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Modal characterization of composite flat plate models using piezoelectric transducers

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ABSTRACT

This paper aims to estimate the modal parameters of composite flat plate models through Experimental Modal Analysis (EMA) using piezoelectric transducers. The flat plates are composed of three ply carbon-epoxy fibers oriented in the same direction. Five specimens with different unidirectional fiber nominal orientations θ_k (0°, 30°, 45°, 60° and 90°) were tested. These models were instrumented with one PZT (Lead Zirconate Titanate) actuator and one PVDF (Polyvinylidene Fluoride) sensor and an EMA was performed. The natural frequencies and damping factors estimated using only a single PVDF response were compared with the estimated results using twelve measurement points acquired by laser doppler vibrometry. For comparison purposes, the percentage error of each natural frequency estimation and the percentage error of the damping factor estimations were computed, as well as their averages. Even though the comparison was made between a SISO (Single-Input, Single-Output) and a SIMO (Single-Input, Multiple-Output) techniques, both results are very close. The vibration modes were estimated by means of laser measurements and were used in the modal validation. In order to verify the accuracy of the modal parameters, the Modal Assurance Criterion (MAC) was employed and a high correlation among mode shapes was observed.

1. Introduction

Modal analysis is sometimes defined as the study of the dynamic behavior of the structure in terms of its vibration modes. A vibration mode is characterized by its modal parameters: natural frequency, damping factor and mode shape. According to [1], Rayleigh was the first to use a basic principle to describe the dynamic behavior in terms of vibration modes, over a century ago. With the better understanding of the aircraft dynamic behavior in mind, modal analysis was firstly used as an engineering tool around 1940 [2]. Since then, vibration tests suffered a great evolution, particularly in the 1970s. This evolution occurred as a consequence of combined improvements in other areas, such as digital signal processing, modal identification methods, finite

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element method and piezoelectric materials. In 1984, Ewins [3] wrote the first ever book on modal analysis [2]. Ever since, multiple techniques in the field of modal analysis have been developed.

Recent researches in vibration control have been undertaken, aiming to minimize the displacement response. One branch of those investigations is the application of sensors and actuators as active elements integrated on the structure. Such structures, known as smart structures, can be devised using piezoelectric materials [4]. Basically, piezoelectric materials produce an electric displacement when subjected to a mechanical stress; similarly they can produce a mechanical strain when subjected to an electric field. Thereby, they can be used either as sensors or actuators or both; however they are mostly used for specific applications, better exploring their piezoelectric properties (predominant coupling). In 1954, Jaffe et al. [5], invented the ceramic Lead Zirconate Titanate (PZT) that is commonly applied as actuator and in 1969 Kawai [6] proposed the plastic film Polyvinylidene Fluoride (PVDF), which is mainly used as sensor.

Piezoelectric materials are a type of smart materials. Several definitions can be found in the literature for smart materials, but perhaps one of the most suitable ones is “a material that converts energy between multiple physical domains” [7]. In piezoelectric materials the electrical and mechanical domains are coupled, meaning that these materials are able to convert electrical energy into mechanical energy and *vice versa*. Due to this very important characteristic they can be used in multiple applications as actuator and/or sensor. The mechanical-to-electrical coupling responsible for converting mechanical energy into electrical energy is known as direct effect, while the electrical-to-mechanical coupling is known as converse piezoelectric effect. However, the piezoelectric materials also exhibit thermomechanical coupling, known as pyroelectric effect. This effect can be a problem if only electromechanical coupling is wanted, since a high variation in temperature can produce an undesirable influence on the piezoelectric element properties. When a piezoelectric material is subjected to a mechanical stress, it produces an electrical displacement (direct piezoelectric effect), while when an electric field is applied the outcome is a mechanical strain (converse piezoelectric effect). A detailed explanation can be found in the literature [8].

Composite materials are revolutionizing the aeronautical industry, in particular the military branch, since their application allowed to design lighter aircraft, more fuel-efficient and thus enhancing their performance. Some applications involving tailoring fiber orientations of composite materials to enhance aeroelastic behavior have been done, for example in the Grumman's experimental X-29 [9] and in the Sukhoi's Su-47 Berkut [10] aircraft, where the fiber orientations were adjusted to make up for their forward-swept wing configuration. Several other applications are reported in [11,12].

This present work aims at performing modal characterization of composite flat plate models using piezoelectric materials as sensors and actuators. A single PVDF working as sensor and one PZT operating as actuator have been used in Experimental Modal Analysis (EMA). The EMA was conducted to estimate the modal parameters of the composite flat plate models. The results were compared to the estimated values obtained by using several measurement points through the application of a noncontact technique (laser doppler vibrometry).

2. Brief piezoelectric background for experimental applications

As stated, the application of piezoelectric transducers as sensors and actuators is possible due to the direct and converse piezoelectric effects, respectively. A proper knowledge of the piezoelectric operating principle requires the understanding of the constitutive matrix for the corresponding piezoelectric material, which is very important from both experimental and numerical perspectives. From the experimental point of view, the understanding of the piezoelectric element datasheet is essential, since it provides the necessary information about the electromechanical coupling, which is required in order to know how the element deforms and consequently allows to identify where the PZT should be most suitably placed to excite the vibration modes of interest. Numerically, it is also vital (i) to know how to generate the numerical model, (ii) to define the piezoelectric properties, (iii) to apply the electric field and (iv) naturally to understand how it works. The constitutive equations for several piezoelectric materials are the same, *e.g.*, the PZT type PSI-5H4E used in this work. For this PZT some terms of the constitutive equations are zero, as follows

$$\begin{Bmatrix} S_1 \\ S_2 \\ S_3 \\ S_4 \\ S_5 \\ S_6 \end{Bmatrix} = \begin{bmatrix} \frac{1}{Y_1^E} & -\frac{\upsilon_{12}}{Y_1^E} & -\frac{\upsilon_{13}}{Y_1^E} & 0 & 0 & 0 \\ -\frac{\upsilon_{12}}{Y_1^E} & \frac{1}{Y_1^E} & -\frac{\upsilon_{23}}{Y_1^E} & 0 & 0 & 0 \\ -\frac{\upsilon_{31}}{Y_3^E} & -\frac{\upsilon_{32}}{Y_3^E} & \frac{1}{Y_3^E} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{G_{23}^E} & 0 & 0 \\ 0 & 0 & 0 & 0 & \frac{1}{G_{13}^E} & 0 \\ 0 & 0 & 0 & 0 & 0 & \frac{1}{G_{12}^E} \end{bmatrix} \begin{Bmatrix} T_1 \\ T_2 \\ T_3 \\ T_4 \\ T_5 \\ T_6 \end{Bmatrix} + \begin{bmatrix} 0 & 0 & d_{13} \\ 0 & 0 & d_{23} \\ 0 & 0 & d_{33} \\ 0 & d_{24} & 0 \\ d_{15} & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{Bmatrix} E_1 \\ E_2 \\ E_3 \end{Bmatrix},$$

$$\begin{Bmatrix} D_1 \\ D_2 \\ D_3 \end{Bmatrix} = \begin{bmatrix} 0 & 0 & 0 & 0 & d_{15} & 0 \\ 0 & 0 & 0 & d_{24} & 0 & 0 \\ d_{13} & d_{23} & d_{33} & 0 & 0 & 0 \end{bmatrix} \begin{Bmatrix} T_1 \\ T_2 \\ T_3 \\ T_4 \\ T_5 \\ T_6 \end{Bmatrix} + \begin{bmatrix} \varepsilon_{11} & 0 & 0 \\ 0 & \varepsilon_{22} & 0 \\ 0 & 0 & \varepsilon_{33} \end{bmatrix} \begin{Bmatrix} E_1 \\ E_2 \\ E_3 \end{Bmatrix}. \tag{1}$$