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EXPERIMENTAL AEROELASTIC INVESTIGATION USING PIEZOELECTRIC TRANSDUCERS FOR MODAL PARAMETERS IDENTIFICATION

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Summary: *The aim of this work is to achieve the V-g/V-f diagram using piezoelectric transducers as both sensor and actuator. One of the most commonly employed experimental techniques to perform an aeroelastic analysis is the Operational Modal Analysis (OMA). The OMA method estimates the natural frequencies and the damping factors of any structures and can be applied in both flight and wind tunnel tests. However, high noise levels on the acquired data are generally observed by applying this methodology since only structural response is used to obtain the Frequency Response Function (FRF). With the noise effect minimization in mind, some statistical procedures can be applied, although they can lead to inaccuracies in the data acquisition. Nonetheless, the quality of the acquisition can be improved when obtaining the FRF taking into account not only the structural response but also the excitation. This test methodology is so-called Experimental Modal Analysis (EMA). The EMA technique can be applied to improve the data acquisition by "forcing" the input of correlated measures and thus decreasing noise. The noncorrelated inputs (such as noise) tends to disappear by using the average number of a set of acquisitions. Another advantage related to the application of the EMA technique in aerolastic analysis is the ability to efficiently excite the vibration modes, which sometimes are not adequately excited by aerodynamic/turbulence forces. For this work a wind tunnel test* *campaign was conducted and the modal parameters (natural frequencies and damping factors) were achieved by employing EMA methodology using both SISO (Single - Input, Single - Output) and SIMO (Single - Input, Multiple - Output) techniques. These modal parameters were extracted for each airspeed condition until the pre-flutter speed is reached and both techniques were done by using a PZT (Lead Zirconate Titanate) excitation. For the SISO testing, a single PVDF (Polyvinylidene Fluoride) was used to acquire the structure's dynamic response at same time that a laser doppler vibrometry was employed to measure two points. The estimated modal parameters were used to plot the V-g/V-f diagrams using both techniques and the flutter speed was estimated. A very good agreement was found between each other by comparing the results.*

1. INTRODUCTION

The term "aeroelasticity" first appeared in the Roxbee Cox & Pugsley report [1]. Per definition, aeroelasticity (dynamic) is the study of the interaction between aerodynamic, elastic and inertia forces [2]. Aerodynamic forces are produced by the fluid flow which the body is subject. Elastic forces are related with the elastic reaction generated when the body is deformed. Inertial forces are generated due to the acceleration of the body mass. Among the aeroelastic phenomena, flutter is considered the most important [3] and the most difficult to predict [4]. The prediction of this phenomenon involves the identification of closed modes, which in itself is a difficult task as claimed by Ewins [5]. In both wind tunnel and flight tests, the acquired data commonly presents high noise levels, which increases the difficulty to identify the modal parameters evolution. Aeroelastic investigation is associated to the modal parameters identification, hence it can be said that experimental aeroelastic tests evolved together with vibration tests.

Especially from the 1970's, the vibration tests have undergone great evolution driven by the development of other areas such as the digital signal processing, modal identification methods, finite element method and piezoelectric materials. Due to the advent of the digital Fast Fourier Transform (FFT) spectrum analyser in 1970's, the experimental modal analysis have steadily growing in popularity since then [6]. In 1984 D. J. Ewins ([7]) wrote the first ever book on modal analysis [8]. According to [9], the concept of modal testing is much older than its name, dating back to the early days of vibration measurement. Modal analysis is usually defined as the study of structure's dynamics behaviour in terms of its vibration modes. A vibration mode is characterized by its modal parameters: natural frequency, damping factor and mode shape. According to [10], Rayleigh was the first to use a basic principle to describe a structure's dynamic behaviour in terms of its vibration modes over a century ago. With the better understanding of aircraft's dynamic behaviour in mind, modal analysis was first used as an engineering tool around 1940 [8].

The modal parameters, natural frequencies and damping factors, can be estimated from any of the Frequency Response Function (FRF) measurements on the structure[1] [11]. The FRF can

[1] Except those for which the excitation or response Degree of Freedom (DOF) is in a nodal position, *i.e.*, where the mode shape is zero.

be interpreted as a structural transfer function, which relates input with output. Depending on the considered output, such as displacement, velocity and acceleration, the FRF is so-called receptance, mobility or accelerance, respectively. Nonetheless, it may be used any convenient response characteristics to express the dynamic properties of a system [8]. Considering that the transfer function equation relates an input force with output response, both parameters (input and output) may be easily known when the modal tests are conducted in environment where noise emission is adequately controlled. Any external input such as aerodynamic excitation can enter in the signal acquisition and rendering it noisier. The input force can be estimated through load cell or the excitation signal itself; and the response is provided by the used sensor. If these two quantities are considered the FRF will present good quality. Nevertheless, when the modal testing is conducted in wind tunnel, all the aerodynamic forces can not be measured and thus unable to be accounted for in the FRF. These aerodynamic/turbulence forces are exogenous inputs that make a poor acquisition set which gets worse by increasing the wind speed.

Some procedures to improve the data acquisition for wind tunnel and flight tests are still being investigated, such as the use excitation mechanisms. There are several excitation mechanisms which are used to excite the aircraft structure such as Control Surface Pulses, Oscillating Control Surfaces, Thrusters, Inertial Exciters, Aerodynamic Vanes, Dynamic Engineering Incorporated (DEI), Rotating Cylinder Exciters and Random Atmospheric Turbulence [12]. One of the pioneering works (beginning about 1957) based on the use of vanes to generate aerodynamic forces was carried out by Lockheed-California Company in conjunction with flutter tests on the F-104 fighter and the Electra transport aircraft [13]. Also the Douglas Aircraft Company used aerodynamic vanes installed on all surfaces for flutter excitation of the DC-10 aircraft. Aiming to improve flight flutter test process, the NASA Dryden Flight Research Center investigates different wingtip exciter vanes using two aircraft: F/A-18 SRA (Systems Research Aircraft) and the F/A-18 HARV (High Alpha Research Vehicle) [14]. Several data were acquired and the transfer functions were compared in different conditions. In the conclusion of the NASA report [14] were cited improvements in aeroelastic and aeroservoelastic flight testing. Again two aerodynamic rotating vanes were tested in flight as exciters applied to the F-18 SRA, with the purpose of identifying dynamical systems in the presence of high noise levels [15]. Moreover, other works were done using the control surfaces themselves to excite the aircraft, such as [16].

A commonly research line is based on the employment of sensors and actuators as active elements integrated on structure. These structures known as smart structures can be built using piezoelectric materials. Several experimental and numerical works were conducted by using smart structures to buffet alleviation [17, 18, 19, 20], flutter suppression [21, 22, 23, 24], gust response alleviation [25], energy harvesting [26, 27, 28], active vibration control [29, 30, 31, 32, 33], structural damage identification/health monitoring [34, 35, 36, 37, 38, 39] , flight control [40], morphing aircraft and adaptive control [41, 42, 43, 44, 45]. Despite the several above cited applications, the application of piezoelectric material for aeroelastic investigations was not yet well explored.

This application, if correctly explored is able to improve the acquired data from a flight test or a wind tunnel test such as demonstrated in a previous work [46]. One of the conclusions of Nissim work [47] was that small vanes and aileron rotations yield large responses, allowing large response-to-noise ratios during test flights. The above mentioned response-to-noise ratio also can be obtained by means of piezoelectric material employment, especially considering a not so large structure such as wind tunnel models. A good signal/noise relation allows obtaining a more clean FRF by using the average number of a set acquisitions (auto-correlation function). In the present work this characteristic is explored by employing piezoelectric transducers for experimental aerolastic investigation by means of modal parameters identification.

2. PIEZOELECTRIC MATERIALS AND ITS EMPLOYMENT ON EXPERIMENTAL AEROELASTIC INVESTIGATION

The first ever recorded flutter occurred in 1916 on a Handley Page O/400 twin engine biplane bomber [48] due to a problem related to the elevator which right and left parts were independently actuated [49]. This problem was solved by interconnecting the elevator parts with a torque tube. Flutter is an aeroelastic phenomena which per definition is a dynamic instability associated with the interaction of aerodynamic, elastic and inertial forces [50]. This unstable self-excited vibration extracts energy from the air stream and can lead to a catastrophic structural failure [51]. There are several different types of flutter (several of them described by Weisshaar [52]), however, all of these are commonly of binary type. Despite unusual, there have been cases where a combination of more than two modes has led to flutter.

Experimental flutter investigations in wind tunnel or in flight are generally performed based on modal parameters identification for each airspeed condition. Using the modal parameters, natural frequencies and damping factors, achieved for each condition, the v-g/v-f diagram is plotted. By analysing the v-g/v-f diagram one can observe the evolution of frequency and damping factor as a function of airspeed (or dynamic pressure), therefore the flutter speed can be estimated. The identification of the flutter boundary is a one of the mandatory requirements to certify an aircraft. Several researches aiming to improve the efficiency of flight flutter test programs were conducted at NASA Dryden Flight Research Center. Among these concepts, there is an enhanced excitation systems which may dramatically reduce the cost and risk associated with envelope expansion [53]. One can state that by using piezoelectric transducers, it is possible to obtain similar improvement which is close related to the data acquisition procedure.

The history of piezoelectric materials begins in 1880 with the brothers Jacques Curie and Pierre Curie. They were the first ever to observe the connection between macroscopic piezoelectric phenomena and crystallographic structure. Using nothing more than a tinfoil, glue, wire, magnets and jeweller's saw, they were able to measure surface charges on prepared crystals (tourmaline, quartz, topaz, cane sugar and Rochelle Salt among them) due to mechanical stress [54]. Ever since, this effect was named piezoelectricity. However, the converse effect (stress due to applied electric field) was mathematically deduced by Lippmann in 1881 from fundamental thermodynamic principles and immediately demonstrated by Curie brothers. Leo [55] attributes the initial growing interest in piezoelectric materials to the First World War and the development of new means of warfare and its development was even more stimulated by

Second World War. A very important study conducted back then by Langevin was the development of an underwater device (transducer) that produces a mechanical signal and measures its electrical response as means of locating submarine using a piezoelectric crystal.

Piezoelectric materials have electrical and mechanical domains coupled[2], although they are also able to convert electrical to mechanical energy and vice versa [56]. Thus allowing its application to multiple purposes as actuators and/or sensors. In general, piezoelectric materials have a prevalent coupling, which means that some materials are more adequate to be applied specifically as sensors or actuators. Nonetheless, they are usually applied such that its better piezoelectric properties (predominant coupling) are well explored. Hence, the PVDF (Polyvinylidene Fluoride) is widely used as sensor and the PZT (Lead Zirconate Titanate) as actuator. The PZT was invented in 1954 by Jaffe et al. [57] and then in 1960 Kawai [58] developed the plastic film PVDF.

The PVDF have a small thickness and a high flexibility which can be advantageous for aeroelastic applications. Nevertheless, despite these characteristics it is always important to check the instrumentation influence. According to [8] the structure's dynamic behaviour can be affected not only by the excitation system but also by a force or response transducer. In aeroelastic investigations employing piezoelectric transducers, the used adhesive is very important, especially to embed the actuator. Previous work by the author [46] shown that the cyanoacrylate adhesive have fast degradation due to the PZT excitation which turns it in a noise source for the data acquisition. This noise in the acquired data suffered a drastically decrease only by changing the cyanoacrylate by a structural epoxy adhesive.

The employed adhesive and also the thickness itself have direct relationship with the transduction capability and the breaking resistance (especially for the PZT). Electromechanical comparisons of the transduction capabilities of the clamped-free using different piezoactuators (MFC 8528-P1, PSI PZT-5A, PSI PZT-5H and MIDE QP10N) were conducted by [59]. By analysing the characteristics and properties of several adhesives presented in [60], it is possible to observe that epoxy can be applied in multiple kinds of metals and nonmetals, however, due to incompatibility between epoxy and aluminum it is necessary to use a modified epoxy as for instance the epoxy-phenolic. Nevertheless, the datasheet [61] of the epoxy used in this work shows that the application to the aluminum can be done.

An interesting feature is that the cross-sensitivity and the size effect of the PVDF has an influence on measured frequency range [62], so these effects can be used to optimize the measurements. The PVDF response is a function of the selected impedance. Preferably the impedance for the employed PVDF (series model SDT1-028K) is 10 $M\Omega$ and the low frequency response curve of this PVDF is available in [63]. PVDFs are basically capacitors which develop charge within their dielectric and consequently they are very high impedance devices. This characteristic makes them very susceptible to electrical interference (electrical noise) unless another grounded surface is brought very close [64]. The employed PVDF consists of a thin rectangular piezo film together with a molded plastic housing and a coaxial cable, so it has the advantage to

[2]There is also the thermomechanical coupling. The effect known as pyroelectric can be a problem if only electromechanical coupling is wanted, because higher temperature variations can produce an undesirable influence.

be electrically "shielded".

Other important point which must be analysed is the excitation intensity. When the excitation is unable to excite the vibration modes of interest, a commonly adopted action is to increase the excitation level. A high excitation level may lead to nonlinear problems, thus, depending on the testing structure may be better to use more excitation point. Sometimes, only changing the excitation location may be enough. According to [65] the locations of actuators and sensors have a major influence on the performance of the control system. There are some tools to find a better or optimal actuator position such as using a quadratic cost function considering the measurement error and control energy, [66], [67], [68]. To define the optimal location, [69], and [70] aimed to maximize controllability through measuring the gramian matrix. In [71] a Modified Independent Modal Space Control (MIMSC) method was used to choose the optimal location and to control the gain of piezoelectric actuators. The effects which piezoelectric actuator and bonding layers have on the elastic and inertial properties of flexible beams was investigated: it was noted that the control force increases together with bonding layer thickness; on the other hand, the displacement decreases which leads to a significant increase in the required control voltages.

When a high actuation authority is required the Macro Fiber Composite (MFC) is commonly employed, especially when the structural flexibility is desirable. Nevertheless, the MFC actuator requires high voltage input. According to [59], this is a common disadvantage of MFC since the input voltage range is -500 to $+1500V$, while the typical voltage input required by a monolithic piezoceramic material is $\pm100V$. Probably, the structural flexibility of the MFC is the main reason to find several works using MFC as actuator in aerodynamic shape control. The MFC is more flexible than the majority of PZTs which means that the MFC can be subjected to higher deformations without breaking, such as a Limit Cycle Oscillation (LCO) condition. Nevertheless, experimental aeroelastic researches are usually conducted until pre-flutter condition is reached, so the PZT element can be safely used. A high excitation level can lead not only to nonlinear structural response but also to nonlinear piezoelectric response. By applying an increasingly high electric field, it will eventually result in saturation of the dipole motion, so the relationship between the applied field and electric displacement will be nonlinear [55]. Similarly, for high levels of applied stress the relationship between stress and electric displacement will become nonlinear due to saturation of electric dipole motion.

Before embedding any piezoelectric element on the structure, one important aspect which should be observed is the operating modes, because they show how the excitation or sensing can be made. To avoid mistakes, it is indicated that the piezoelectric constitutive equation be analysed, not only the piezoelectric strain coefficient d_{mj} terms but also their location. The constitutive properties of the piezoelectric materials can be represented by the complete set of constitutive equations, Eqs. 1 and 2.

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

$$\left\{\begin{array}{c} D_1 \\ D_2 \\ D_3 \end{array}\right\} = \begin{bmatrix} 0 & 0 & 0 & 0 & d_{15} & 0 \\ 0 & 0 & 0 & d_{24} & 0 & 0 \\ d_{13} & d_{23} & d_{33} & 0 & 0 & 0 \end{bmatrix} \left\{\begin{array}{c} T_1 \\ T_2 \\ T_3 \\ T_4 \\ T_5 \\ T_6 \end{array}\right\} + \begin{bmatrix} \varepsilon_{11} & 0 & 0 \\ 0 & \varepsilon_{22} & 0 \\ 0 & 0 & \varepsilon_{33} \end{bmatrix} \left\{\begin{array}{c} E_1 \\ E_2 \\ E_3 \end{array}\right\}. \tag{2}$$

The Eqs. 1 and 2 can be rewrite in compact form as a matrix expression,

$$\begin{array}{l} \underline{S} = \mathbf{s}^E \underline{T} + \mathbf{d}' \underline{E} \\ \underline{D} = \mathbf{d} \underline{T} + \varepsilon^T \underline{E}, \end{array} \tag{3}$$

where $\underline{S}$ is strain components vector; $\mathbf{s}^E$ is the matrix of compliance coefficients (^{E} denotes a constant electric field); $\underline{T}$ is the stress components vector; $\mathbf{d}$ is the matrix of piezoelectric strain coefficients (the prime notation denotes a matrix transpose); $\underline{E}$ is the electric field vector; $\underline{D}$ is the internal electric displacement vector; and ε^T is the matrix of dielectric permittivities (^{T} is stress component notation); and E is the electric field vector. The matrix of compliance coefficients $\mathbf{s}^E$ is associated to the short-circuit elastic moduli Y_i^E, i = 1, 2, 3 directions; and the Poisson's ratio of transverse strain υ_{ij} in the j direction to the axial strain in the i direction when stressed in the i direction; and short-circuit shear moduli G_{23}^E, G_{13}^E, G_{12}^E.

One can obtain information regarding the operating modes which can be employed by associating the datasheet information represented in the previous equations (1) and (2), such as the piezoelectric strain coefficients. The used PZT has "symmetric" properties for the plane (1 and 2 directions), thus by applying an electric field in 3 direction (thickness) the piezoelectric element will equally deform (for a square PZT) in the plane. However, the application of an electric field in thickness will also produce a very small strain in the thickness itself. The aforementioned directions are related to the "standard" Cartesian system coordinate which is demonstrated in literatures, such in [55].

3. SETUP AND DEFINITION OF EXPERIMENTAL TESTING PARAMETERS

The accuracy of the results achieved in any experimental testing is related to several aspects. Beyond the above mentioned aspects, it is of crucial importance to properly define the testing parameters for the data acquisition procedure. It requires a broad background in digital signal processing including analogue-to-digital conversion, Discrete Fourier Transform (DFT), frequency response analysis. One of those aspects is regarding to the knowledge of the employed instrumentation. The PVDF can be used to measure strain in a similar way to the one of conventional strain gauges, as long as the strain signal is dynamic [72]. Some works were performed comparing PVDF and strain gauge, *e.g.*, [73].

The employment of piezoelectric transducers for aeroelastic investigations can be done by constructing the FRF such as in a common Experimental Modal Analysis (EMA). Directly using the PVDF signal response (amplified) together with the excitation signal supplied to PZT, the FRF[3]. can be computed, so the FRF will be dimensionless (Volt/Volt). A suitable average number of a set of acquisitions (auto-correlation function) can be used to minimize the noise, thus improving the data acquisition. This allows eliminating the exogenous inputs in this procedure, once the noise tends to be a non correlated input.

The definition of testing parameters can be done (or confirmed) by means of fast investigations. For instance, these investigations can be conducted to help defining the excitation signal, FRF estimator, window function, average number and frequency resolution, which are better applied for the specific testing conditions. Commonly, excitation signals fall into four general categories: steady-state, random, periodic and transient [75]. Some characteristics and capabilities of excitation signals are usually analysed: RMS to peak ratio; signal to noise ratio; test time; leakage minimization; removes distortion; controlled frequency content; controlled amplitude content; nonlinearities characterization [76]. Comparisons between different excitation signals are widely performed *e.g.* [77] [78]. Focusing on the excitation to optimise the FRF measurements in presence of nonlinearities, the leakage reduction and elimination of nonlinearities distortions were assessed in [79].

The search for a proper selection of the excitation signal can be performed already considering the FRF estimator and window function. From experimental viewpoint, usually it is very easy to change the FRF estimator and window function, thus different calculated FRFs can be compared between each other in terms of both noise and ordinary coherence. Furthermore, for aeroelastic analyses, this can be very useful especially by conducting the investigation in a wind tunnel testing in pre flutter speed. Hence, these testing parameters are chosen aiming to improve the acquisition in worst and most important condition.

One of the most employed excitation signals is the random (pure), which according to [78] have the following advantages: fair general excitation type; fair signal to noise ratio; fair RMS to peak ratio; reduces distortion; good measurement test time; works well with zoom. Although, it has some drawbacks: leakage a serious problem; more averages required; poor characterization of nonlinearities.

When a finite length of time history is assumed as periodic, the leakage may appear. This problem is directly associated to the signal truncation and can be minimized by using a window

[3]It is a structural transfer function, although it is a unusual FRF (receptance, mobility or accelerance), several works can be found where the term FRF is employed since it is also subjected to the modal analysis foundation (the structure under test must be observable, linear, time invariant and obeys Maxwell's theory of reciprocity [74])

function such as uniform, hanning, hamming, blackman, Kaiser-Bessel, flat top and force window. The choose of a suitable window function is sometimes very difficult and none of them are able to completely extinguish the leakage. According to [80], it must be pointed out that the use of any window has an effect on the measured data, although it is a necessary evil in order to reduce the leakage effects. For random excitation, usually the hanning function is indicated to be applied in the reference (signal of excitation force) and response signals. Nevertheless, these windowing can cause amplitude distortions of as much as 16 %. Despite this distortion, it is better than if no window is used [80]. Other possibility for random signal is a hamming function which is best applied when the dynamic range is about 50 dB [81].

Other problem that can occurs, is the aliasing, which is directly associated to frequency resolution of acquisition. When a continuous signal in time is discretized, the frequency resolution (or sampling rate) should be sufficient to reproduce this signal. This problem is normally observed at high frequencies, lightly damped modes and closed modes, because higher frequency resolution is required. Therefore, the frequency resolution is a key factor for flutter identification. The Whittaker-Kotelnikov-Shannon (WKS) sampling theorem states that a signal can be perfectly reconstructed using a sampling rate of at least 2 samples per cycle [82], but to plot the curve shape, generally it is adopted a sampling rate of approximately 10 per cycle.

4. METHODOLOGY

In the present work, piezoelectric transducers were employed to perform aeroelastic investigation of a aluminum wing model with a ballast mass on the tip. Through wind tunnel testing, the modal parameters were estimated at each dynamic pressure condition until the pre-flutter speed is reached by using a single PVDF. The results were compared to those achieved by laser vibrometry which were acquired simultaneously. A single PZT was employed as actuator and the excitation signal was used to compute the FRFs for both techniques: SISO (Single -Input, Single Output) by PVDF response and SIMO (Single - Input, Multiple Output) by laser doppler vibrometers.

The testing model consist of a flexible beam model made of aluminum with an adjustable ballast mass on its tip as illustrated in the Fig. 1. This model is a clamped-free beam, where the points called "point00" and "point50" represents the clamped condition. By changing the ballast mass position, the distance of the elastic line to the cg (center of gravity) is altered, so the structure's dynamic behaviour is also changed. Wind tunnel testing was conducted for three different mass ballast conditions ($\varDelta CG$): 5 mm, 10 mm and 15 mm. For the first case (5 mm), the modal parameters achieved at each dynamic pressure condition were used to plot the v-g/v-f diagram and the pre-flutter speed (here expressed in terms of dynamic pressure) was reached. This v-g/v-f diagram permits to compare the PVDF and laser vibrometry results between each other, including the pre-flutter condition. The flutter speed also was estimated for other testing cases, $\varDelta CG\ = 10,\, 15,\, mm$ and the evolution of the natural frequencies of closed modes was plotted until pre-fluter condition. Aiming to verify the improvement on the acquired data in term of noise, different average numbers of set of acquisition (auto-correlation function) were used. For the first case ($\varDelta CG\ = 5,\, mm$) it was used an average number equal to 20 and for the remaining cases a very higher average number equal to 200 was used.

Before conducting the tests, the piezoelectric devices position should be defined. The PZT was embedded near the root aligned to $45°$ using the structural adhesive *3M™ Scotch-weld™ Epoxy Adhesive DP460 Off-White* [61]. Firstly, the PZT model PSI-5H4E was cut in the dimensions specified in the Fig. 1. In general, cutting the PZT in the desirable dimensions is a delicate procedure because it is very susceptible to be broken. Nonetheless, by applying a layer of isopropyl alcohol 99 % (or above 90 %) in a smooth glass, the piezoelectric ceramic sheet can be fixed and thus be safely cut using a simple thin cutting blade [83].

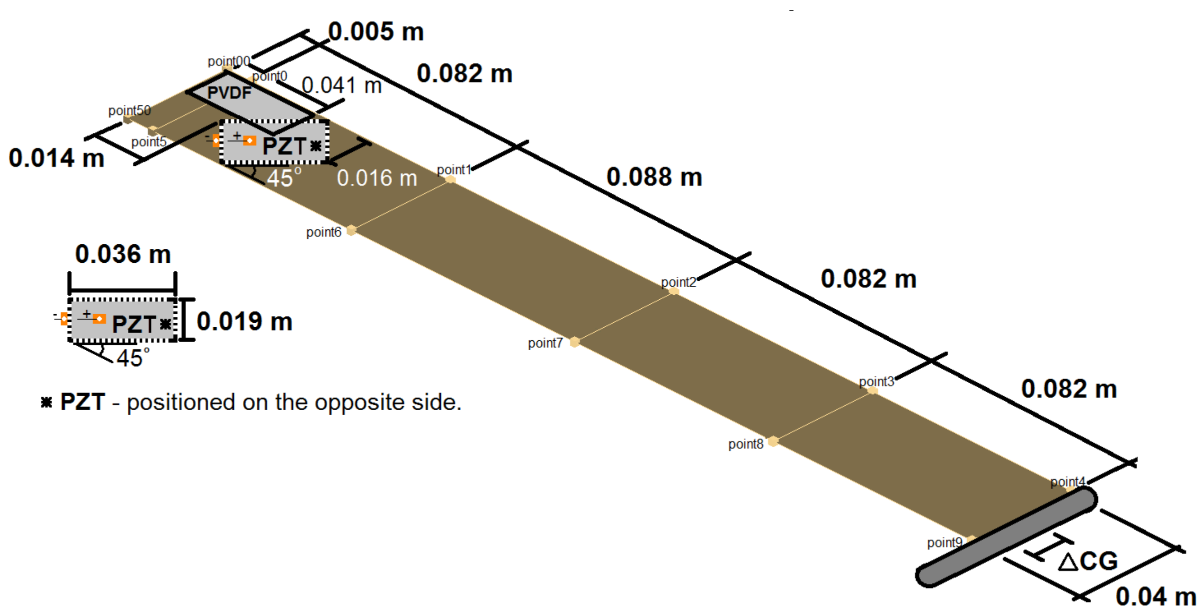
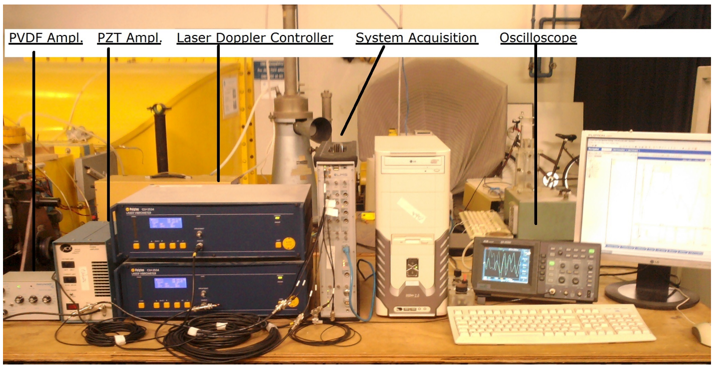


Figure 1. Testing model - positioning and dimensions of piezoelectric transducers.

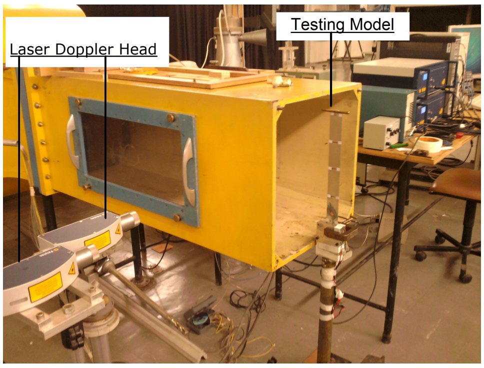
A single PVDF series model SDT1-028K was used as sensor and embedded near the root aligned to the testing structure (see Fig. 1) using a double-side adhesive. The use of double-side adhesive is recommended by PVDF datasheet [84], since it has the advantage of ease application besides allowing to remove and to reapply the PVDF.

The laser vibrometry was conducted using a Compact Laser Vibrometer (CLV) model $Polytec^{©}CLV-2534-2$ [85]. The wing model was tested for each one of the three mass ballast conditions and considering different speeds. Therefore, for comparison effect, it is indispensable that the available laser sensor heads always keep the position, thus the two sensor heads were employed to measure velocity at the points near the root namely “point0” “point5”. Due to the lower response of the points near the root, it can be set such that no overload appears even in pre-flutter condition. Velocity was used instead of displacement, because it can measure frequencies higher than 0.5 Hz. Worth remembering that by integrating or differentiating, it is possible to change the response between displacement, velocity and acceleration. Before each testing, the CLV was turned on for 20 minutes to stabilize, as indicate in CLV user’s manual [85]. Preferably, the signal intensity which is sensed by CLV should be above 70 %. This requisite is easily satisfied by simply adjusting the focus moving the lens or changing the distance of the target, since that in all tests it remained above than 90 %.

The experimental apparatus is shown in the Fig. 2. The data acquisition procedure was conducted by using the $LMS^{©}SCADASIII^{®}$ hardware with $LMS^{©}SpectralTesting^{®}$ software. The excitation channel (commonly used in the shaker device) was used to supply the Piezo Power Amplifier model $QuickPack^{®}QPA202$. The excitation signal, type random (pure), after amplified to $\pm$ 50 V (100 V considering peak to valley) was supplied to the PZT. The FRFs for both techniques (PVDF and CLV) were computed by applying a hanning window function to the excitation signal and using it as reference. An amplifier was used to increase PVDF response before supplying it to the acquisition system. All the selected parameters were defined by consulting the respective user's manual or after conducting a specific investigation.



(a) Instrumentation



(b) Wind Tunnel Testing

Figure 2. Experimental Apparatus

The wind tunnel has an open test section and the testing model is mounted in a rigid base , Fig. 2. Aiming to verify any influence of the base, one accelerometer was employed to measure the base response. One oscilloscope was used to confirm the excitation signal intensity and also to show in "real time" the structure response by CLV. This monitoring is very important, because it is another tool to identify if the pre-flutter boundary is almost reached. If the boundary was exceeded the wind tunnel speed should be immediately turned off to avoid breaking the PZT.

Keeping the testing parameters for all tests, the modal parameters (natural frequencies and damping factors) were estimated using the *LMS Test.Lab* $Polymax^{®}$ modal identification method. This method has good capability to work with noisy data [86]. The modal parameters were estimated by choosing the first stable root which presented repeatability for damping factor estimation. For this procedure, it was used the default tolerances (2 % to vector, 1 % to frequency, 5 % to damping and 32 to model size).

5. RESULTS

With the testing model with the mass ballast positioned at 5 mm, the modal parameters (natural frequencies and damping factors) were achieved for no dynamic pressure condition using a single PVDF and two CLV responses. Afterwards, a wind tunnel testing was conducted for different dynamic pressures until pre-flutter condition. The v-g/v-f diagram was plot using the modal parameters identified for each condition.

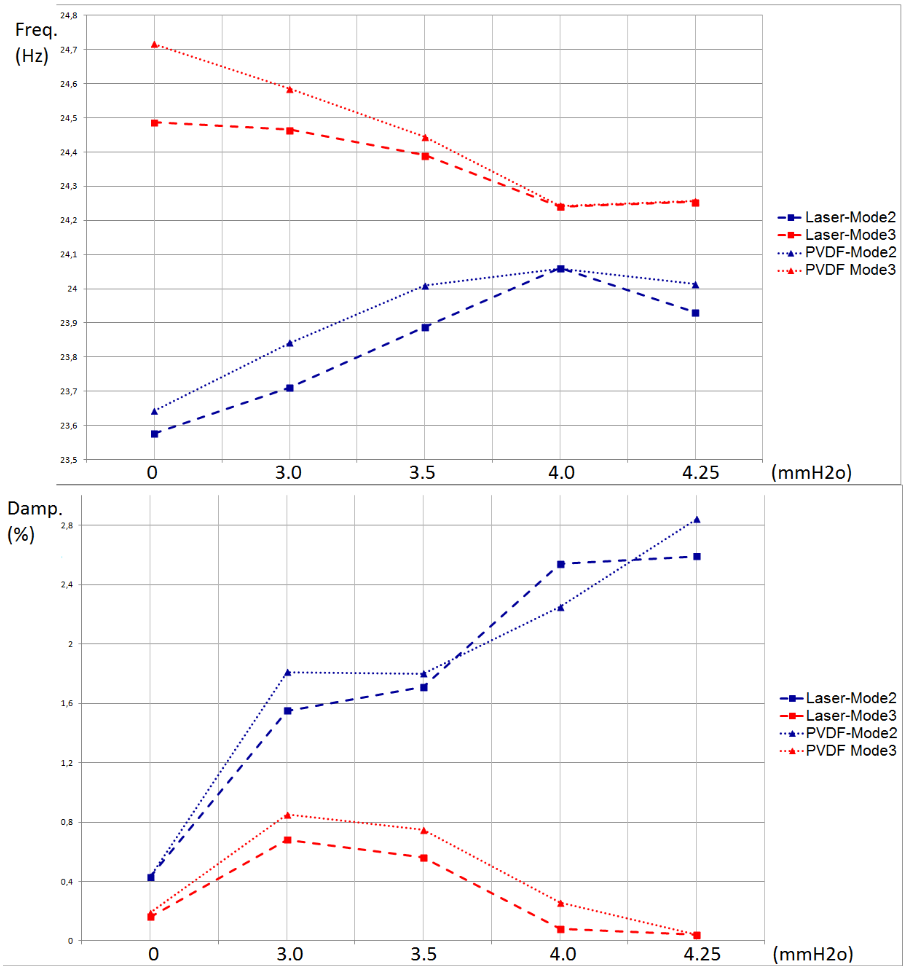
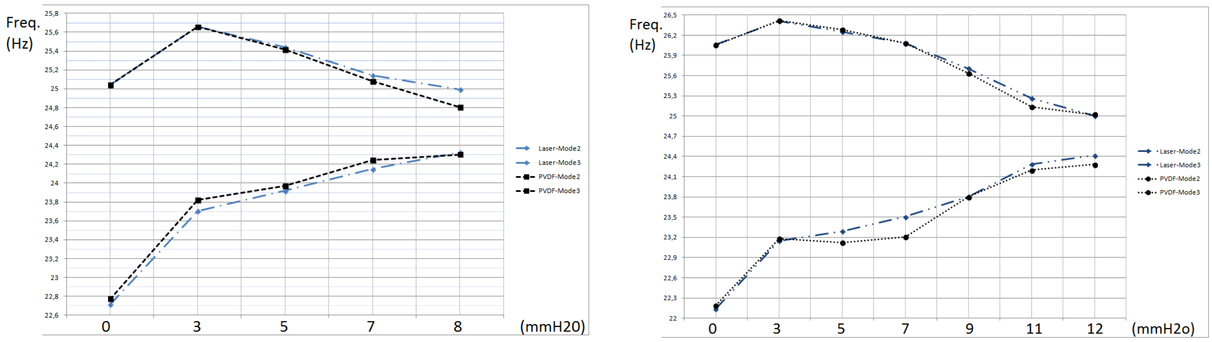


Figure 3. 5 mm - v-g/v-f Diagram.

As can be seen in the Fig. 3, the v-g/v-f diagram shows very close results. The evolutions of both, frequencies and damping factors, as function of dynamic pressure were well characterized using a single PVDF response. Same damping result (0.04 %) was achieved for 3^{rd} vibration mode at the pre-flutter condition. This mode corresponds to the critical flutter mode which tends to be negative while the 2^{nd} mode is increased. This is a typically observed flutter behaviour. The identified flutter speed corresponds to dynamic pressure equal to 4.25 mmH_2o, once it was not possible to increase the dynamic pressure without exceeding the flutter boundary. It is worth remembering that only 20 averages number of set acquisition was used.

Using a higher average number equal to 200, the same procedure was employed for the other mass ballast conditions. The flutter speed will increase together this distance (ΔCG), which means that a higher noise level tend to be input on the acquisition. Despite being the worst noise condition, very good results were obtained. As can be seen in the Fig. 4, a high average number shows an even better results accordance. For the mass ballast condition ΔCG = 10 and 15 mm, the flutter speeds were estimated as corresponding to 8 and 12 mmH_2o of dynamic pressure, respectively.



(a) 10 mm (b) 15 mm

Figure 4. Closed Modes Evolution.

6. CONCLUSIONS

By comparing the results achieved by a single PVDF and two CLV responses between each other, a high accordance was found. The modal parameters were estimated for each dynamic pressure using a single PVDF response until the pre-flutter condition. By analysing these results, the flutter speed associated to the correspondent dynamic pressure was estimated to each testing case. The excitation signal was used as reference to compute the FRFs for both techniques, a high average number (200) of a set acquisitions employed in the mass ballast condition 10 and 15 mm shows a good capability to eliminate exogenous input. Using a single PZT transducer as actuator, both bending and torsion vibration modes for the frequency range of interest (until 200 Hz) were successfully excited. The employment of EMA methodology allowed to achieve FRFs with low noise levels, considering that the tests were performed in a very noisy environment.

Despite the low thickness and flexibility, the PVDF can be very intrusiveness to the results, since that the testing model is also very flexible, thus becoming more susceptible to instrumentation influence [87]. Nevertheless, very good results were achieved by using a single PVDF, SIMO methodology tends always to be more accurate.

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