et al.* (1996); Salawu (1997); Doebling *et al.* (1998); Zou *et al.* (2000); Carden and Fanning (2004); Montalvão *et al.* (2006); Worden et al. (2008); Fan and Qiao (2011); Liu and Nayak (2012), who have shown comprehensive reviews on SHM systems.

The first papers published in damage detection were based on natural frequencies variations between the undamaged and damaged structures (Adams *et al.*, 1975; Vandiver, 1977). Natural frequency-based methods use the natural frequency change as the basic feature for damage identification. However, as the natural frequencies and damping factors are global parameters, these methods were not capable of locating the damage. After that, Pandey *et al.* (1991) investigated the parameter defined as curvature of mode shapes, which was based on local parameters. Other researchers, such as Sampaio *et al.* (1999) and Maia *et al.* (2003), also investigated the curvature of mode shapes. Juneja *et al.* (1997) developed a damage detection measurement using a limited instrumentation and using the contrast maximization to find the excitation forces that create maximum differences in the response of the intact and damage structure. To increase the reliability of the approach under modeling and measurement errors, the contrast maximization approach is combined with an approach based on changes in frequency signature. The detectability of any particular damage with the proposed technique depends on the ratio of the magnitude of damage and the magnitude of errors in the measurements, as well as on how much the damage influences the measurements. Wang *et al.* (1997) formulated a new damage detection algorithm to use an original analytical model and FRF data measured before and after to damage for structural damage detection. Based on nonlinear perturbation equations of FRF data, an algorithm has been derived, which can be used to determine a damage vector, indicating both location and magnitude of damage. Thyagarajan *et al.* (1998) investigated the optimization of Frequency Response Functions (FRFs) in order to diagnose damage by using a minimum number of sensors.

Monaco *et al.* (2000) presented a formulation based on a new experimental procedure to employ in problems of damage analysis of structural elements. The proposed method depends on the acquisition and comparison of Frequency Response Functions (FRFs) of the monitored structure before and after damage occurrence. Structural damages modify the dynamic behavior of the structure and, consequently, by using the FRFs, it is possible the calculation of a representative Damage Index (DI). Kessler *et al.* (2002) investigated the feasibility of modal evaluation techniques in detecting damage for health monitoring of composite structures. The studied characteristics showed that these methods can detect various types of damage. Also, the authors discussed the precision in determining the damage location and the sensitivity to the damage density. Mickens *et al.* (2003) developed a vibration-based method of damage detection for monitoring ageing structures. The method intended to detect damage during operation of the vehicle before occurring the catastrophic failure. Furukawa et al. (2006) presented a statistical damage detection method by using uncertain FRFs, which considers the effects of the measurement errors and does not assume any distribution functions. Kurata *et al.* (2010) proposed two types of error functions in order to estimate the error intrinsic to a hypothesized damage state. The first error function compares the modal properties (e.g. modal frequency and mode shape) of the true and trial models. The second error function is based on the flexibility of the structure. The proposed model is verified numerically and, after that, through experimentation by using an aluminum plate with a crack intentionally introduced near a welded stiffener element.

Ooijevaar *et al.* (2010) investigated experimentally 16-layers unidirectional carbon fiber PEKK reinforced plate structure with two stiffener sections. The authors decided to investigate the dynamic response of an intact plate and a damaged plate by using the Modal Strain Energy Damage Index algorithm in order to detect and localize impact defects. Salehi *et al.* (2010) presented a technique of damage detection based on real and imaginary parts of measured FRFs. The method uses intact and damaged state information of structure. Hence, the need for analytical model is eliminated. Also, the authors used real and imaginary residual FRF shape signals in order to detect damage. Bandara *et al.* (2011) introduced a new damage index by using principal component analysis (PCA). This index can detect damage of building structures even if noise pollutes frequency response functions (FRFs). Elshafey *et al.* (2011) discussed the experimental applicability of the modified mode shape difference technique in damage identification and localization. Lin *et al.* (2012) presented a damage location index (SubFRFDI) in order to detect the damage locations for building structures under earthquake excitations by using a novel substructure-based FRF approach. Reddy and Swarnamani (2012) showed the effectiveness by using frequency response function (FRF) curvature energy damage index. Also, the authors established the capability of the method to detect and to localize damage.

Medeiros *et al.* (2012) presented a study case about the usage of health monitoring metrics and techniques for detecting damage by using numerical simulations (Finite Element Analysis) and experimental data (vibration test) of a cantilever beam. The approach based on Frequency Response Function (FRF) is used. Also, Ribeiro *et al*. (2012) and Medeiros *et al.* (2013) presented an investigation about the damage effects on the structural response, considering filament winding composite tubes damaged by impact loading. The computational analyses were carried out by using an impulse load, which excited the structure, and piezoelectric, which measured the output data. The results showed that the application of vibration-based methods for detecting damage is feasible. Borges (2012) investigated experimentally and numerically through the vibration-based method the changes in a metal-composite bonded joint using piezoelectric patch and accelerometers in order to monitoring the damage in the joint. This damage, artificial debonding, is simulated by inserting Teflon tapes within the joint.

For the large and complex structures, as well as for structures with hard access, it is very difficult to detect damage by using local damage detection methods, because this type of methodology can be only used to inspect accessible components of a structure. In order to detect damage throughout the whole structure, especially some large, complicated structure, a methodology, which uses global vibration based, has been more adequate. Recently, this type of methodology has been used for composite structures. In this paper, there is an investigation in order to develop a vibration-based damage identification method for composite structures. This investigation consists of analyzing experimentally the mode shapes and Frequency Response Functions (FRFs) from undamaged and damaged composite plates in order to evaluate different types of metrics for damage identification. Thus, rectangular plates made of composite material, resin epoxy and carbon fiber, were submitted to a vibration tests. The experimental tests were carried out by using an impact hammer, which excited the structure with pulse signal, and accelerometers, which measured the output data. Firstly, experimental dynamic analyses in undamaged composite plates were carried out in order to obtain the Frequency Response Functions. Secondly, one plate was damaged by impact loading ("non-controlled damage") and other plate was damaged by manufacturing (controlled damage). Furthermore, experimental dynamics analyses were performed in order to obtain the Frequency Response Functions for both damaged plates. Experimental results were analyzed by using different metrics, which were compared in terms of their capability for identifying damage. Finally, it was discussed the advantages and limitations to use vibration-based damage detection method into the context of SHM (Structural Health Monitoring).

2. VIBRATION BASED METHODS: METRICS FOR DAMAGE DETECTION

Vibration based methods have been recognized as an important group of methods for developing SHM systems. As commented earlier, they are based on the observation of changes in the system's vibration responses, which result from damage occurrence. Some of them use model-based diagnostics defined in the following way: the undamaged model of a particular structure is evaluated, and this model is compared to the model identified from the measured data of the structure in the current state. Differences between these two models indicate the structure modification (e.g. stiffness or strength), which may be caused by damage. In order to help in the identification of this modification, several different types of metrics have been developed for the detection and monitoring of damage in structures and they are shown by the literature. Normally, a frequency response function (FRF), which relates the structural response to an applied force, is used by the metrics. The FRF response may be written in displacement, velocity or acceleration. Theoretically, the FRF can be expressed in terms of the system properties such as mass, stiffness, damping, and modal properties. Using the measured FRF-data has a great benefit once they provide much more damage information in a desired broadband frequency range than the modal data. In fact, the modal data are identified mainly from a very limited number of FRF data around the resonance frequency. For this reason, an FRF scheme is considered a more reasonable tool for detecting the structural damage.

As previously commented, different modal parameters can be used to calculate those metrics such as resonance frequencies, amplitudes, phases and vibration modes. These parameters must be chosen regarding several factors, such as the type of analysis used, previously known experimental data of the structure, the type of sensors attached to the structure, as well as their location and the type of damage, which is required to detect. Hence, in the present paper, different metrics were compared by using the FRFs magnitude and frequency:

- ✓ The first metric uses the differences in the FRFs (Mickens *et al.*, 2003). In this type of metric, it is considered that the FRFs are sensitive to small changes and damage in a structure. To quantify this sensitivity, a damage indicator was developed to calculate the difference in the FRF responses between intact (undamaged) and damaged structures. The damage indicator for the structure is developed considering firstly the percent difference between the magnitude of the FRFs of the undamaged and damaged structures. Any physical quantity can be used to compute the FRF, such as acceleration/force, velocity/force, displacement/force, strain/force or PZT (piezoelectric) sensor voltage/PZT excitation voltage. The damage indicator *D* is obtained by computing the mean value of *y(f)* for the frequency range of interest.

$$y(f) = abs\left(\frac{\left|H^i\right| - \left|H^d\right|}{\left|H^i\right|}\right), \tag{1}$$

$$D = \frac{\Delta f}{f_2 - f_1}\sum_{i}^{n} y_i(f), \tag{2}$$

where the superscripts *i* and *d* denote the intact and damage structures, respectively, and the vertical bars represent the magnitude of the function. Also, f_1 is the lower frequency and f_2 is the upper frequency of the range of interest and Δf is the frequency increment between measurement points. In addition, the equations (1)-(2) provide a damage indicator, which gives a normalized measurement of damage in the structure. These values once collected for different sensor/actuator pairs can roughly quantify the amount of damage in a structure. The *D* expression returns values greater than zero if any variation in the structural dynamic behavior occurs, and D will return "zero", if there is not any damage in the structure.

- ✓ The second metric uses the changes in measured FRFs in order to determine the Damage Index (*DI*) (Monaco *et al.*, 2000). This method is based on the acquisition and comparison of FRFs from the monitored structure before and after damage occurrence. As commented previously, structural damages modify the dynamic behavior of the structure and, consequently, its FRFs, this makes possible the calculation of a representative *DI*. In this approach, the calculated *DIs* are the averages of the differences between intact and damaged structures. Two *DI* expressions have been considered:

$$DI_1 = \frac{\sum_{j=1}^{n}\left|FI_i - FD_i\right|}{\sum_{j=1}^{n}\left|FI_i\right|}, \tag{3}$$

$$DI_2 = \sum_{j=1}^{n}\frac{\left(\dfrac{\sum_{j=1}^{n}\left|FI_i - FD_i\right|}{\sum_{j=1}^{n}\left|FI_i\right|}\right)}{n}, \tag{4}$$

where FI_i and FD_i are respectively the *n* values of the intact and damaged structures FRFs and *n* depends on the chosen sampling frequency and frequency bandwidth of acquisition. Both *DI* expressions return values greater than zero, if any variation in the structural dynamic behavior occurs, and they will return "zero", if there is no damage in the structure.

- ✓ The third metric used the change in measured parameters metric (CMPM) (Prada *et al.*, 2012). This metric uses previously numerical or experimental modal characteristics of the undamaged structure. After that, it uses the parameters provided by a sensor in the damaged structure. In addition, it has the advantage of being simple to be implemented and only one sensor may be used in the structure.

$$CMPM = \frac{\left(\dfrac{\varphi}{F_{UD}}\right)}{\left(\dfrac{\varphi}{F_{Dj}}\right)_{sensor}}, \tag{5}$$

ISSN 2176-5480

where φ are the resonance frequencies for damage or intact structure, F_{UD} and F_{Dj} are the amplitudes for the intact (undamaged) and damaged structure, respectively by the j sensors. This damage index return values closer to “one”, if there is not any variation in the structural dynamic behavior.

- ✓ The fourth metric used the FRF curves and discrepancy rate between the undamaged FRF and the damaged FRF, which are measured at specific positions (Rahmatalla *et al.*, 2012).

$$RD = \frac{\log_{10}\left(H\right)_d - \log_{10}\left(H\right)_i}{\log_{10}\left(H\right)_i} \times 100(\%), \tag{6}$$

where the superscripts *i* and *d* denotes the intact and damage structures, respectively, *RD* is the receptance difference.

3. EXPERIMENTAL ANALYSES

The experimental analyses were carried out with vibration tests in CFRP (carbon fiber reinforced polymer) plates by using accelerometers attached to one of its faces and used as sensors. The CFRP plate is made of 8 plies stacked in $[0]_8$ layup configuration. The coupons are manufactured by using a filament winding process. The plates made of carbon fiber with epoxy resin were manufactured using a parallelepiped shape mandrel and cured into a controlled oven. The mechanical properties of the composite plates can be found at Ribeiro *et al.* (2012). However, once this material is classified, then all mechanical properties for a similar material can be found at Tita *et al.* (2008). The plates geometries consist of 305 mm length, 244 mm width and 2.16 mm total thickness.

The plates were hanged in a frame by using elastomeric wires in order to simulate “free-free” boundary condition. The applied input was a pulse signal through an impact hammer in order to produce the excitation on the structure. Thus, firstly, FRFs were obtained for two intact plates. After that, one plate was damaged by manufacturing a center hole (controlled damage), and the other plate was damaged by impact loading (uncontrolled damage). Then, secondly, FRFs were obtained for two differently damaged plates The experimental results were analyzed for intact and damaged by using the metrics described earlier, which are compared in terms of their capability for damage detection, showing the limitations and advantages for each one. As shown in Fig. 1(a-c), different types of damage were analyzed on the composite plates. A grid of 9 (lines) vs. 7 (columns) measurement points (markers) was printed on the face of each vibration test plate as verified in Fig. 1.

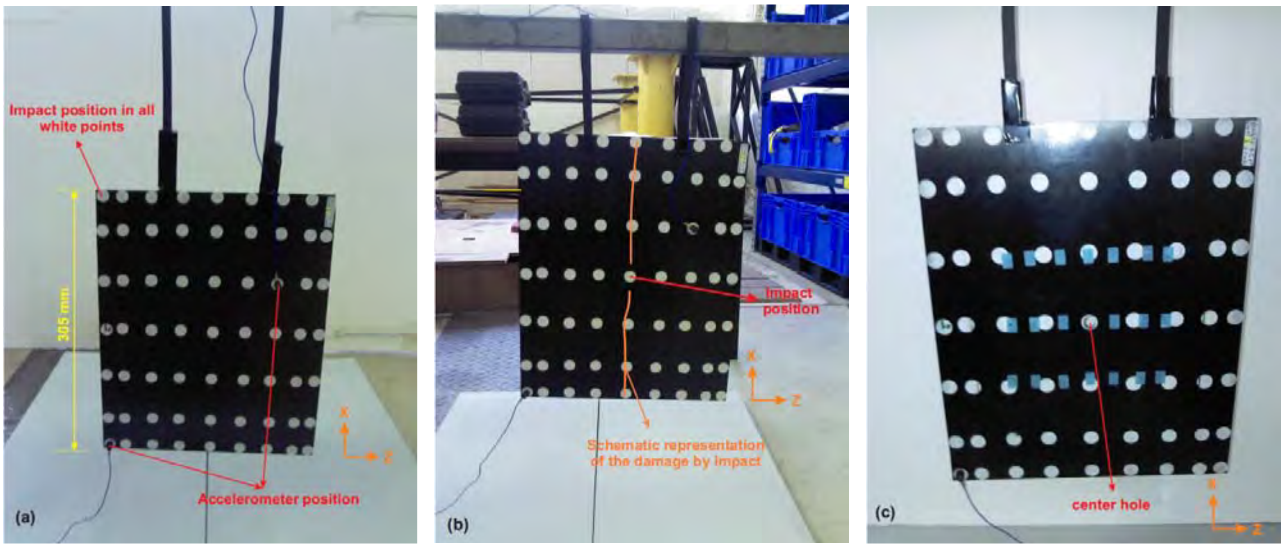

Figure 1. Experimental models: (a) Intact (b) damaged by impact and (c) damaged by a center hole

As highlighted previously, four experimental models were studied in this work. The first and second model (Plate 1-I and Plate 2-I), represent the intact plate, i.e. without damage. They should be used as reference for comparison to other models, i.e. with damage. The third model (Plate 1-D) contains a damage area represented by a center hole in the plate. The fourth model (Plate 2-D) contains a damage area caused by an impact test performed in a drop-tower. More details about the experimental setup for the vibration test can be seen in Fig. 2. It is possible to observe the elastomeric wires attached to the specimen, the accelerometers and the hammer linked to a LMS equipment, which is connected to a personal computer equipped with data acquisition software and a PC analyzer interface. Every undamaged and damaged type was assessed by acquiring the FRF signatures for both the accelerometers and for all impacted positions as shown by the grid markers in the Fig. 1.

The experimental analyses consist of verifying the vibration response of the plates. The data acquisition set-up used in the experimentation was controlled by the Test.Lab software (LMS Test.Lab), which is a plug and play, multifunction analog, digital and timing I/O board for USB bus computers. The input signals are generated by using an impact force hammer (PCB Piezotronix) in all grid markers in the plate. This type of input can provide an excitation over a wide range of the required frequencies. This is important because different types of damages can affect different frequency ranges of a structure, and the resonant and anti-resonant characteristics of a structure may be good indicators of damage. This approach, which uses impulse vibration, is a more global indicator of damage compared to other methods, which uses single frequency tone bursts and wave reflection. The FRFs can indicate damage, which is inside the structure. However it is important to highlight that they may not be as sensitive to small damage on the surface as compared to wave propagation methods. The output was measured by using two accelerometers (PCB Piezotronix). Each time signal gathered consisted of 2048 points and were sampled until 1024 Hz. As commented earlier, the FRFs were calculated from both the measured force and response signals (accelerometers). The number of averaging individual time records was selected to be four in order to reduce the random fluctuation in the estimation of the FRFs.

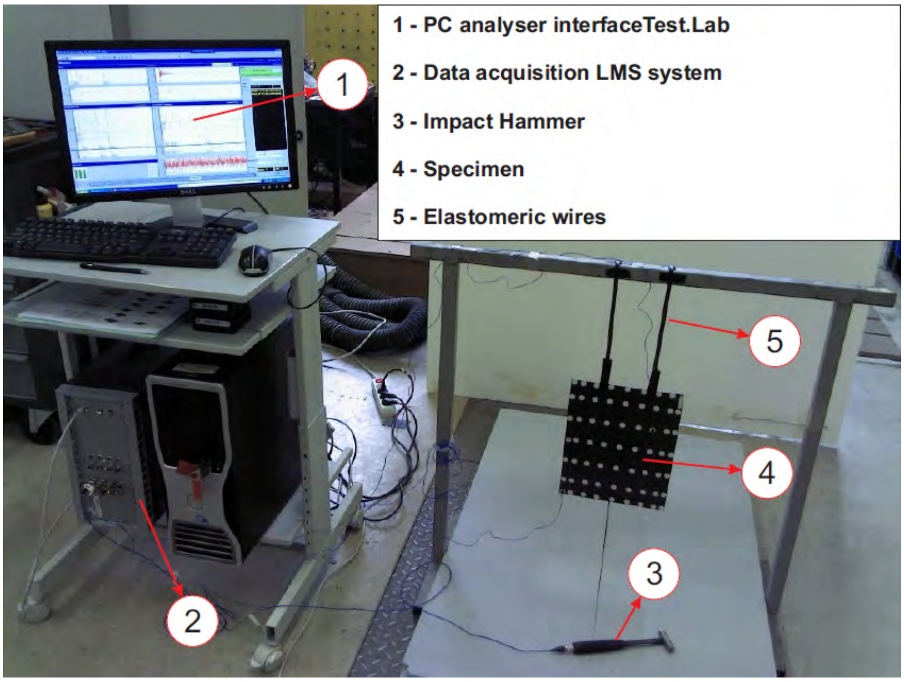

Figure 2. General layout of the used equipment

When all 63 measurements through the grid markers were obtained and stored, the FRFs were calculated and displayed on the screen of the PC, where resonant frequencies could be identified by using the signal processing software Test.Lab with PolyMAX non-iterative frequency domain parameter estimation method (Peeters *et al.*, 2004). It is based on a (weighted) least-squares approach and uses multiple-input/multiple-output frequency response functions as primary data. The PolyMAX or polyreference least-squares complex frequency-domain method can be implemented in a very similar way as the industry standard polyreference (time-domain) least-squares complex exponential method. Thus, in a first step, a stabilization diagram is constructed containing frequency, damping and participation information. Next, the mode shapes are found in a second least-squares step, based on the user selection of stable poles. One of the specific advantages of the technique lies in the very stable identification of the system poles and participation factors as a function of the specified system order, leading to easy-to-interpret stabilization diagrams. The modal coefficients are computed, and the mode shapes are obtained (Heylen *et al.*, 1997).

4. RESULTS AND DISCUSION

Table 1 shows the different resonance frequencies measured by accelerometers, which were obtained by the experimental FRFs for the undamaged and damaged settings of the plates. In addition, it can also be observed that the values obtained for the different types of damage in the plate do not exhibit high changes. However, for the Plate 2, the

ISSN 2176-5480

second and third modes presented significant differences. This is due to the fact that the presence of the damage changed strongly the stiffness of the structure. This fact associated to the small magnitude of the exciting pulse loading, which avoided that the structures could behavior in anon-linear regime, making the resonance frequencies remain practically unaltered. Therefore, a SHM metric, which accounts only the variation in the resonance frequencies, might not be the best strategy for this type of damage.

Table 1. Resonance frequencies obtained by experimental tests for both damaged and intact plates.

		ω_1 [Hz]	ω_2 [Hz]	ω_3 [Hz]	ω_4 [Hz]	ω_5 [Hz]
	Mode Type	1st torsion	1st flexural	2nd torsion	2nd flexural	3rd torsion
Plate 1	Intact	61.31	148.85	159.82	222.02	249.61
	Damaged	59.52	149.32	158.06	223.06	249.57
Plate 2	Intact	62.41	154.48	161.77	221.72	249.18
	Damaged	63.87	131.15	154.86	221.70	248.57

Table 2 shows the different damping factors by the experimental FRFs for the undamaged and damaged settings of the plates. It can be observed that the damping values, for some modes, change when the resonance frequencies were modified by damage. Thus, damage detection in a structure based on damping is an alternative procedure. This is due to the fact that the damping changes have the ability to detect the nonlinear, dissipative effects produced by cracks.

Table 2. Damping factor obtained by experimental tests for both damaged and intact plates.

		Damping ω_1	**Damping ω_2**	**Damping ω_3**	**Damping ω_4**	**Damping ω_5**
	Mode Type	1st torsion	1st flexural	2nd torsion	2nd flexural	3rd torsion
Plate 1	Intact	1.35%	0.59%	0.80%	0.35%	0.82%
	Damaged	1.05%	0.39%	0.14%	0.41%	0.51%
Plate 2	Intact	0.82%	0.62%	0.77%	0.40%	0.51%
	Damaged	1.01%	0.71%	0.85%	0.33%	0.43%

Figures 3 and 4 show the frequency response functions for both intact and damaged structure, Plate 1 and Plate 2, which were obtained from accelerometers by PolyMAX method. Initially it can be seen that the damage caused by impact or a center hole changed the shape of the FRF and the amplitudes, especially in the regions closer to the resonance frequencies.

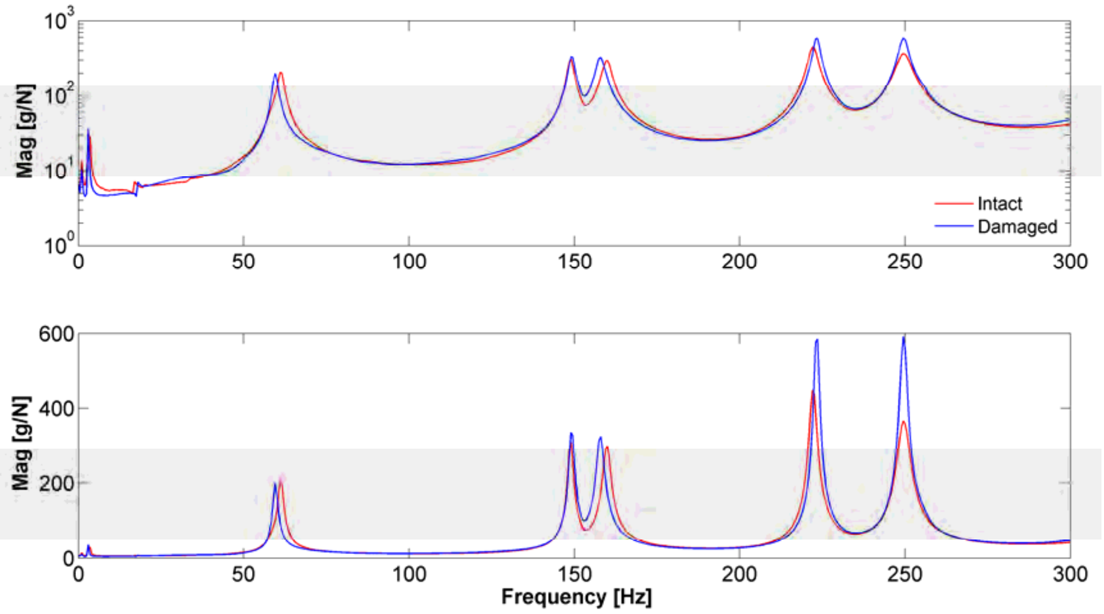

Figure 3. Experimental FRFs for intact and damaged structure - Plate 1

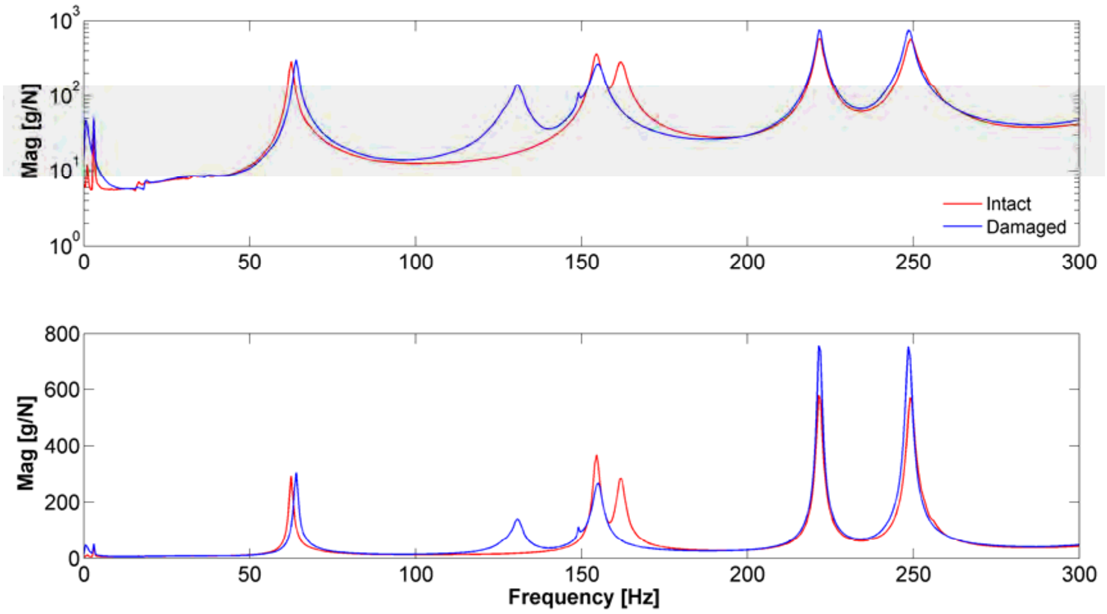

Figure 4. Experimental FRFs for intact and damaged structure - Plate 2

Regarding to the first metric, which was used for damaged detection, the damage indicator *D* is calculated by using the Eq. (2). This experimental study begins with the dynamic system FRF data in the range of 0.01-300 Hz in steps of 0.5 Hz. This value is close to zero for no damage in the structure; otherwise it is greater than one. A level of resolution for the intact models was computed by impacted and drilling hole damaged model and comparing these to the intact models data. The damage values for these analyses are given in Tab. 3. As expected, these values confirm that it is possible to identity damage in a structure. It can be observed that the damage indicator is higher to damage by impact than the central hole. Thus, the damage indicator values also provide the severity of each damage.

Table 3. Damage indicator (*D*) for the structure.

Damage Indicator	Intact	Damaged
Plate 1	0.0	0.1170
Plate 2	0.0	0.3686

Regarding to the second metric, it was used the Eq. (3) and (4) for calculating the damage index. In this metric was considered the FRF data in the range of 0.01-300 Hz in steps of 0.5Hz. The damage values for these analyses are given in Tab. 4. These values confirm what was present for the damage index *D*. In addition, it can be seen that the damage indicator is higher to damage by impact than the central hole. Thus, the damage indicator values also provide the severity of each damage.

Table 4. Damage indicator (*DI*) for the structure.

Damage Indicator	Intact	DI_1	DI_2
Plate 1	0.0	0.2162	1.1142
Plate 2	0.0	0.2877	3.5109

Regarding to the third metric, it can be observed that different metric values based on the magnitude of the amplitude of the FRFs in specific frequencies were calculated by using relations among the response from either sensors or both. Based on the data from the experimental FRFs, for both plates, the Tab. 5 was constructed by the calculated damage metrics by using the Eq. (5). It can be seen from Tab. 5 and Fig. 5 that the metrics obtained by only one of FRF presented better results. These values confirmed what was expected.

Table 5. Damage indicator (CMPM) for the structure.

	ω_1	ω_2	ω_3	ω_4	ω_5
Mode Type	1st torsion	1st flexural	2nd torsion	2nd flexural	3rd torsion
Plate 1	0.9979	1.0811	1.0961	1.2997	1.6146
Plate 2	1.0218	0.4478	0.9879	1.3052	1.3225

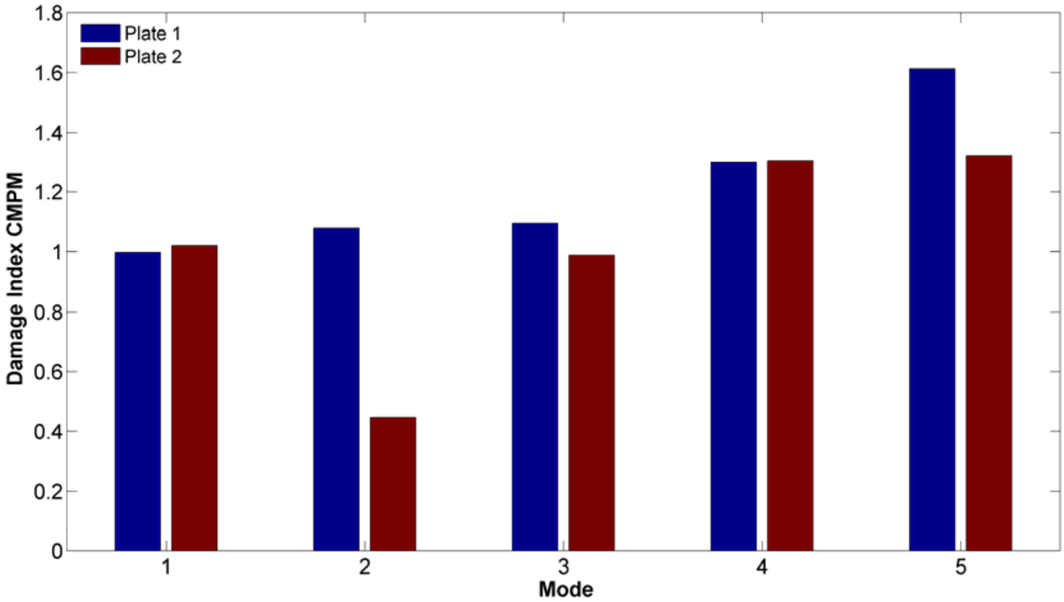

Figure 5. Damage index CMPM for the structure

Regarding to the fourth metric used in this work, the Fig. 6 and 7 represents the FRF curves and discrepancy rates among the damaged and intact FRFs estimated at measured points (grid markers). It is observed that the maximum discrepancy in receptance magnitude is located at the resonance frequencies. The variation in this parameter can be used as information in order to determine if there is damage in the structure.

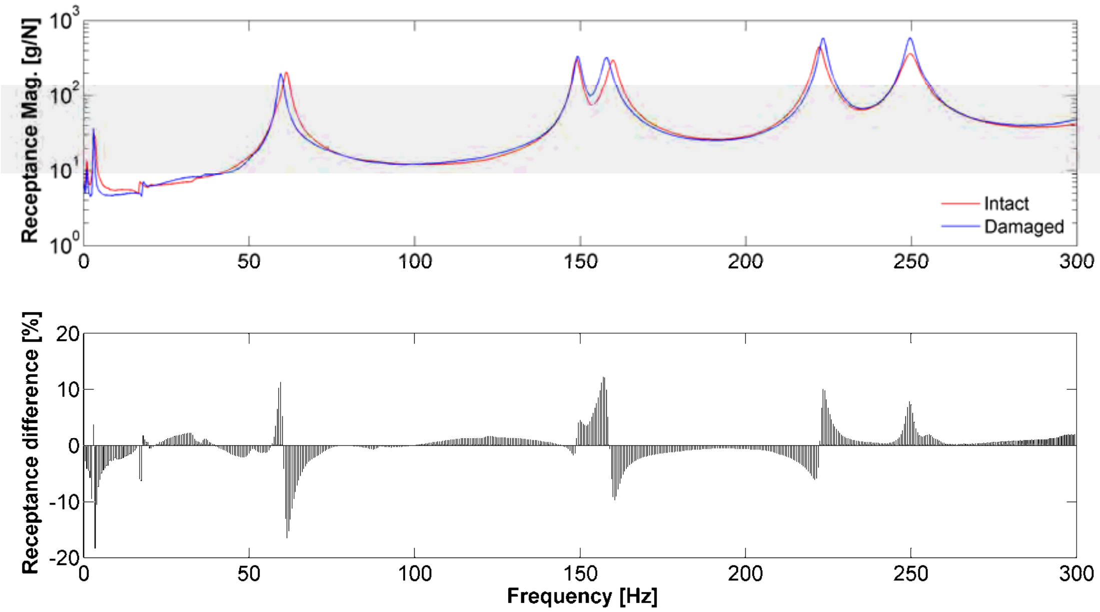

Figure 6. Experimental FRFs and the receptance differences (%) for the plate 1

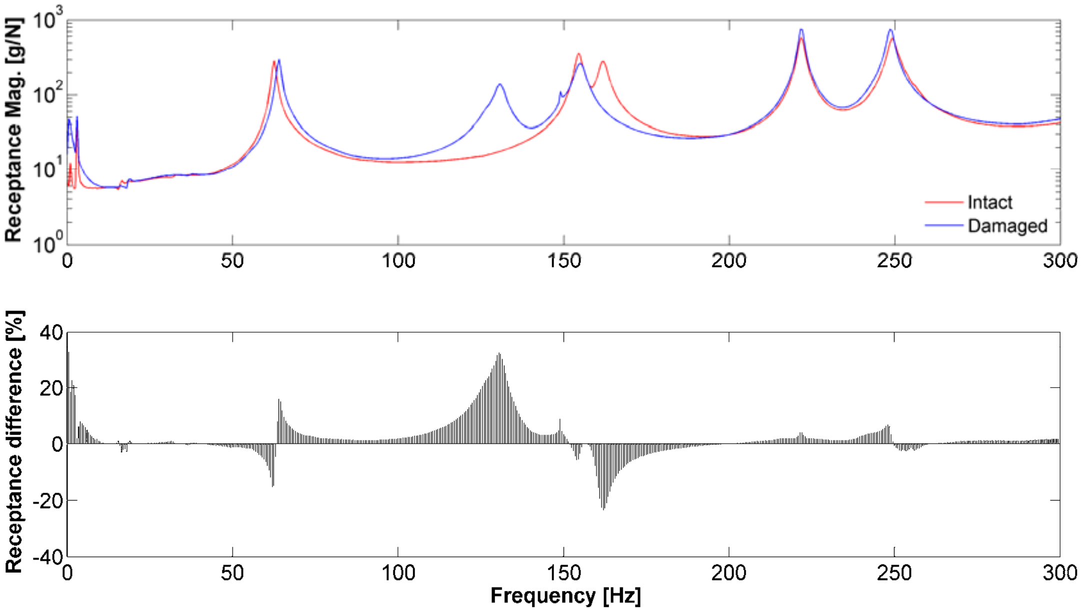

Figure 7. Experimental FRFs and the receptance differences (%) for the plate 2

5. CONCLUSION

There are many advantages in using the method based on FRFs in a SHM system. Among these advantages, it can be emphasize the easily implementation and has low cost. Also, it can be provided the global behavior of the overall condition of the system. On the other hand, there are also limitations, since they provide little information about the location and severity of the damage, unless large quantities of sensors are employed.

Therefore, in this study, an experimental investigation was conducted into the use of frequency response techniques for the detection of damage in composite plates. The experimental results showed that the vibration-based damage identification methods combined to the metrics can be an alternative to design and to evaluate SHM systems. Furthermore, the results using only one sensor indicate a severe limitation of the applied methods to provide information about the location or type of damages. In fact, to these tasks, it is recommended a net of sensors. Therefore, the applied methods with only one sensor are suitable for a system SHM, which is simply used to identify the presence or not of the damage in the structure.

The experimental results showed also some limitations of the vibration-based methods, such as information about the location and type of damage. On the order hand, there are many advantages in employing the method based on FRFs in a SHM system for composite plate. For example, vibration-based methods combined to modal analysis provide global as well as local information on structural health condition and do not require direct human accessibility to the structure. In some cases, the sensor can be embedded in the laminate structure. Also, the methods are cost effective and easy to operate, and has the potential for damage detection in flight with appropriate structural modeling. Therefore, it is possible to conclude that there is a great future perspective for the application of vibration-based methods on SHM systems for composite structures. Further work should predict the damage location, detection and severity estimation.

6. ACKNOWLEDGEMENTS

The authors would like to thank Sao Paulo Research Foundation (FAPESP process number: 2012/01047-8), as well as National Council for Scientific and Technological Development (CNPq process numbers: 135652/2009-0 and 208137/2012-2), and FAPEMIG for partially funding the present research work through the INCT-EIE.

7. REFERENCES

Adams, D., 2007. *Health Monitoring of Structural Materials and Components: Methods with Applications*. John Wiley & Sons, New York, 1st edition.

Adams, R., Walton, D., Flitcroft, J.E. and Short, D., 1975. “Vibration testing as a nondestructive test tool for composite materials”. *ASTM special technical publication*, Vol. 580, pp. 159–175.

ISSN 2176-5480

Bandara, R.P., Chan, T.H. and Thambiratnam, D.P., 2011. "Structural damage identification with noise polluted frequency response functions (frfs)". In *Proceedings of the 14th Asia-Pacific Vibration Conference*. Hong Kong Polytechnic University, Hong Kong.

Borges, E.N., 2012. "*Manufacturing, Computational Modeling and Experimenting Evaluation of Hybrid Bonded Joints Monitored through Smart Composites*". Master's thesis, São Carlos School of Engineering, University of São Paulo, São Carlos, São Paulo, Brazil. (in portuguese).

Carden, E.P. and Fanning, P., 2004. "Vibration based condition monitoring: A review". *Structural Health Monitoring*, Vol. 3, No. 4, pp. 355–377.

Doebling, S.W., Farrar, C.R. and Prime, M.B., 1998. "A summary review of vibration-based damage identification methods". *Shock and Vibration Digest*, Vol. 30, pp. 91–105.

Doebling, S.W., Farrar, C.R., Prime, M.B. and Shevitz, D.W., 1996. "Damage identification and health monitoring of structural and mechanical systems from changes in their vibration characteristics: A literature review". Technical report, Los Alamos National Laboratory Report LA-13070-MS, Los Alamos, New Mexico.

Elshafey, A.A., Marzouk, H. and Haddara, M.R., 2011. "Experimental damage identification using modified mode shape difference". *Journal of Marine Science and Application*, Vol. 10, No. 2, pp. 150–155.

Ewins, D.J., 2000. *Modal Testing: Theory, Practice and Application*. Research Studies Press LTDA, Baldock, England, 2nd edition.

Fan,W. and Qiao, P., 2011. "Vibration-based damage identification methods: A review and comparative study". *Structural Health Monitoring*, Vol. 10, No. 1, pp. 83–111.

Furukawa, A., Otsuka, H. and Kiyono, J., 2006. "Structural damage detection method using uncertain frequency response functions". *Computer-Aided Civil and Infrastructure Engineering*, Vol. 21, No. 4, pp. 292–305.

Heylen, W., Lammens, S. and Sas, P., 1997. "*Modal analysis theory and testing*". Leuven: KUL Press, pp. 340.

Juneja, V., Haftka, R. and Cudney, H., 1997. "Damage detection and damage detectability analysis and experiments". *Journal of Aerospace Engineering*, Vol. 10, No. 4, pp. 135–142.

Kessler, S.S., Spearing, S., Atalla, M.J., Cesnik, C.E. and Soutis, C., 2002. "Damage detection in composite materials using frequency response methods". *Composites Part B: Engineering*, Vol. 33, No. 1, pp. 87 – 95.

Kurata, M., Kim, J.H., Lynch, J.P., Law, K.H. and Salvino, L.W., 2010. "A probabilistic model updating algorithm for fatigue damage detection in aluminum hull structures". In *Proceedings of the ASME 2010 Conference on Smart Materials, Adaptive Structures and Intelligent Systems SMASIS2010*. Philadelphia, Pennsylvania, USA.

Lin, T.K., Hung, S.L. and Huang, C.S., 2012. "Detection of damage location using novel substructure-based frequency response function approach with a wireless sensing system". *International Journal of Structural Stability and Dynamics*, Vol. 12, No. 04, p. 1250029.

Liu, Y. and Nayak, S., 2012. "Structural health monitoring: State of the art and perspectives". *Journal of the Minerals, Metals & Materials Society*, Vol. 64, No. 7, pp. 789–792.

Maia, N., Silva, J., Almas, E. and Sampaio, R., 2003. "Damage detection in structures: from mode shape to frequency response function methods". *Mechanical Systems and Signal Processing*, Vol. 17, No. 3, pp. 489 – 498.

McConnell, K.G. and Varoto, P.S., 1995. *Vibration Testing: Theory and Practice*. John Wiley & Sons, New York, 2nd edition.

Medeiros, R., Ribeiro, M.L, Sartorato, M. and Tita, V., 2013. "Computational simulation using PZT as sensor elements for damage detection on impacted composite cylinders". In *Proceedings of the 1st International Symposium on Solid Mechanics MecSol2012*. Porto Alegre, Rio Grande do Sul, Brazil.

Medeiros, R., Sartorato, M., Ribeiro, M.L., Vandepitte, D. and Tita, V., 2012. "Numerical and experimental analyses about SHM metrics using piezoelectric materials". In *Proceedings of ISMA2012-USD2012*. Leuven, Belgium.

Mickens, T., Schulz, M., Sundaresan, M., Ghoshal, A., Naser, A. and Reichmeider, R., 2003. "Structural health monitoring of an aircraft joint". *Mechanical Systems and Signal Processing*, Vol. 17, No. 2, pp. 285 – 303.

Monaco, E., Franco, F. and Lecce, L., 2000. "Experimental and numerical activities on damage detection using magnetostrictive actuators and statistical analysis". *Journal of Intelligent Material Systems and Structures*, Vol. 11, No. 7, pp. 567–578.

Montalvao, D., Maia, N. and Ribeiro, A., 2006. "A review of vibration-based structural health monitoring with special emphasis on composite materials". *Shock and Vibration Digest*, Vol. 38, No. 4, pp. 295–324.

ISSN 2176-5480

Ooijevaar, T., Loendersloot, R., Warnet, L., de Boer, A. and Akkerman, R., 2010. “Vibration based structural health monitoring of a composite t-beam”. *Composite Structures*, Vol. 92, No. 9, pp. 2007 – 2015.

Pandey, A., Biswas, M. and Samman, M., 1991. “Damage detection from changes in curvature mode shapes”. *Journal of Sound and Vibration*, Vol. 145, No. 2, pp. 321 – 332.

Peeters, B., der Auweraer, H.V., Guillaume, P. and Leuridan, J., 2004. “The polymax frequency-domain method: a new standard for modal parameter estimation?” *Shock and Vibration*, Vol. 11, No. 3-4, pp. 395–409.

Prada, M.A., Toivola, J., Kullaa, J. and Hollmén, J., 2012. “Three-way analysis of structural health monitoring data”. *Neurocomputing*, Vol. 80, No. 0, pp. 119 – 128.

Rahmatalla, S., Eun, H.C. and Lee, E.T., 2012. “Damage detection from the variation of parameter matrices estimated by incomplete frf data”. *Smart Structures and Systems*, Vol. 9, No. 1, pp. 55–70.

Reddy, D.M. and Swarnamani, S., 2012. “Application of the frf curvature energy damage detection method to plate like structures”. *World Journal of Modelling and Simulation*, Vol. 8, No. 2, pp. 147–153.

Ribeiro, M.L., Tita, V. and Vandepitte, D., 2012. “*A new damage model for composite laminates*”. Composite Structures, Vol. 94, No. 2, pp. 635 – 642.

Ribeiro, M.L, Medeiros, R., Sartorato, M. and Tita, V., 2012. “Detecção de dano em cilindros de compósito empregando material piezelétrico”. In *Proceedings of the VII Congresso Nacional de Engenharia Mecânica CONEM2012*. São Luís, Maranhão, Brasil.

Salawu, O., 1997. “Detection of structural damage through changes in frequency: a review”. *Engineering Structures*, Vol. 19, No. 9, pp. 718 – 723.

Salehi, M., Ziaei-Rad, S., Ghayour, M. and Vaziri-Zanjani, M.A., 2010. “A structural damage detection technique based on measured frequency response functions”. *Contemporany Engineering Sciences*, Vol. 3, No. 5, pp. 215–226.

Sampaio, R., Maia, N. and Silva, J., 1999. “Damage detection using the frequency-responose-function curvature method”. *Journal of Sound and Vibration*, Vol. 226, No. 5, pp. 1029 – 1042.

Thyagarajan, S., Schulz, M., Pai, P. and Chung, J., 1998. “Detecting structural damage using frequency response functions”. *Journal of Sound and Vibration*, Vol. 210, No. 1, pp. 162 – 170.

Tita, V., de Carvalho, J. and Vandepitte, D., 2008. “Failure analysis of low velocity impact on thin composite laminates: Experimental and numerical approaches”. *Composite Structures*, Vol. 83, No. 4, pp. 413 – 428.

Vandiver, J., 1977. “Detection of structural failure on fixed platforms by measurement of dynamic response”. *Journal of Petroleum Technology*, Vol. 3, No. 3, pp. 305–310.

Wang, Z., Lin, R. and Lim, M., 1997. “Structural damage detection using measured FRF data”. *Computer Methods in Applied Mechanics and Engineering*, Vol. 147, No. 1 - 2, pp. 187 – 197.

Worden, K., Farrar, C.R., Haywood, J. and Todd, M., 2008. “A review of nonlinear dynamics applications to structural health monitoring”. *Structural Control and Health Monitoring*, Vol. 15, No. 4, pp. 540–567.

Zou, Y., Tong, L. and Steven, G., 2000. “Vibration-based model-dependent damage (delamination) identification and health monitoring for composite structures a review”. *Journal of Sound and Vibration*, Vol. 230, No. 2, pp. 357 – 378.

8. RESPONSIBILITY NOTICE

The authors are the only responsible for the printed material included in this paper.