

AERODYNAMIC AND AEROELASTIC CHARACTERIZATION OF A FORWARD-SWEPT, LAMINAR AIRCRAFT WING UNDER REALISTIC FLIGHT CONDITIONS

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Abstract: This study presents the aerodynamic and aeroelastic characteristics of a forward-swept laminar wing model tested in a cryogenic transonic wind tunnel under flight-relevant Mach and Reynolds numbers. A novel pitch oscillator enabled forced pitch oscillations, allowing for dynamic load and response analysis. Static tests reveal typical lift and drag trends with increasing Mach number, accompanied by increased bending deformation and reduced twist. Pressure measurements at four spanwise locations identify a spanwise-shifting shock system, including a double-shock structure near the root, which emerges only above critical flow conditions. Unsteady acceleration data show amplified tip accelerations and stronger trailing-edge responses, whose frequency spectra reveal the structural eigenmodes with slight shifts due to aerodynamic effects. Unsteady pressure coefficients reveal a distinct phase shift at the shock location, causing a significant lag in the pressure response relative to angle of attack. Overall, the results provide a detailed insight into the coupled aerodynamic and aeroelastic behavior of a forward-swept, laminar wing under transonic flow.

1 INTRODUCTION

The need for reducing one's emissions is commonly shared among many organizations within the aerospace industry. Among other strategies, one approach is to develop novel wing designs that may offer improved lift and drag characteristics, thus being aerodynamically more efficient. In that regard, forward-swept wing (FSW) configurations are receiving renewed attention [1–6] owing to their potential advantages in aerodynamic performance – e.g., improved lift distribution, low wave drag – compared to conventional backward-swept wings. In particular, when combined with airfoil shapes that feature a naturally laminar flow (NLF), these benefits can be amplified: by minimizing skin friction drag associated with maintaining extensive laminar boundary layers, an FSW configuration may achieve higher aerodynamic efficiency, overall. At this stage, it is worth noting however that FSWs come with aeroelastic challenges, e.g., the risk of torsional divergence due to outboard bending-torsion coupling, flutter, and dynamic loads due to inflow gusts or model excitations. In particular, the latter is a prominent topic within the aeroelasticity community, with gust- and maneuver-load experimental and numerical studies being conducted in almost all groups and/or institutes across the globe. Yet, only few research teams have access to transonic wind tunnel facilities and even less can perform transonic tests at flight-realistic flow conditions, which is where the present study contributes.

To investigate the aerodynamic and aeroelastic characteristics of a forward-swept wing configuration with a naturally laminar flow design, a scale model is experimentally tested at realistic flight conditions (i.e., in terms of Mach and Reynolds numbers) in a wind tunnel. A wide range of advanced measurement equipment are employed to capture steady and dynamic aerodynamic loads, pressures, and accelerations. Besides, using temperature-sensitive paint and a marker tracking system, the surface flow (e.g., transition behavior) and model deformation (e.g., bend, twist) characteristics are measured. The experimental setup allowed the model to be kept at a steady angle of attack or to be applied a forced dynamic pitch motion using a state-of-the-art pitching oscillator (for further details the reader is referred to [7]). The work presented here is part of the German Aerospace Research Programme (Luftfahrtforschung, LuFo) VI/1 and VI/2 projects “Wing Technology Validation for Ultra Green Aircraft” (ECOWING-D) and “Ultra High Efficient Wing and Movables for Next Generation Aircraft” (ULTIMATE). The present paper is organized as follows: Section 2 describes the experimental means and setup employed within the test campaigns, including the wind tunnel facility, the wing model, the measurement equipment, as well as the test conditions. Then, Section 3 covers steady and unsteady characteristics of the wing model across various test conditions, outlining common trends and specific dependencies. Finally, conclusions and perspectives are provided in Section 4.

2 EXPERIMENTAL MEANS AND SETUP

In this section, the wind tunnel facility, the wing model and its instrumentation, and the experimental test conditions are discussed.

2.1 Experimental Facility

The experimental campaigns are conducted in the European Transonic Windtunnel (ETW), which is a closed-vein, closed-circuit wind tunnel whose test section extends over 2.0 m (H) $\times$ 2.4 m (W) $\times$ 9.0 m (L) – see Fig. 1. The flow conditions in its test section can be varied by adjusting the Mach number ($Ma = 0.15 - 1.35$) and the total pressure ($p_{tot} = 115 - 450$ kPa). In addition, a high-Reynolds-number flow condition can be achieved for a model-scale aircraft wing due to the cryogenic nature of the wind tunnel [8]. More specifically, the tunnel is operated using nitrogen gas, which is injected downstream of the test section (cf. Fig. 1) in its liquid form with temperatures of approximately $T = 110$ K, leading to total temperatures of $T_{tot} = 110 - 313$ K. Owing to these low gas temperatures, and coupled with the high-speed flows, a scaled-down aircraft wing model can realize realistic, full-scale flow conditions (i.e., in both, Mach number and chord-based Reynolds number).

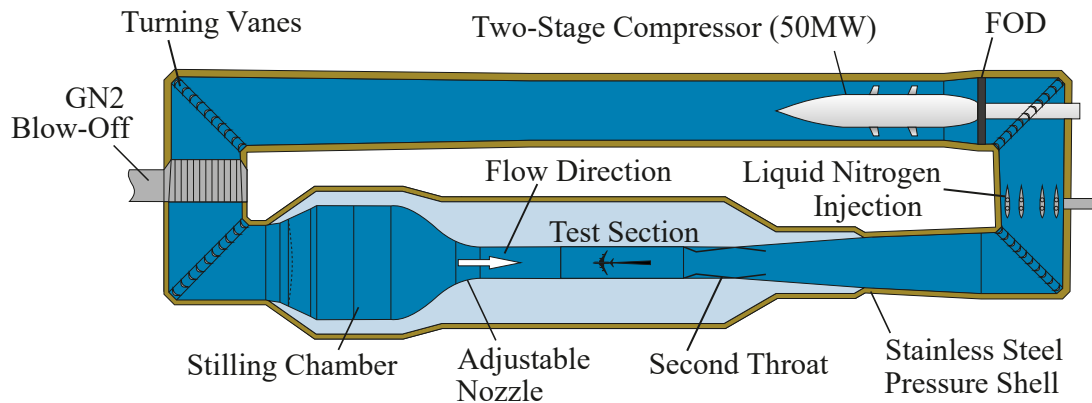


Figure 1: Schematic of the European Transonic Wind Tunnel (copyright ©ETW).

Together with the Institute of Aeroelasticity at DLR, the ETW test section gains the capability of

dynamically exciting a wing model by means of a state-of-the-art pitch oscillator, which enables pitch oscillations with variable frequency and amplitude (see Fig. 2). As an example, Figs. 2(b) and 2(c) respectively depict the angle-of-attack time history and spectra when the wing model is sinusoidally excited with a pitch oscillation of frequency $f_{osc} = 29.5$ Hz and amplitude $A_{osc} = \pm 0.5^\circ$.

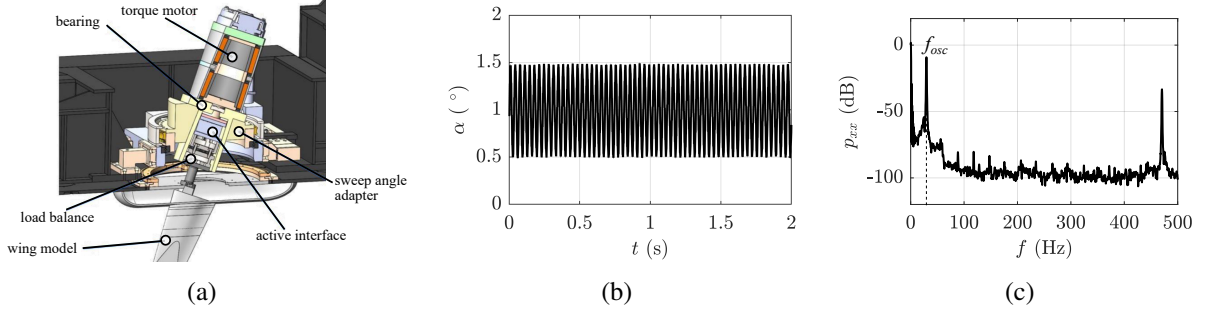


Figure 2: Pitch oscillator design and capabilities: CAD view of the setup (a), time-history signal (b) and power spectral density (c) of the dynamic angle-of-attack excitation.

2.2 Wind Tunnel Model

The so-called NLF-ECOWING-FSW configuration tested here is a forward-swept, semi-span wing model with naturally laminar flow design, which is based on the TuLam short- to medium-range aircraft [9]. The wing model is mounted to the tunnel ceiling via a fuselage and belly fairing (see Fig. 3). It is equipped with a large number of sensors, among which steady and unsteady pressure (Kulites) transducers as well as acceleration (PCB) and temperature sensors. More specifically, it features 62 static pressure ports at its most inboard crosssection (near the root) and 25, 20, and 16 unsteady pressure sensors at the midboard, outboard, and tip cross-sections, respectively. Acceleration sensors are located at five spanwise positions, with one near the leading-edge and another closer to the trailing-edge. At the intersection to the tunnel ceiling, the wing root is mounted on a piezoelectric 6-component load balance, which allows to capture dynamic force and moment data. The wing planform is coated with four patches of cryogenic temperature-sensitive paint (cryoTSP [10, 11], see Fig. 3(a)), which are applied to capture laminar-to-turbulent transition characteristics. In addition, stereo pattern tracking (SPT) markers are placed onto the model pressure surface to capture wing deformations (i.e., bend and twist) - see Fig. 3(b). Before the wind tunnel tests, structural assessments are performed to identify the model's structural eigenfrequency and eigenmodes. To excite the wing structure, the model is struck at arbitrary locations across its planform. The structural response is measured using the acceleration sensors installed in the model. As reference, eigenmodes and their corresponding frequencies are obtained for the wing model when the piezoelectric balance is turned off and the brakes for the turntable and pitch oscillator are respectively engaged and open. Results for the most relevant modes are summarized in Table 1.

Table 1: Structural eigenmodes and corresponding eigenfrequencies of the wing model, as obtained from the structural test performed before the wind tunnel test.

Mode	Description	f , Hz
1	1. bending	25.02
2	2. bending	115.66
3	1. torsion	273.74

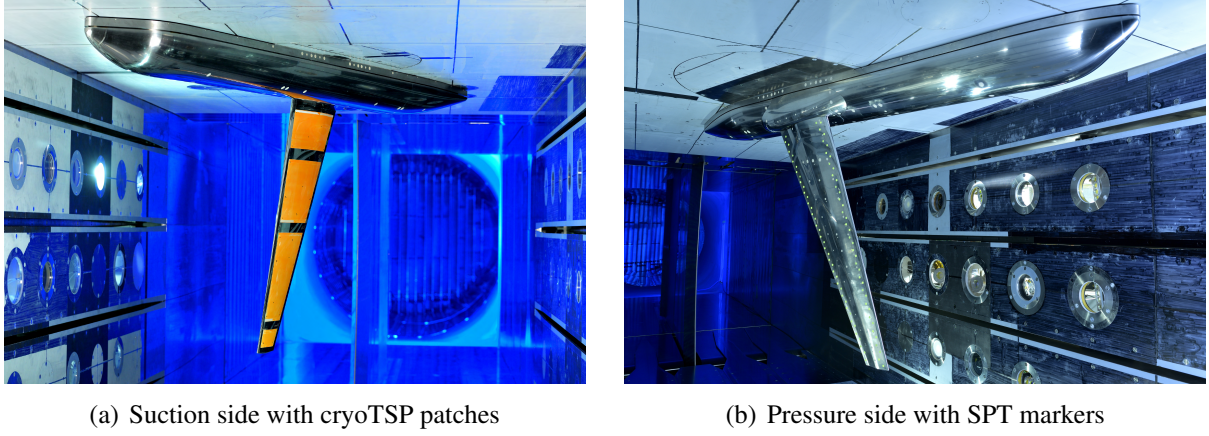


Figure 3: The FSW-NLF wing model with a fuselage and belly fairing installed in the test section (copyright ©ETW/Airbus/DLR).

2.3 Experimental Matrix

Throughout the wind tunnel test campaigns, an extensive test matrix is explored, including - but not limited to - various Mach numbers, total temperatures and pressures, and thus several chord-based Reynolds numbers. The model incidence could be varied in both, a (quasi-)steady fashion for measuring aerodynamic polars and in high-frequency dynamic pitch oscillations for investigating the wing's unsteady behavior. A summary of the possible test conditions is provided in Table 2, of which, for the sake of conciseness, only a subset will be discussed in this paper. At this stage, it is worth noting that the experimental conditions are explored over two separate test campaigns, labeled "Performance Test" and "Dynamic Test", which featured the same wing model, yet with a different mounting setup. In the subsequent work, the steady results (i.e., aerodynamic polars, bending and twist distributions) are obtained during the Performance Test, which covered wider incidence and Mach number ranges, whereas the unsteady (thus dynamically excited) results originate from the Dynamic Test featuring the pitch oscillator. This being said, a common reference, or "baseline", condition is chosen, for which a more detailed investigation is conducted. This baseline condition refers to $Ma = 0.78$, $Re_c = 16 \times 10^6$ (i.e., $T_{tot} = 124.0$ K, $p_{tot} = 122.2$ kPa), with the model's upper-side transition being free and - for what concerns the dynamic results - a pitch oscillation being enforced as described in Fig. 2.

Table 2: Summary of experimental test conditions covered in both, Performance and Dynamic Test campaigns.

Parameter	Range
Mach number, Ma	0.20 - 0.82
Reynolds number, Re_c	6 - 16×10^6
Angle of attack, α	$-3.5 - 4.0^\circ$
Oscillation amplitude, A_{osc}	$0.05 - 0.5^\circ$
Oscillation frequency, f_{osc}	0 - 92.1 Hz
Non-dimensional oscillation frequency, k	0 - 0.4

3 RESULTS AND ANALYSIS

This section describes the steady and unsteady characteristics of the NLF-ECOWING-FSW model, in regard to both its aerodynamic and aeroelastic behavior across various flow conditions.

3.1 Steady Characteristics

First, Fig. 4 depicts the wing's coefficients in lift (C_L), drag (C_D), pitching moment (C_{M_y}), and rolling moment (C_{M_x}) as a function of the angle of attack across a range of Mach numbers ($Ma = 0.76 - 0.82$). As can be seen, the lift coefficient steadily increases when the model is pitched to higher angles of attack, with some small lift drop occurring around $\alpha = 3.5^\circ$ when the Mach number is not large enough. For instance, once the flow becomes sufficiently fast, flow separation appears to cause this abrupt lift drop at the higher incidence. The drag coefficient follows a rather common behavior, gradually increasing as the incidence becomes higher. As the model incidence exceeds $\alpha = 0^\circ$, the drag coefficient gradient becomes significantly higher, as would be expected by the larger wing area facing the inflow. What concerns the moment coefficient polars, both are seen to steadily increase over the angle of attack; The pitching coefficient, however, exhibits a change from "nose up" to "nose down" directions when going beyond a certain incidence angle (i.e., $\alpha \geq 2.5^\circ$). All coefficients are seen to depend on the Mach number, such that the lift and rolling moment coefficients decrease whereas the drag coefficient increases as the Mach number gets higher. Notably, only the pitching moment coefficient exhibits less clear trends towards the Mach number.

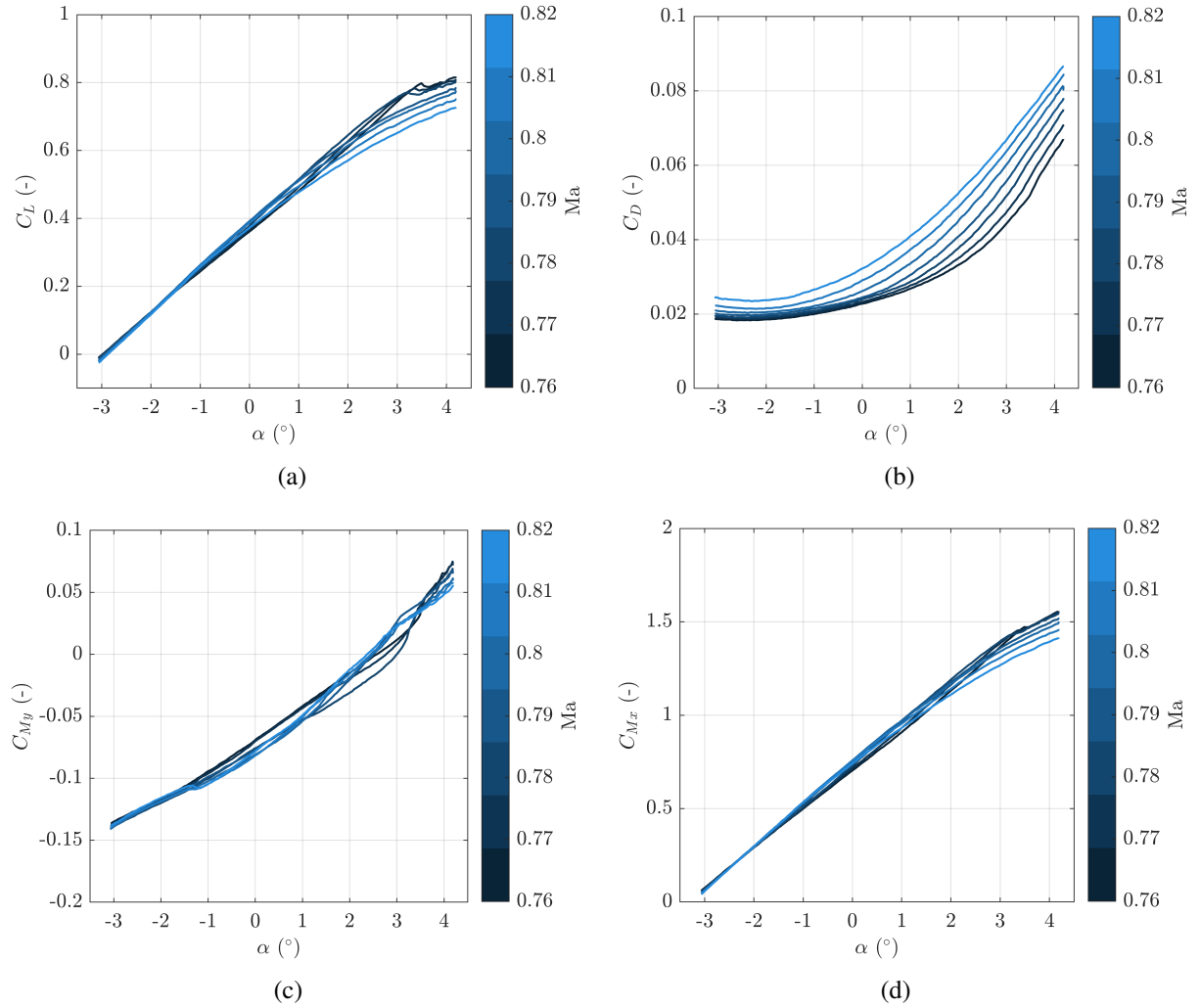


Figure 4: Polars of the steady aerodynamic force, $C_L(\alpha)$ (a), $C_D(\alpha)$ (b), and moment, $C_{M_y}(\alpha)$ (c), $C_{M_x}(\alpha)$ (d), coefficients across a range of Mach numbers ($Ma = 0.76 - 0.82$).

To get further insight into the wing's aerodynamic performance, Fig. 5 shows the pressure distribution at four spanwise cross sections, as obtained via steady (inboard - S_1) and unsteady (midboard - S_2 , outboard - S_3 , and tip - S_4) pressure measurements - this now being done for the characteristic reference, or "baseline", Mach number case only ($Ma = 0.78$). To identify regions of supersonic speed and shock locations, the critical pressure coefficient is indicated by a dashed line. Please note that unsteady pressure sensors (i.e., at $S_2 - S_4$) are only instrumented on the model suction surface. As can be seen from Fig. 5, the wing exhibits a spanwise shock whose relative chordwise position (x/c) shifts towards the trailing-edge from the inboard to outboard/tip cross sections. In addition, at the inboard cross sections, a second shock forms further upstream, thus creating a double shock system (see sections S_1 and S_2). As one may expect, the pressure coefficients depict large fluctuations (indicated by the grey area) where the shocks occur. At this stage, it is worth noting that the shock presence and location are strongly dependent on the flow conditions (i.e., Mach number, Reynolds number, angle of attack). For instance, once the wing model is dynamically pitched around a mean incidence of $\bar{\alpha} = -3.5^\circ$, no shocks develop across the wing span. Similarly, if the present baseline case is tested at a lower Mach number, e.g., $Ma = 0.73$ instead of $Ma = 0.78$, no shocks seem to develop either.

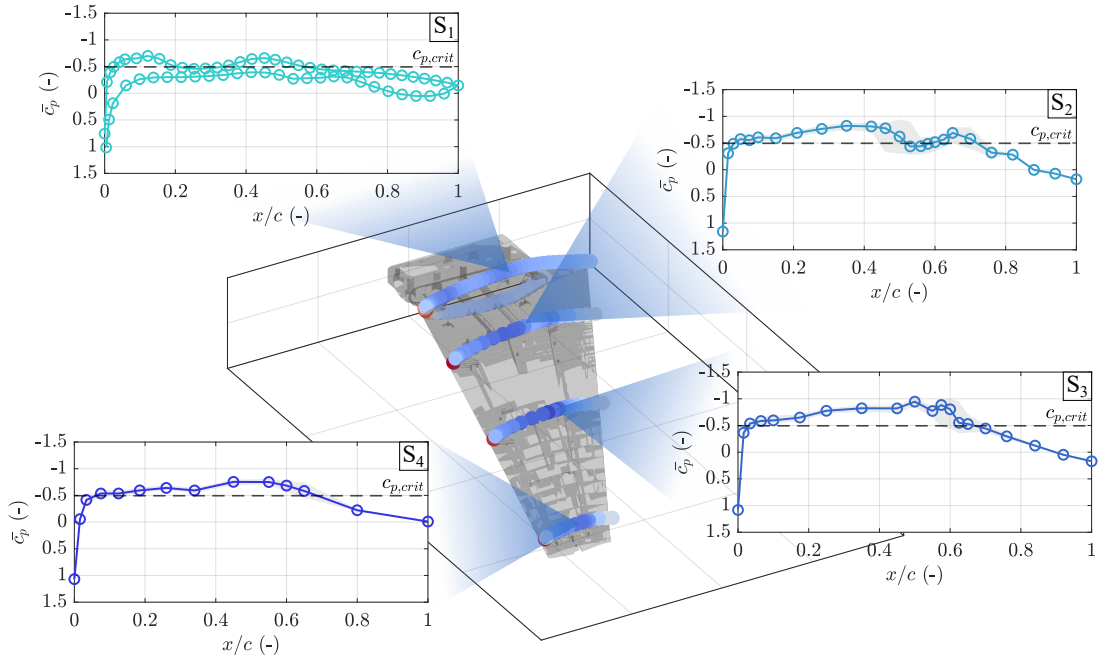


Figure 5: Mean pressure distributions measured at four spanwise cross sections, as obtained from steady (S_1) and unsteady ($S_2 - S_4$) pressure transducers for the baseline flow condition (i.e., $Ma = 0.78$, $Re_c = 16 \times 10^6$, $\bar{\alpha} = 1^\circ$).

Next, Figure 6 depicts the bending and twist distributions over the wing span at a model incidence of $\alpha = 1^\circ$ (Fig. 6(a)) and the maximum deflections at the wing tip as a function of the angle of attack (Fig. 6(b)), as obtained by capturing the displacement of the SPT markers for various Mach numbers. It can be seen that the wing follows a rather typical bending and twist behavior across its span; The wing's vertical displacement (d_z) increases from in- to outboard positions, resulting in a maximum displacement at the tip of $d_z \geq 9$ mm. The twist curve, on the other hand, linearly increases up to almost 80% of the span before flattening towards the tip, leading to a tip twist of roughly $\tau_{tip} \approx 0.22^\circ$. When isolating the tip deformations separately in Fig. 6(b), one can observe how the vertical displacement and twist at the tip linearly increase with the model incidence, leading to maxima of up to $d_{z,tip} \approx 19$ mm and $\tau_{tip} \approx 0.48^\circ$ at an approximate incidence of $\alpha = 4^\circ$.

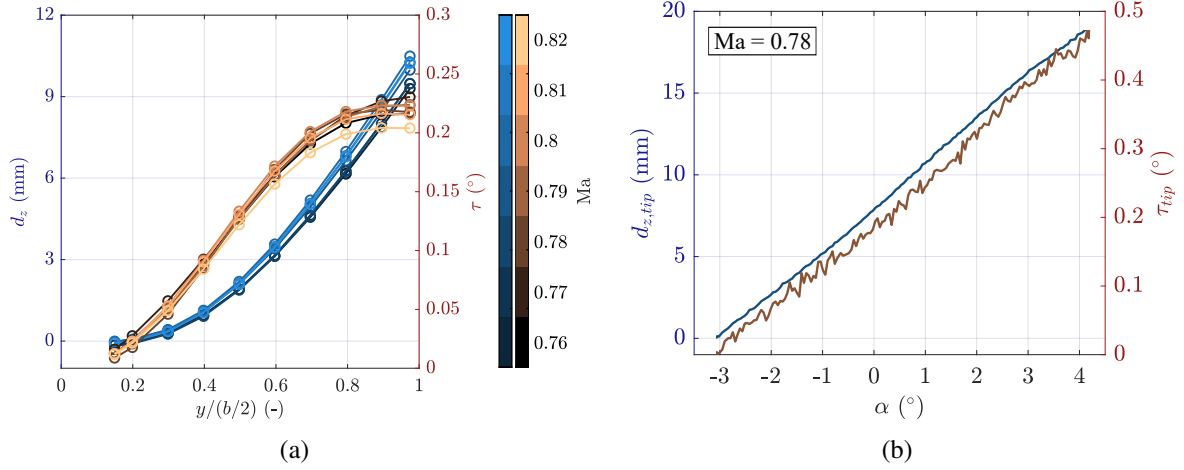


Figure 6: Spanwise bending and twist distributions (a) and tip deflections and twist as a function of the incidence (b), as obtained via the optical SPT markers.

3.2 Unsteady Characteristics

To explore the unsteady behavior of the wing model, Fig. 7 outlines the model's vertical accelerations (a_z) over time when the wing is exposed to a sinusoidal pitching excitation of frequency $f_{osc} = 29.5$ Hz and amplitude $A_{osc} = \pm 0.5^\circ$ (cf. Fig. 2). First, one can observe how the peak-to-peak accelerations increase from inboard to outboard cross sections, which is expected due to the elastic characteristics of the flexible wing structure. More interestingly, when comparing the sensors installed near the leading-edge to their trailing-edge counterparts, the former measure significantly lower accelerations across all spanwise sections. This indicates that the FSW model's trailing-edge area seems to experience larger accelerations, which may be attributed to the thinner structure and/or the distance to the rotational axis, around which the pitch oscillations are applied.

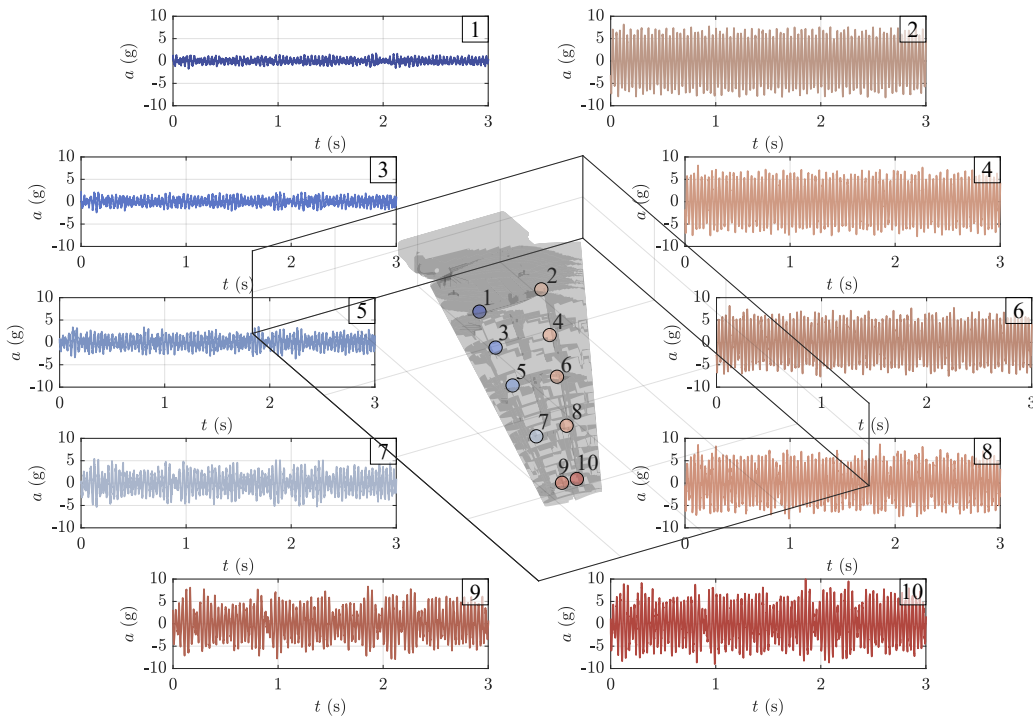


Figure 7: Time-history signals of the accelerations measured across the wing model when tested at the baseline flow condition (i.e., $Ma = 0.78$, $Re_c = 16 \times 10^6$, $\bar{\alpha} = 1^\circ$).

To further investigate the model accelerations, Fig. 8 depicts their frequency spectra from in-board (top-left) to outboard/tip (bottom) positions, with the leading-edge and trailing-edge sensors being plotted in grey and black, respectively. As can be seen across all spectra, several dominant frequency peaks emerge, among which the structural eigenfrequencies, identified previously during the pre-test structural assessment (cf. Table 1), can be recovered. Whilst the most prominent frequency corresponds to the excitation by the pitch oscillator (i.e., f_{osc}), the first (f_1) and second (f_2) bending as well as the first torsion (f_3) mode seem to respectively occur at $f_1 = 24.3$ Hz, $f_2 = 117.2$ Hz, and $f_3 = 284.5$ Hz. These do not exactly match with the values provided in Table 1, which is expected owing to the aerodynamic effects (e.g., aerodynamic stiffening, damping, etc.) slightly shifting the frequencies as well as inducing the broadband-like character - see Fig. 8.

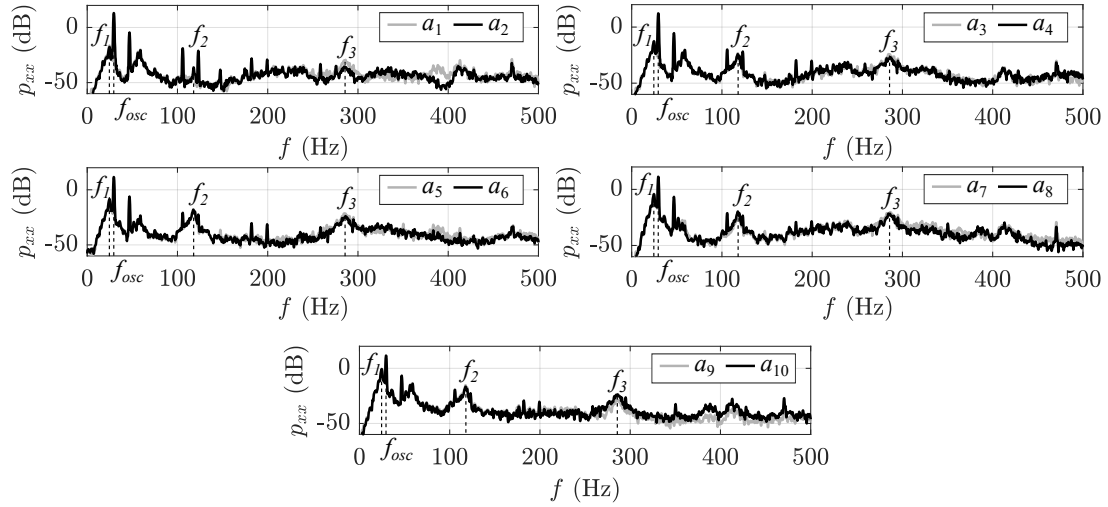


Figure 8: Power spectral densities of the model accelerations obtained at all sensor positions, highlighting the excitation frequency (f_{osc}) and the structural eigenfrequencies f_{1-3} .

Aside from the above, it is worth characterizing how the wing model dynamically responds to the enforced pitch oscillations. This is looked upon in Fig. 9, which depicts the amplitude and phase characteristics of the unsteady pressure signals with respect to the angle of attack (i.e., $|c_{p,\alpha}|$ and $\Phi_{c_p,\alpha}$) for the three spanwise cross sections equipped with unsteady pressure transducers ($S_2 - S_4$). First, looking at the amplitude in Fig. 9(a), the unsteady pressure coefficients indicate a stable flow characteristic with only a weak response of the pressure with respect to the pitch oscillations across the full chord, except for where the shock manifests. There, the amplitude more than triples, which represents significant shock oscillations leading to high unsteady pressure fluctuations. This effect appears to be more pronounced at the midboard and outboard cross sections, when compared to their tip counterpart, which may correlate with the strength of the shock. In addition to the amplitude, the phase indicates that the pressure response is roughly of opposite phase compared to the excitation signal for all chordwise locations, except again for the shock locations. While the pressure response is quasi-steady with a phase of -180° before the shock occurs, a sudden phase shift (from -180° to 90°) happens at shock onset, which represents a delay of the pressure response with respect to the excitation signal (α). This is commonly observed in transonic flow conditions, often indicating an aerodynamic hysteresis phenomenon (i.e., delayed shock motion).

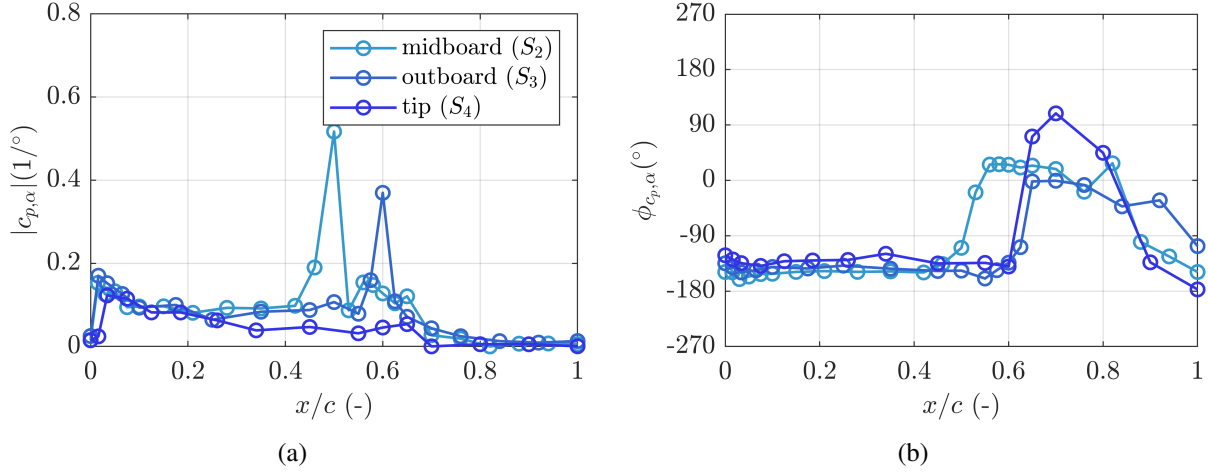


Figure 9: Amplitude, $|c_{p,\alpha}|$, and phase, $\Phi_{c_{p,\alpha}}$, of the unsteady pressure coefficients with respect to the excitation signal (α), as obtained at a pitch oscillation frequency of $f_{osc} = 29.5$ Hz and baseline flow conditions (i.e., $Ma = 0.78$, $Re_c = 16 \times 10^6$, $\bar{\alpha} = 1^\circ$) for the three outer-span sections ($S_2 - S_4$).

4 CONCLUSION

The present work explored the aerodynamic and aeroelastic characteristics of a forward-swept, laminar wing model when experimentally tested in a cryogenic, transonic wind tunnel at flight realistic flow conditions (i.e., in terms of Mach and Reynolds numbers). More precisely, static and dynamic test campaigns were conducted, in which the wing model's aerodynamic and aeroelastic behavior were investigated for a wide experimental matrix. The dynamic tests comprised forced pitch oscillations induced by a specifically designed, novel pitch oscillator.

Steady results revealed rather common aerodynamic polars, with the lift (resp. drag) coefficients decrease (resp. increase) as the Mach number gets higher. Besides that, the wing model is seen to exhibit larger deflections (i.e., bending) and smaller twist angles across its span when being exposed to higher Mach-number flows. Pressure distributions at four spanwise locations reveal a shock that occurs across the span as well as a double shock system near the wing root. These shocks are found to occur at varying chordwise positions, depending on the span section. In addition, the shock characteristics are strongly driven by the flow conditions (e.g., Mach number and incidence), as no shocks may develop when the Mach number and/or the angle of attack are lower than reference case discussed here. Unsteady results showed increasingly large accelerations towards the wing tip, with more pronounced excitations measured at the trailing-edge sensors compared to their leading-edge counterparts. Frequency spectra of the acceleration time signals revealed that the structural eigenmodes could be recovered, albeit at slightly different frequencies and with a broadband-like character owing to aerodynamic effects. Finally, amplitude and phase characteristics of the unsteady pressure coefficients clearly show the shock locations and their influence on the pressure response. More specifically, the shocks induce a sudden phase shift by approximately 270° , causing the wing's pressure response to lag behind the angle of attack.

Upon all the above, a good understanding of the FSW model's aerodynamic and aeroelastic characteristics could be gained. Nonetheless, despite covering various flow conditions, even more test parameters remain for further analysis and exploration. In particular, diving deeper into the unsteady response behavior under dynamic loads - as induced by the pitch oscillator - will be the topic of future work [7].

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