MODAL PARAMETERS IDENTIFICATION OF COMPOSITE WING MODELS USING PIEZOELECTRIC MATERIAL

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Abstract
This paper aims estimate modal parameters of thin composite wing models through experimental modal analysis (EMA) using piezoelectric materials. The wing models are flat plate based on three ply carbon-epoxy fiber in same directions. Five specimens with different unidirectional fiber nominal orientation ($\theta_k = 0°, \theta_k = 30°, \theta_k = 45°, \theta_k = 60°, \theta_k = 90°$) are tested. These models were instrumented with one PZT (Lead Zirconate Titanate) actuator and one PVDF (Polyvinylidene Fluoride) sensor and results compared with vibrometer laser measurements. The orthotropic materials have different stiffness properties to each direction. These characteristics can be used to optimize or improve the dynamic behavior. Several examples, especially for aeronautic application can be cited, e.g., wings with negative deflection where fiber orientation was used to resolve divergence problem that these wings shows. An investigation about the dynamic behavior is conducted the modal parameters extracted. Using twelve points measured by vibrometer laser the vibration modes were achieved and modal assurance criterion (MAC) were calculated to assess the correlation between modes.

1. Introduction

From the 1970s to nowadays, vibration tests undergone great evolution. This evolution occurred due improvement of other areas, *e.g.*, digital signal processing, modal identification methods, finite element method, piezoelectric materials, etc. D. J. Ewins [1], in 1986, wrote the first ever book on modal analysis. Since then, a large number of techniques about modal analyses have been developed. Recently, a lot of research in vibration control has been developed aiming the minimization of displacement response. One branch of investigation is the uses of sensor and actuator as active elements integrated on structure. These structures, known as, smart structures, can be created using piezoelectric materials. Basically, the piezoelectric phenomenon produces an electric field when subject to displacement, similarly, produces a displacement when subject to electric field. Thereby, they can be used as sensors or actuators. However, popularly are most used to specific applications, enjoying the better properties. In 1954, Jafett at all, invented the ceramic Lead Zirconate Titanate (PZT) that is quite a lot used as actuator and, after 1960, Kawai created the plastic film Polyvinylidene Fluoride (PVDF) used mainly as sensor.

Composite materials are revolutionizing the aeronautical industry, specially the military, became possible project aircraft more fuel efficient, lighter and high performance. In some applications, the fiber orientations of composite materials are used to enhance the aeroelastic behavior, *e.g.*, X29, SU47 aircraft where the fiber orientation were adjusted to make up for negative deflection.

Piezoelectric material is a type of smart materials. Some definitions can be found for smart materials, but perhaps a most appropriate is “a material that converts energy between multiple physical domains” [2]. In piezoelectric materials the domains electrical and mechanical are coupled, in other words, these materials are able to convert electrical to mechanical energy and vice versa. Due this very important characteristic is that can be used in a lot of application as actuator or sensor. The mechanical-to-electrical coupling responsible to convert mechanical in electrical energy is known as direct effect, whereas, the electrical-to-mechanical coupling is known as converse piezoelectric effect. However, the piezoelectric materials also exhibit thermomechanical coupling, known as pyroelectric effect and it can be a problem if only electromechanical is wanted, because, high variation in temperature can produces an undesirable influence on piezoelectric elements. When the piezoelectric material is subject to a mechanical stress produces an electrical displacement (direct effect), and produces a mechanical strain when is applied an electric field (converse piezoelectric effect). A detailed explanation is presented by [3].

The present work aims study the use of piezoelectric materials as sensor and actuator to perform experimental modal analysis (EMA). Five models with different fiber orientation were tested using PZT as actuator, PVDF as sensor and the results are compared with vibrometer laser results. Through this study, the influence of instrumentation were also evaluated. The instrumentation changes the structural damping, and increases the local stiffness and mass. Consequently, the dynamic behaviour is altered, because the natural frequency of a structure is a function of mass and stiffness properties.

2. Methodology

The data acquisition is realized using the LMS ©SCADAS III ®hardware with LMS ©Spectral Testing ®software. The receptance frequency response function is defined as:

$$Y(\omega) = \frac{Ve^{i\omega t}}{Fe^{i\omega t}} = \frac{V}{F} \tag{1}$$

The numerator of eq.1 is velocity, and it is provided by response of Laser Vibrometer. The Laser Vibrometer can measure velocity or displacement, but the minimum frequency in range measure for displacement is 10 Hz, while, using velocity is possible measures frequencies afterwards 0.5 Hz. Therefore, it was chosen velocity, and before each shot test the Laser is turned on for 20 min to stabilize, as indicate in User’s Laser Manual. Worth remembering, that integrating or differentiating is possible change the signal type between displacement, velocity and acceleration.

The natural frequencies and damping factors are achieved using one PVDF sensor and PZT actuator. These results are compared with Laser Vibrometer measures in several points. Using these several laser measured points the modes shapes are extracted and MAC is performed. Comparing the results between two techniques (Laser Vibrometer vs PVDF sensor) is possible verify if the technique using piezoelectric materials applied to perform EMA was dominated and is possible too verify likely problems or points to pay attention. The advantages of using an optical noncontact positioning device, according to [4], are evident especially when considering the capabilities of measuring the position of several markers simultaneously.

Returning to Eq.1, the force in denominator equation is provided by one PZT embedded in near root region in angle of 45° as scheme illustrated by Fig.2. The PZT is embedded using 3M Scotch-weld Structural Adhesive DP460 Off-White,[5]. The excitation used is type Random and your intensity is adjusted to each model. Several investigations about this excitation is performed, this study is present in Related Investigations Section. The excitation channel of $LMS^{©}$ $SCADAS\,III^{®}$, commonly used in shaker device was used to supply the Piezo Power Amplifier model $QuickPack^{®}QPA202$. The Piezo Power Amplifier, on the other hand, was used to supply the signal excitation (volts) to $SCADAS\,III^{®}$. Through the amplifier, the output voltage can be amplified 20 times (20X) and to perform the EMA this device was adjusted to increase by about $12.5X$. The maximum input voltage supplied to amplifier was $\pm 4V$, this means that the maximum voltage supplied to PZT was ± 50 V of peak (± 100 V of vale).

There are a compromise between the excitation intensity and parameters set up in SCADAS III ®. The structural response is increased together with excitation, this imply that, the sensibility of acquisition should be tuned to each condition, so that not appear overload. The quantity of signal should be respected to a good acquisition. A signal quantity greater than 70 % must be satisfied according to LMS user's manual [6].

The composite models were mapped in twelve points by Laser Vibrometer and a complete illustrative scheme contains Laser points measured, position and dimensions of piezoelectric elements are presented in Fig.1.

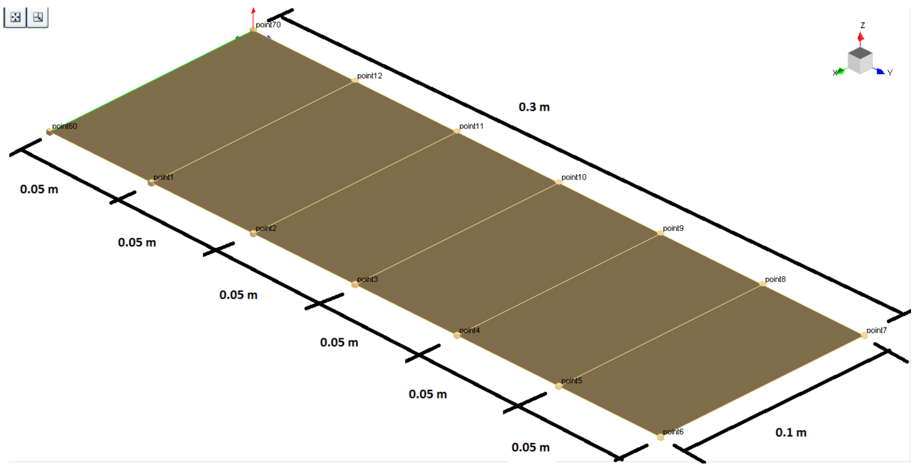
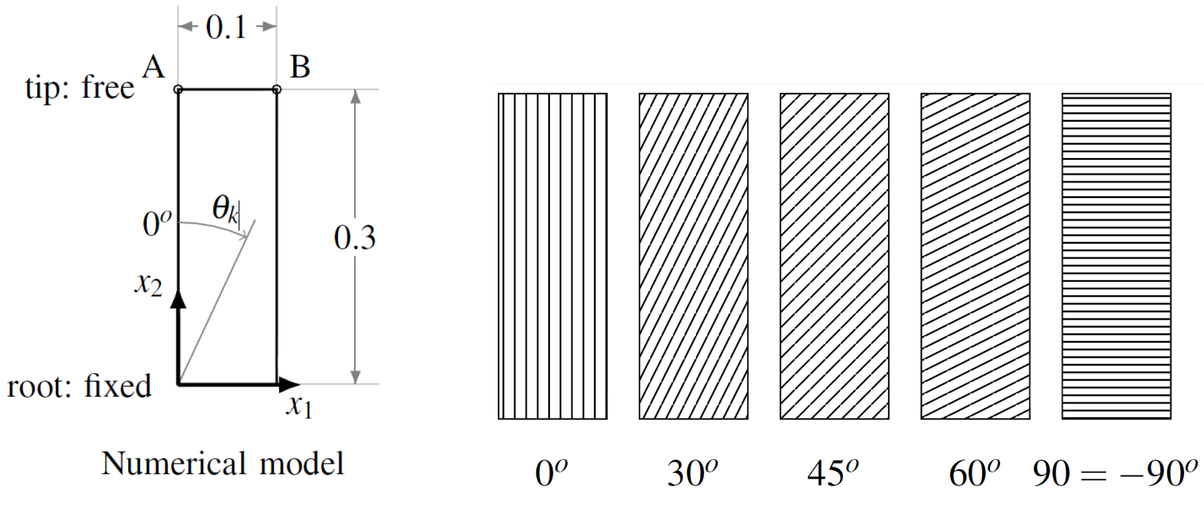


Figure 1. Composite model - Laser measurements, positioning and dimensions

Each specimen has a different nominal orientation of fiber $\theta_k = 0°, 30°, 45°, 60°$ and 90° and is shown in Fig.2. This type of material is being used more and more extensively by the aviation industry, which always seeks to work with lightweight structures. Several application examples can be seen in [7] and [8].



(a) θ_k (b) Fiber orientation

Figure 2. Dimensions and nominal orientation (adapted by [9])

They are fixed in additional extension of 0.05 m at the root and has a span of 0.3 m and chord of 0.1 m. These models are flat plates made with carbon fiber roving and epoxy resin and has the lamina thickness is $5 \cdot e^{-4}$ m which together corresponds to $1.5 \cdot e^{-3}$ m.

3. Results

The presentation of all results including vibration modes, coherence, bode diagram and MAC for all composites modes is not possible due to paper length limitation. Therefore, it was opted present the some results for 0° model, vibration modes of 30° and finalize with MAC for $30°, 45°, 60°$ and 90°.

The EMA is conducted to achieve the modal parameters of composite models. In this modal test are extracted the modal parameters using piezoelectric materials as sensor and actuator and results are compared with the Vibrometer Laser.

A voltage about ±12.5 v supplies the PZT and they excites the structure using random excitation. The FRFs of Laser measurements were estimated using the H_V estimator, Eq.**??**, and presented in Fig.3. Similar to obtained in Al models tests, the FRFs achieved showed very noisy signal after 230 Hz, but as previously mentioned the vibration modes that we have interest are not affected. Therefore, no action was taken.

It was shown that the values of coherence, Eq.1, are necessarily between 0 and 1 ($0 \geq \gamma(\omega)^2 \leq 1$). If analize the coherence of composite model 0°, it can conclude shows good results, Fig.3. Therefore, the graphical coherence scale was changed to 0.8 to 1, because if use full scale the coherence virtually could not be seen.

The same short graphical coherence scale was adopted to show PVDF results, Fig.4. In early tested Al models the coherence of PVDF showed slightly better results and it was repeated here. In other words, they were simultaneously acquired using same windowing, average, estimator,

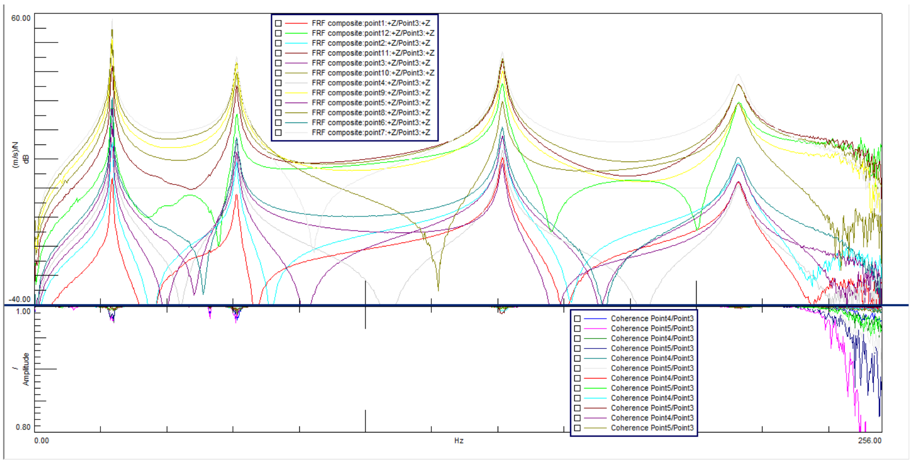


Figure 3. [0°] Laser Measurements - Coherence

time acquisition, frequency resolution and other defined tests parameters.

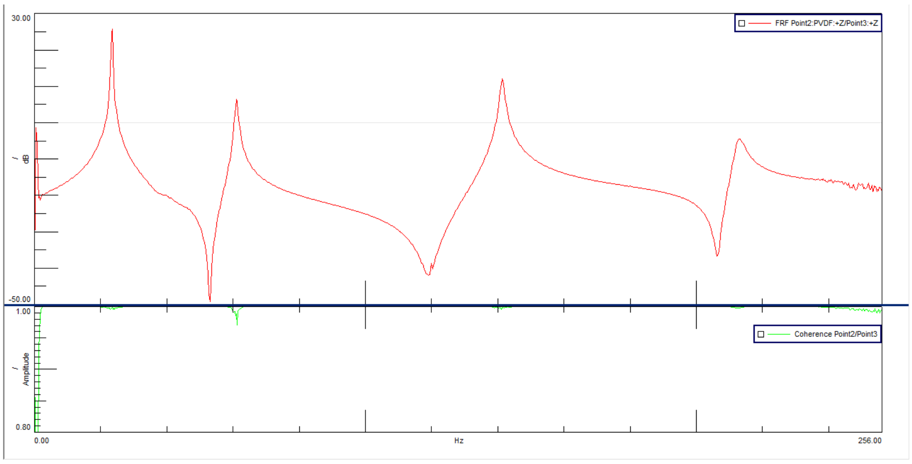
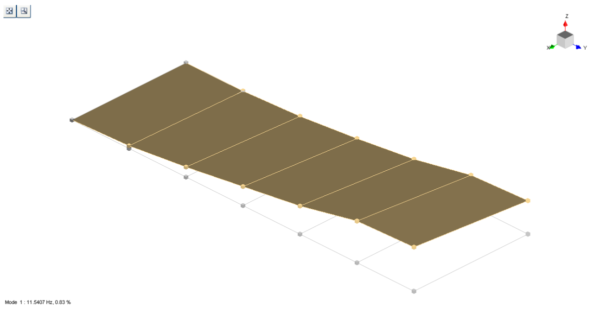


Figure 4. [0°] PVDF - Coherence

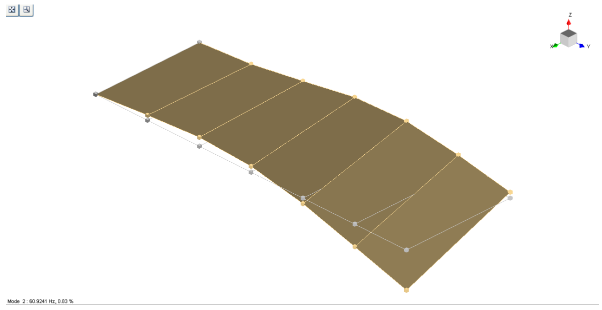
If looking closely at the Fig.4, near 0 Hz can be seen that there is one strange peak and because this, in this region the coherence goes to 0 (0.8 is shown in the graphical). Indeed, the right reason to this is not known, but very probably is because this frequency range is out of operational range of device. The PVDF response can be improved changing the chosen impedance. This parameter is set up in conditioner and they should be between 1 $M\Omega$ and 10 $M\Omega$. The Low Frequency Response curve of is available in PVDF user's Manual, [10].

The composite model 30° was tested using the same early procedure and the mode shapes of 30° model are presented in Fig.5. Analysing the vibration modes extracted can note that only fundamental frequency is pure bending mode and the others are combinations of bending and torsion. Although it are not pure modes, it is easy conclude that correspond to structure.

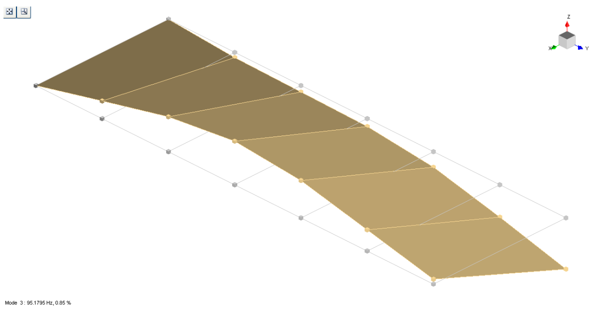
Commonly, the procedure used to verify the accuracy of modal test is called of modal validation. There are several tools and methods for doing so. Some of them still have variations, *e.g.*, the MAC. The validation, generally, can be done comparing modal results from the different estimation techniques. Other used technique is the comparison of numerical modes versus experimentally obtained modes. Some strategies are used to analyze the vibration modes, *e.g.*, the



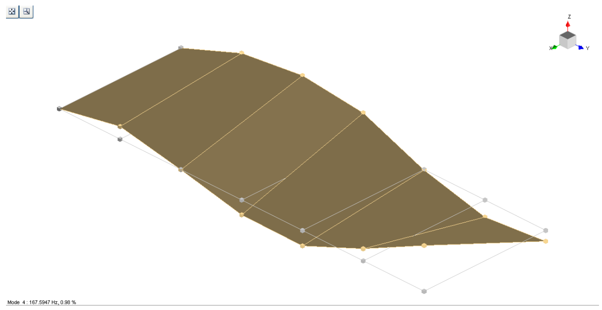
(a) 1^{st} - 11.54 Hz



(b) 2^{nd} - 60.92 Hz



(c) 3^{rd} - 95.18 Hz



(d) 4^{th} - 167.59 Hz

Figure 5. [30°] Vibration Modes

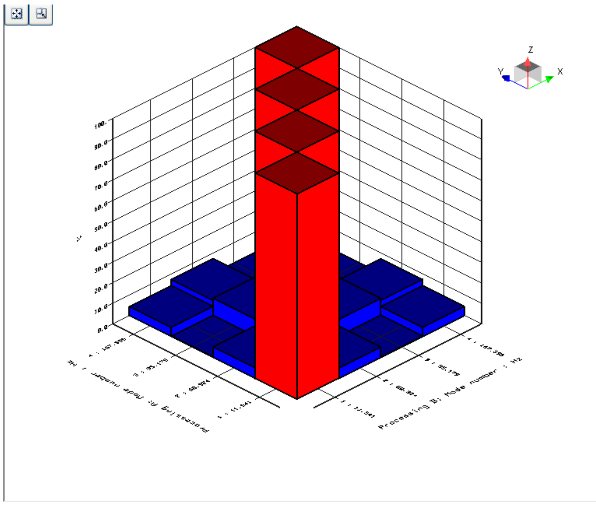
Mode	Laser [Hz]	PVDF [Hz]
1	23.262	23.441
2	61.037	61.030
3	141.362	141.332
4	212.729	212.822

Table 1. Natural frequencies comparison - 0°

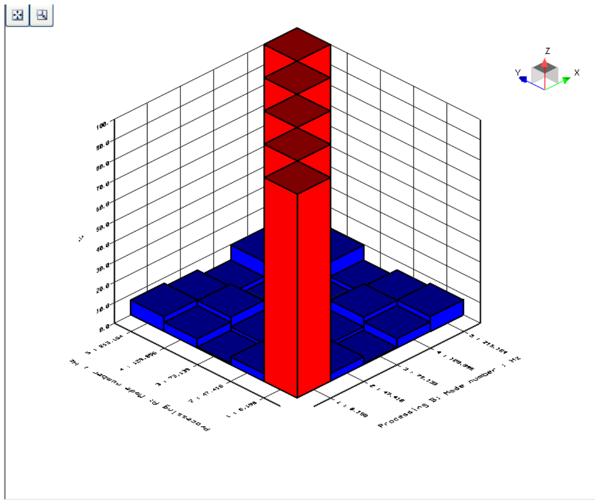
overlaid animation of mode shapes, difference animation of mode shapes, side-by-side and Top-Bottom animation of mode shapes, 3D and table read-out of the MAC. Analysing the calculated MAC, Fig.6, it can be seen that the correlation between achieved vibration modes were 100% and the results out of diagonal are not above 10%. It are very good results, so it can conclude with severity that the this analysis was successfully performed.

The comparison between natural frequencies achieved by laser vibrometer and PVDF are presented in Tab.1. As can be seen, it was obtained very good results, especially if considered that was used twelve points for laser results and only one PVDF.

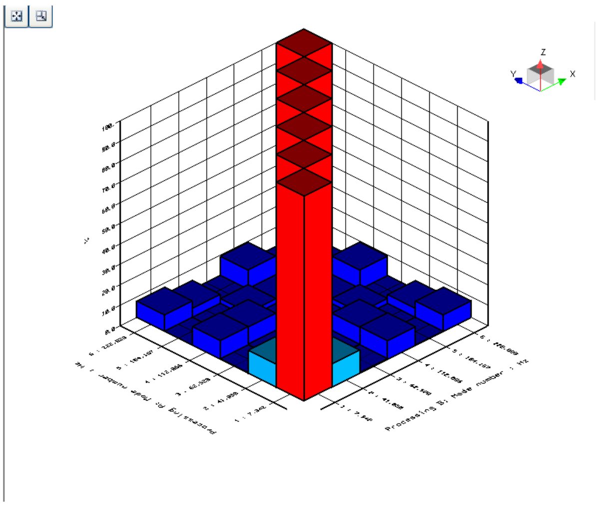
The evolution of damping factor according to fiber orientation are presented in Fig.7. A comparison between laser and PVDF was taken, and these are coherent. It was observed a bigger variation for second vibration mode that was increased of 0° to 60° and decreased in the 90°.



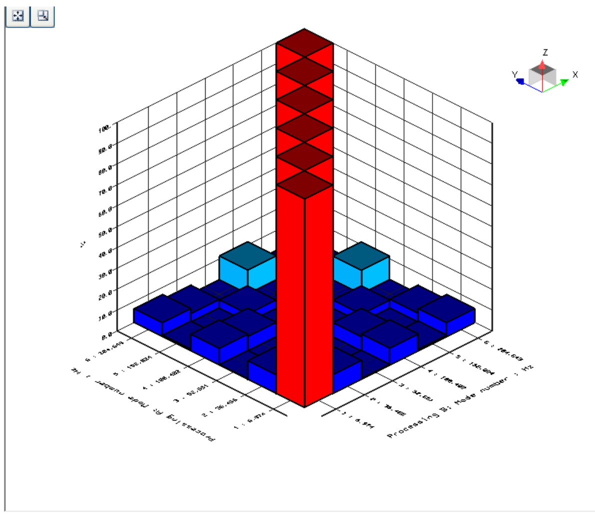
(a) 30° - MAC



(b) 45° - MAC



(c) 60° - MAC



(d) 90° - MAC

Figure 6. MAC - Modal Assurance Criterion

4. CONCLUSIONS

The piezoelectric materials were able to extract the natural frequencies and damping factor in the two cases that were applied. If adopting the Laser Vibrometer results as reference and comparing with PVDF results, it can conclude that are very coherent. In all studies models the coherence results of PVDF were slightly better than Laser. Also, very good results it was achieved in MAC calculation, showing that was possible done the modal validation.

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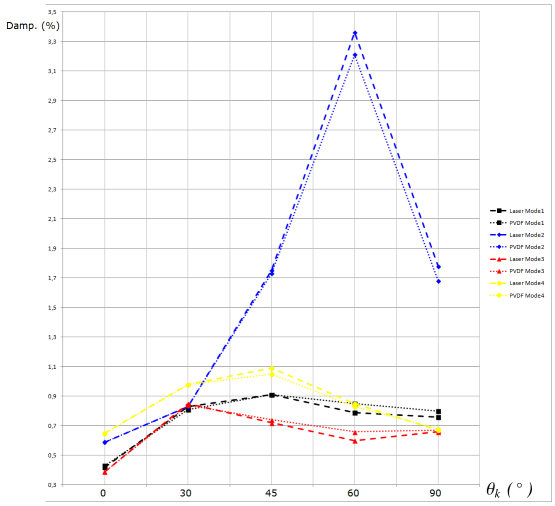

Figure 7. Damping Evolution - PVDF vs Laser Comparison

Aeronutica, ITA.

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