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WIND TUNNEL EXPERIMENT ON A PITCH AND PLUNGE FREE AIRFOIL UNDER TRANSONIC BUFFET

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ABSTRACT

ONERA conducted aeroelastic tests of an OAT15A airfoil mounted on a pitch and plunge Degrees Of Freedom (2 DOF) test setup, subjected to aerodynamic buffet, at ONERA Meudon S3Ch wind tunnel facility, in order to investigate potential fluid-structure interactions (FSI). The test setup allowed for independent tuning of the frequencies of the structural modes related to the pitch and plunge DOFs. A selection of test configurations was investigated, varying the number and the tuning of the DOFs, the Mach number and the angle of attack.

For certain test configurations, with pitch DOF enabled (either in 1 or 2 DOF configuration), an aeroelastic coupling occurs between buffet and structural modes. The magnitude of the dynamic response was very significant and reached LCOs within seconds.

1. INTRODUCTION

Turbulent boundary layer shock wave interactions (TBLI) in flows past airfoils can cause large flow separation and, for certain flight conditions, yield large amplitude self sustained instabilities, a phenomenon known as transonic shock buffet. The phenomenon has been the subject of many investigations, including many wind tunnel test campaigns both on rigid and flexible wings [1][2]. The presence of structural degrees of freedom can lead to aerodynamic / structural couplings, such as lock-in phenomena and limit cycle oscillations (LCO), which can dramatically affect the integrity of the wing. Numerical studies [3][4][5][6][7] have shown to be capable to predict some of these phenomena depending on parameters such as Mach number, angle of attack, mass ratio or the ratio between shock buffet and structural relative natural frequencies. The results of these predictions served as guidelines for the design and test matrix of this wind tunnel test cam-

paign. In particular a lock-in phenomenon is known to occur when pitch and plunge frequencies are higher and lower, respectively, than that of the shock buffet [4][5]. As a consequence the test setup was sized and designed accordingly to investigate these conditions. The present wind tunnel test campaign aims at characterizing this type of Fluid Structure Interactions (FSI) and other that potentially occur on a 2D supercritical airfoil suspended to adjustable and independent plunge and pitch DOFs.

2. EXPERIMENTAL TEST SETUP

The present study was carried out in the continuous closed-circuit transonic S3Ch wind tunnel of the ONERA-Meudon Center. This facility is powered by a 3500 kW two-stage motor-ventilator group and has a test section size of 0.78 x 0.78 x 2.2 m. The Mach number domain extends from 0.3 to 1.2. The stagnation pressure is the atmospheric pressure, and the stagnation temperature ranges between 290 and 320K. The wing is installed upside down in the wind tunnel. Interference effect due to the wall confinement are minimized by adapting the shape of the upper wall of the test section, so that the two-dimensional flow setup provides uniform flow conditions in the test volume, accounting for the image effect of the flow about the lower wall.

The test setup used for the test campaign can be seen in Fig. 1. Splitter plates are used in order to eliminate the influence of the residual leakage at the wind tunnel side walls. Both DOF stiffnesses and the corresponding natural frequencies can be tuned by moving a sliding part along the free length of the specific parts designed to act as longitudinal or torsional springs for the plunge and pitch DOFs, respectively. For instance, increasing the parameter $L_{pitch/axis}$ increases the free length of the pitch blade part, that increases the flexibility to the pitch DOF. In a similar manner, the diamond shaped spring responsible

for the spring stiffness is at its maximum stiffness when clamped at its highest setting, and flexibility is added when lowering the position of the clamping. This setup is an evolution of the one used in a previous test campaign [8].

The model is an OAT15A airfoil with the following characteristics:

- Relative thickness: 12.3%
- Chord: 250mm
- Span: 752mm between splitter plates (aspect ratio AR: 3)
- Trailing edge thickness: 0.5% of the chord length

Instrumentation was defined to characterize both the structural movements of the model and the aerodynamic steady and unsteady behaviour. The distribution of sensors and pressure taps is displayed in Fig. 2. It consists of the following elements:

- 6 accelerometers,
- 46 static pressure taps,
- 36 unsteady pressure transducers,
- 4 optical telemeters.

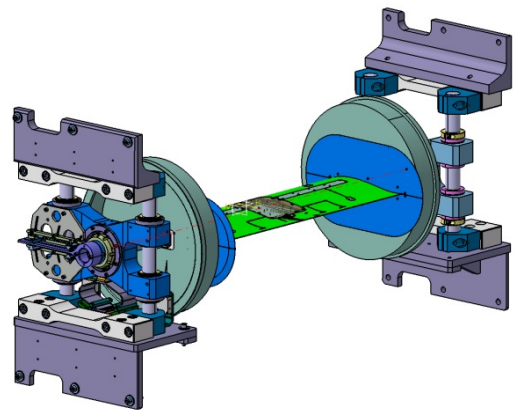
Stereo 3C PIV was implemented using the following devices and settings :

- 2 Phantom V711 cameras
- High-speed laser (1KHz): Photonics DM30-527
- Various Space & Time sampling (up to 6000 images and 2kHz, depending on the size of the Region of Interest - ROI)

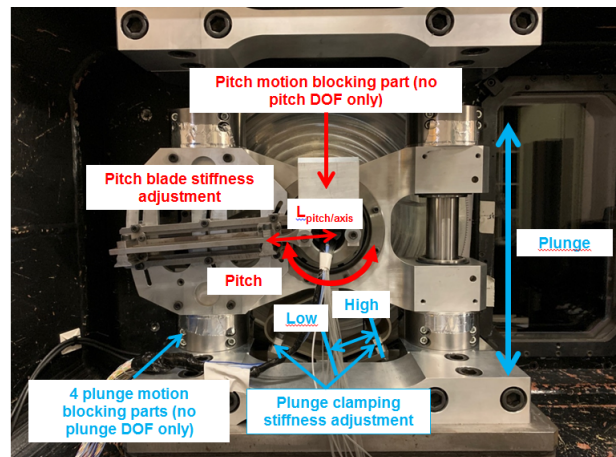
The first step was to assess the actual structural dynamic frequencies of the pitch and plunge DOFs. This was done in a dedicated laboratory, as shown in Fig. 3, in which boundary conditions similar to those of the wind tunnel tests are reproduced. Tests were carried out with variations of the DOFs stiffnesses. Independence of the pitch and plunge DOFs was successfully demonstrated. PIV measurements have not been post processed in detail yet, and therefore are not part of this proceeding.

3. WIND TUNNEL TESTS

During the wind tunnel campaign, the different DOF configurations were tested, namely: rigid (0 DOF), 1 DOF at a time (pitch or plunge) with various stiffnesses, and 2 DOFs simultaneously (pitch and plunge). A view of the model inside the wind tunnel test section can be seen in Fig. 4, and a summary of the test matrix is shown in Table 1. Only the Mach number could be varied inside a test run, any other configuration change (angle of attack, stiffness setting of a DOF) required to stop the wind tunnel and perform a new test run.



(a) CAD view of the test setup



(b) Description of the DOFs adjustments (in presence of additional blocking parts for 0 DOF configuration)

Figure 1: Experimental test setup description

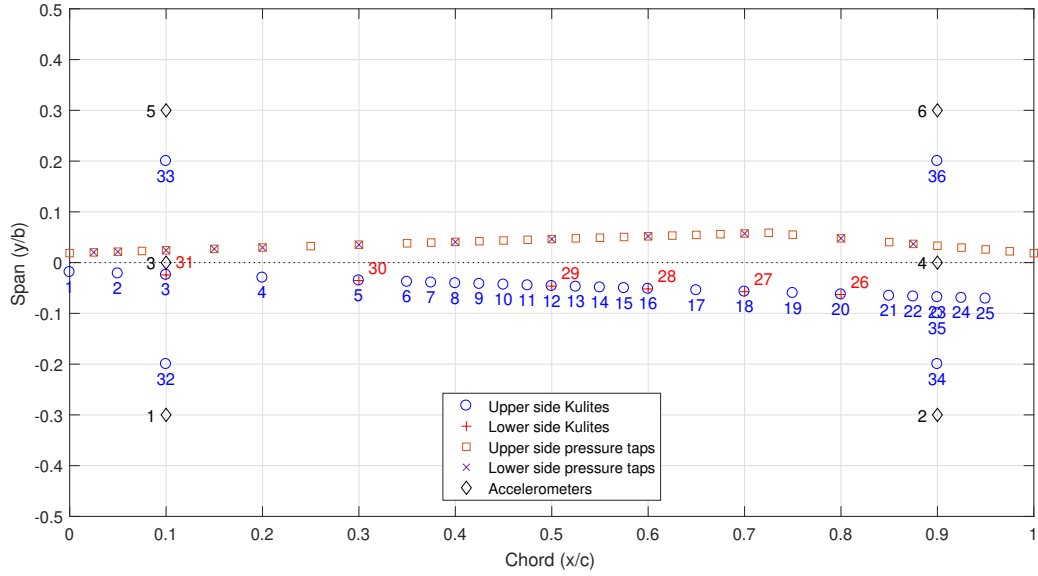


Figure 2: Spatial localization of the sensors and pressure taps implemented in the test model.



Figure 3: Experimental setup for the preliminary laboratory testing of the structural modes of the model.

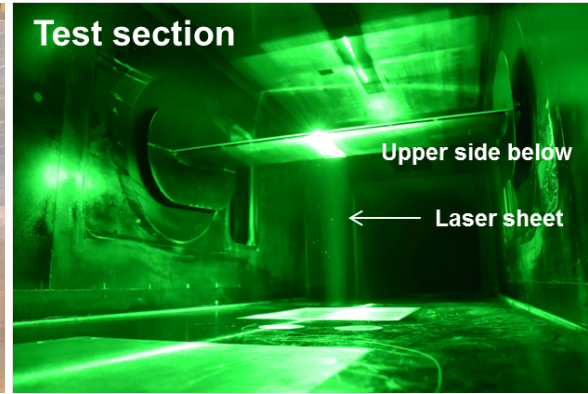


Figure 4: View of the model inside the test section of the S3Ch wind tunnel. The impact of the laser sheet at the upper surface of the airfoil is also shown. The wing is placed upside down.

Table 1: Summary of the test matrix

Configuration	Number of test runs	Angle of attack (°)	DOF setting adjustment	Mach variations
0 DOF	21	0° to 4°	Blocked	0.5 → 0.75 Focus on Mach 0.68 to 0.72 for all configurations
1 DOF: plunge	10	2° to 4°	Low, medium or high Higher is stiffer	
1 DOF: pitch	31	2° to 4°	$L_{pitch/axis} = 63 / \mathbf{80} / \mathbf{100} / 120 / 130\text{mm}$ Lower is stiffer	
2 DOF: pitch & plunge	36	3.5°	Plunge: high $L_{pitch/axis} = 100\text{mm}$	

3.1 0 DOF rigid and 1 DOF plunge configurations

The objective of the rigid configuration investigations was to characterize the occurrence of buffet for different Mach numbers and angles of attack. A synthesis of the main findings is given thereafter. First, transonic shock buffet is observed for angles of attack larger than $\alpha=3.25^\circ$, in a range of Mach numbers from approximately $M=0.69$ to $M=0.72$. These results are slightly different from the ones observed in [1] and [2] for the same OAT15A airfoil. The best explanation for these discrepancies is that this previous test campaign uses the top and bottom adaptive walls, while the current one only uses the upper wall and account for the lower flat wall by an image effect. As a result the flow is corrected for a pair of opposite airfoils. Besides although with 0 DOF the current setup is not as stiff as in [1], which can lead to the observed discrepancies. Indeed, a bending mode is present along the span of the model in the frequency range of interest (around 90Hz depending on test parameters). This mode adds a 3D structural response to the theoretical 2 DOF test setup, not taken into account in 2D numerical simulations. The impact of this bending mode on the observed couplings is significant and will be discussed in more detail later in this paper.

Eventually with the plunge DOF a small difference in the establishment of the buffet was observed. It starts at $\alpha=3.5^\circ$, and the amplitude of the structural response is reduced. In addition, no lock-in between aerodynamic and structural frequencies was observed for this 1 DOF plunge only configuration.

3.2 1 DOF pitch only configuration

Most of the test campaign has been devoted to exploring configurations that include the pitch DOF (either in 1 or 2 DOF configurations). With this DOF, fluid structure interactions and lock-in phenomena are observed.

First, the 1 DOF pitch only configuration was devoted to investigate a large number of testing conditions, including various angles of attack and pitch stiffness settings. The aim was to assess their impact on the onset of buffet and the occurrence of a lock-in between the aerodynamic buffet and structural frequencies. Fig. 5, which shows the occurrence of buffet and lock-in in the map Mach and angle of attack, summarizes the results for the three settings of pitch stiffness, from the most rigid ($L_{pitch/axis} = 63mm$) to the most flexible ($L_{pitch/axis} = 100mm$). In the latter configuration higher angles of attack were not tested due to the large magnitude of the dynamic response. The amplitude of the dynamic response, whether buffet or lock-in, can vary substantially along the parameter range. For the most part, transonic shock buffet consistently appears from $M=0.69$ to $M=0.71$. It also appears at $M=0.67$ following an increase of the angle of attack to $\alpha=4^\circ$. Lock-in

systematically occurs at $M=0.70$ and $M=0.71$, and even starts at $M=0.69$ when the test setting is more flexible, as seen in Fig. 5b and Fig. 5c.

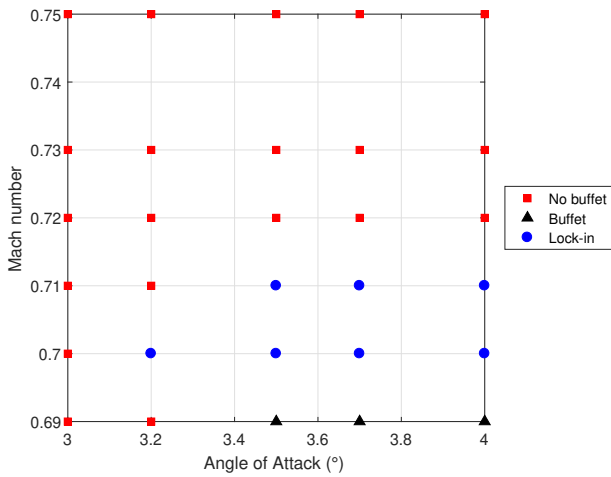
Apart from the increase of the dynamic response with the angle of attack, the magnitude of the response also keeps on increasing when the pitch frequency is set closer to the frequency of the buffet dynamics. For the sake of safety, the test matrix does not include test points where both (pitch and buffet) were supposed to have a similar frequency. A test configuration was selected as the reference configuration ($\alpha=3.5^\circ$, pitch setting $L_{pitch/axis} = 100mm$, plunge setting: high position), for which the coupling phenomenon consistently occurs.

3.3 2 DOF pitch and plunge configuration

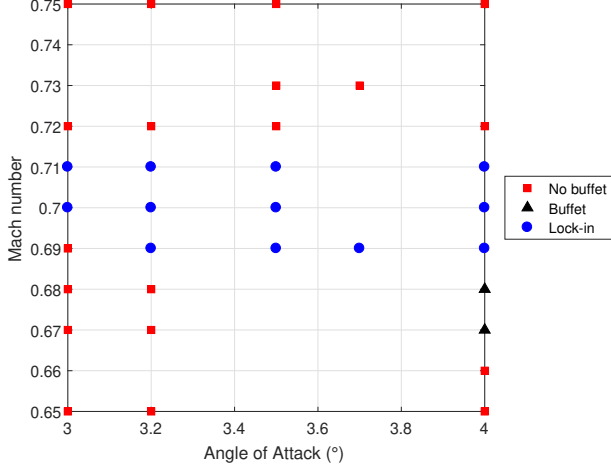
Most of the test runs performed in the 2 DOF pitch and plunge configuration have been dedicated to detailing the reference configuration ($\alpha=3.5^\circ$, pitch setting $L_{pitch/axis} = 100mm$, stiffest plunge setting). Measurements were performed in order to investigate the buffet onset, the transient behaviour of the coupling leading to the lock-in phenomenon, the stabilized lock-in and the offset of the lock-in and buffet altogether. In order to do so, Mach number was initially set below buffet onset, then increased until the appearance of buffet, increased further until a FSI coupling occurs, and increased even further (or decreased) until the FSI behaviour disappears. Spectrograms are plotted showing these four phases, as for instance on Fig. 6, which shows the transformed signal from an unsteady sensor located at the trailing edge and an accelerometer installed inside the model. In Fig. 6 time reads vertically and the evolution of the Mach number is shown at the right. The unsteady sensor spectrogram (Fig. 6a) shows the aerodynamic response, with the buffet onset and the appearance of the coupling, and the end of both coupling and buffet.

The accelerometer spectrogram (Fig. 6b) allows to visualize both the aerodynamic and the structural response. This helps understanding the coupling mechanism. Operational Modal Analyses (OMA) were performed, and allowed to identify the structural modes and frequencies of the model, for each stage of the phenomenon. In the spectrogram in Fig. 6b the peak consistently present around 50Hz corresponds to the plunge frequency, while the one around 100Hz refers to the bending frequency of the model along its span and the one around 120Hz to the pitch frequency. All the peaks that feature frequencies above 150Hz are harmonics of the former.

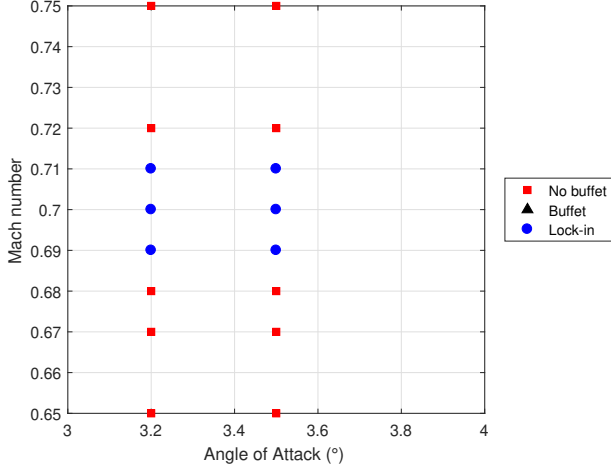
Fig. 6b shows that once buffet sets in, a slight increase of the Mach number leads to a convergence of the buffet and pitch frequencies towards the bending frequency. This phase corresponds to a non intuitive fluid structural coupling that potentially implies several elementary dynamics of the model and flow. The intensifying red color of the peak indicates the sudden increase in the magnitude



(a) $L_{pitch/axis} = 63mm$ (more rigid)



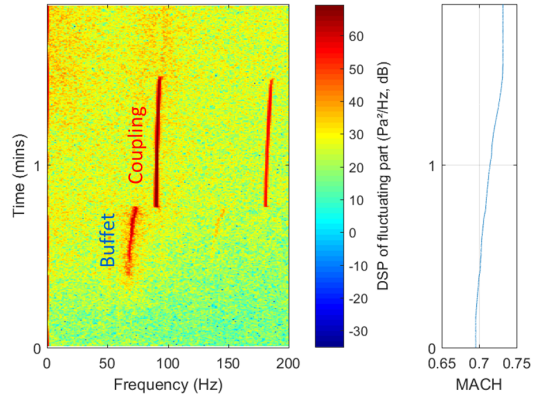
(b) $L_{pitch/axis} = 80mm$



(c) $L_{pitch/axis} = 100mm$ (more flexible)

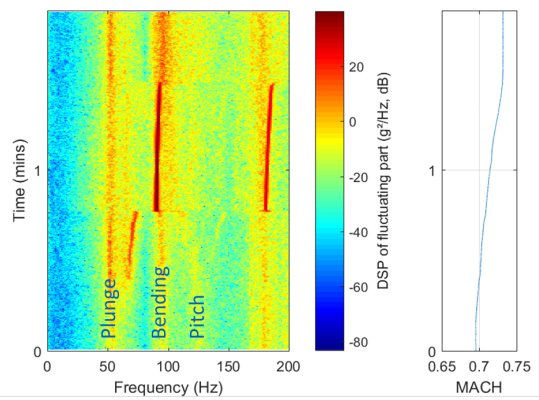
Figure 5: Buffet and lock-in occurrence maps as a function of Mach number and angle of attack for different pitch stiffness settings

DSP of fluctuating part : KE24



(a) Unsteady sensor (KE24, $x/c=0.925$)

Acc - DSP of fluctuating part : Acc1



(b) Accelerometer 1 ($x/c=0.1, y/b=-0.3$)

Figure 6: Spectrograms showing all phases of transient behaviour for $\alpha=3.5^\circ$ and varying Mach number from 0.69 to 0.72 on an unsteady sensor and an accelerometer

of the dynamic response once the coupling is reached. The attraction of the bending mode upon buffet and pitch suggests a lock-in phenomenon.

4. CONCLUSION

A wind tunnel test campaign has been performed at ONERA S3Ch transonic tunnel, in order to explore the aeroelastic response of an OAT15A supercritical profile subjected to 2 DOFs in conditions of transonic upstream flow and shock buffet. Fluid structure interactions could be observed repeatedly, for various test conditions, which includes a large magnitude dynamic response, aeroelastic coupling and a lock-in phenomenon between the transonic shock buffet and the structural modes of the model. The lock-in could only be observed when the pitch DOF was enabled, and was present with or without the plunge DOF. Further analysis of the database is required to further understand the phenomenon.

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