

Dynamic Wind Tunnel Measurements of a Forward-Swept Laminar Wing at Flight-Relevant Conditions using a Pitch Oscillator

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Abstract: This paper presents dynamic wind tunnel measurements conducted within the DLR projects ECOWING and ULTIMATE on a forward-swept semi-span wing with natural laminar flow. A novel pitch oscillator enables unsteady testing across a range of oscillation amplitudes and frequencies. Unsteady pressure data showed some discrepancies from steady-state conditions, with slight increases in standard deviation, particularly near shock locations. In contrast, acceleration measurements revealed significant dynamic response, with higher oscillation amplitudes and frequencies inducing pronounced wing vibrations — especially near the model trailing-edge. These results underscore the importance of dynamic testing for capturing unsteady aerodynamic and, even more significantly, aeroelastic behavior. The developed capability unlocks realistic unsteady aerodynamic and aeroelastic investigations in the European Transonic Wind Tunnel, providing critical data for validating numerical simulations under flight-relevant conditions.

1 Introduction

Unsteady, dynamic phenomena of both aerodynamic and aeroelastic nature remain a critical challenge in the design of next-generation aircraft, particularly for non-conventional configurations such as forward-swept wings (FSWs) featuring naturally laminar flow (NLF). These wing shapes may encounter complex dynamic instabilities when exposed to realistic flight conditions. While steady-state wind tunnel testing provides valuable insights, time-dependent characteristics are essential for validating unsteady aerodynamic models as well as assessing the aeroelastic behavior (e.g., flutter margins, interaction between structural flexibility and transient aerodynamic loads). Therefore, dynamic test capabilities within wind tunnels - for example devices allowing for controlled pitch oscillations - have become pivotal in order to capture these unsteady effects. To address this need, a novel pitch oscillator has been specifically developed for the use in a cryogenic, transonic wind tunnel environment, as part of the German Aerospace Research Programme (Luftfahrtforschung, LuFo) VI/1 and VI/2 projects "Wing Technology Validation for Ultra Green Aircraft" (ECOWING) and "Ultra High Efficient Wing and Movables for Next Generation Aircraft" (ULTIMATE). This pitch oscillator enables highly dynamic testing over a wide range of incidences, for example in the form of sinusoidal pitch excitations or angle-of-attack sweeps, all of which while operating under flight-relevant flow conditions (in Mach and Reynolds numbers). In the wind tunnel tests featured in these projects, dynamic aerodynamic and aeroelastic characteristics of a forward-swept wing model with naturally laminar

flow, the so-called NLF-ECOWING-FSW configuration, are investigated using a wide range of measurement means, including - but not limited to - (un)steady pressure sensors, acceleration sensors, a piezo-electric load balance, optical markers for deformation measurements, and temperature-sensitive paint for transition detection (the reader is also referred to related works on these aspects [1–3]).

The present paper is organized as follows: The experimental means and setup is introduced in Section 2 with specific focus onto the wing model and pitch oscillator used. Next, Section 3 describes some of the dynamic measurement results obtained within this test campaign, before finally conclusions and perspectives are provided in Section 4.

2 Experimental Means & Setup

The present section describes the experimental test facility, the wind tunnel model, and the novel pitch oscillator used for the dynamic wind tunnel measurements.

2.1 Wind Tunnel Facility

The experimental campaign is conducted in the European Transonic Wind tunnel (ETW), which is a closed-vein, closed-circuit wind tunnel whose test section extends over $2.0 \text{ m (H)} \times 2.4 \text{ m (W)} \times 9.0 \text{ m (L)}$ - see Fig. 1. Within the test vein, transonic flow conditions of high Reynolds numbers can be realized for a model-scale aircraft wing. This is achieved due to the cryogenic nature of the wind tunnel [4]; more specifically, by injecting liquid nitrogen downstream of the test section (cf. Fig. 1), the ambient test environment can be cooled down to $T \approx 110 \text{ K}$. Owing to these low temperatures and high wind speeds, a scaled-down wing model can exhibit realistic, full-scale-aircraft flow conditions (i.e., in both, Mach number and chord-based Reynolds number).

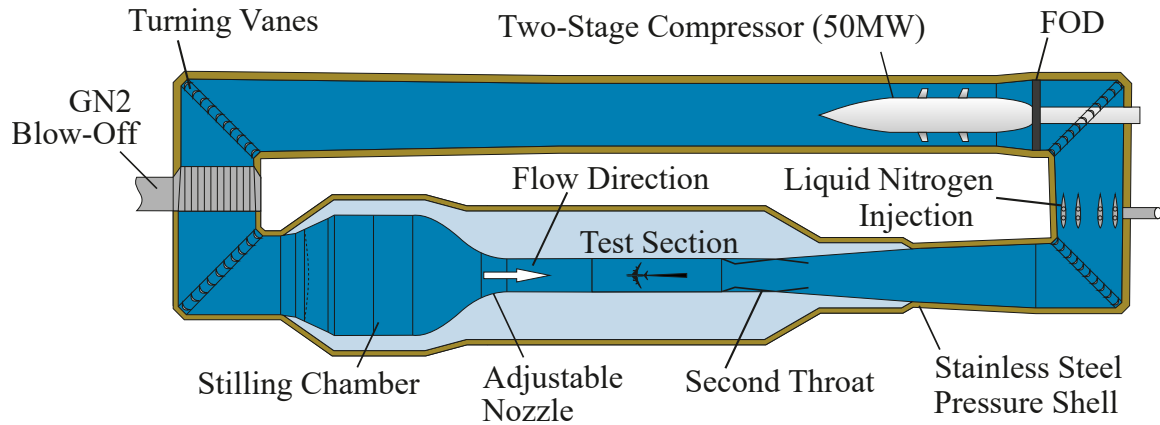


Figure 1: Schematic of the European Transonic Wind Tunnel (©ETW).

2.2 Wind Tunnel Model

The NLF-ECOWING-FSW wind tunnel model tested in this experimental campaign is a semi-span wing configuration with forward sweep and naturally laminar flow technology, based on a short-to-medium range aircraft configuration developed within the DLR project *TuLam* [5]. The configuration has a design cruise Mach number of $M = 0.78$ and a design lift coefficient of $C_L = 0.52$. The wind tunnel model has a semi span of $b/2 = 1.25 \text{ m}$ and a reference (mean aerodynamic) chord length of $c = 0.2865 \text{ m}$. This half-span wing model is mounted to the test section ceiling via a fuselage and belly fairing (see Fig. 2). The model is equipped with large number of sensors, among which steady and unsteady pressure sensors as well as acceleration and temperature sensors. Near the wing root, a wing section (S_1) is covered by 62 steady pres-

sure ports. On top of that, three spanwise positions feature unsteady pressure sensors (Kulites) on the wing's suction side, with respectively 25, 20, and 16 Kulite sensors from inboard to outboard sections (S_2 to S_4). Ten acceleration sensors are distributed across the wing planform to capture the model's vertical accelerations (i.e., in z-direction, normal to the suction surface). In addition, the suction surface is coated with four patches of cryogenic temperature-sensitive paint, whilst the pressure side is covered with stereo pattern tracking (SPT) markers, to respectively capture laminar-to-turbulent transition characteristics and wing deformations.

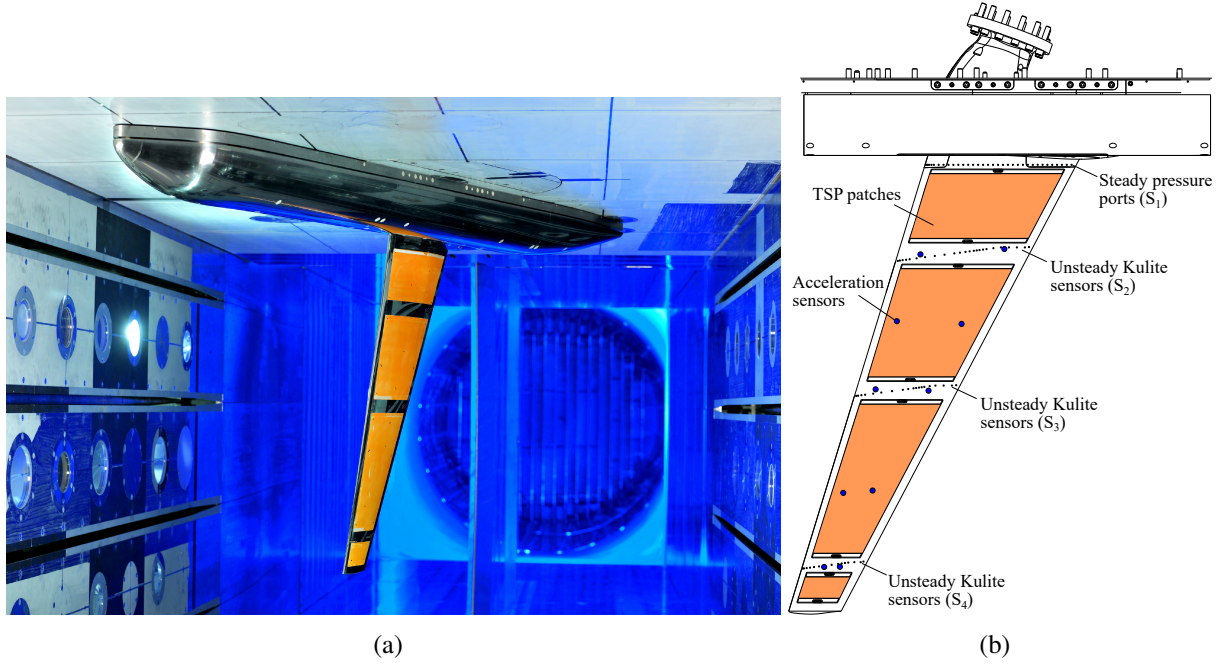


Figure 2: The NLF-ECOWING-FSW wing model with a fuselage and belly fairing installed in the ETW test section (left, ©ETW/Airbus/DLR) and a sketch of the wing planform highlighting its built-in sensors.

To provide some steady-state characteristics of the wind tunnel model, its steady aerodynamic and structural behavior are looked upon. As can be seen from quasi-steady aerodynamic data in Fig. 3(a), the wing exhibits a rather conventional linear lift slope at low to moderate incidences. Notably, the lift coefficients obtained from the steady measurements are higher compared to their dynamic counterparts, due to the fuselage being attached to the load balance. In the dynamic test campaign, only the wing is mounted on the pitch oscillator, and thus, to the load balance. In contrast, the fuselage is attached to the turntable in the ceiling during the dynamic tests and is therefore not pitched with the pitch oscillator. Consequently, the aerodynamic contribution by the fuselage is not considered in the dynamic results. A similar observation can be made from the drag polars obtained from the steady as opposed to the dynamic tests - cf. Fig. 3(b). Finally, it is worth noting that the dynamic measurement data presented in this paper is provided for a reference test condition, i.e., for a flow of Mach number $M = 0.78$ and chord-based Reynolds number of $Re_c = 16 \times 10^6$, while pitching around a mean angle of attack of $\bar{\alpha} = 1^\circ$. In Fig. 3, this reference test conditions is highlighted using a square marker.

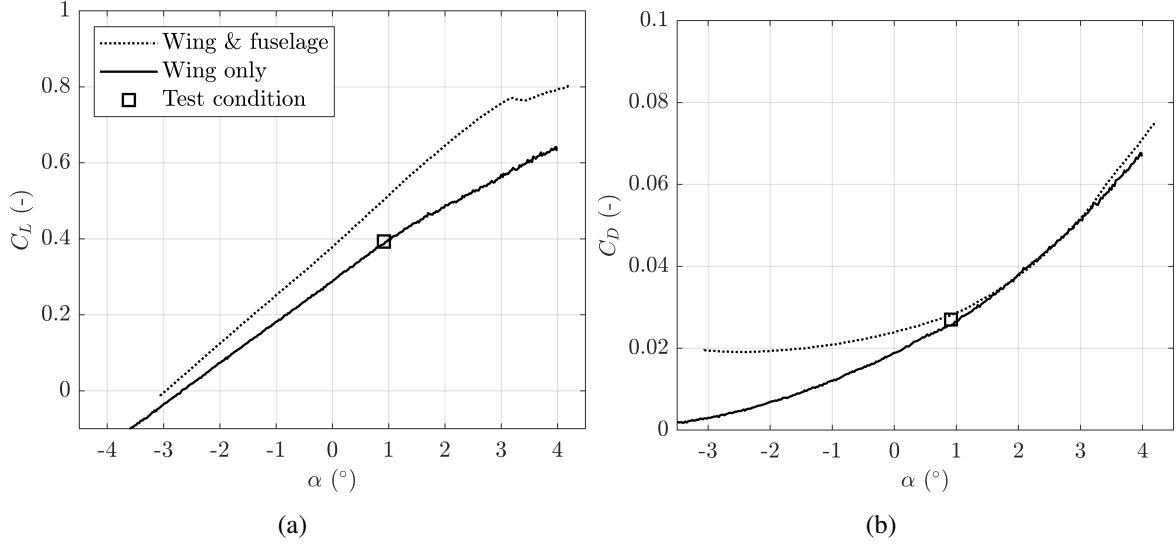


Figure 3: Quasi-steady aerodynamic polars in lift and drag coefficients, as obtained for the wing model with and without the contribution of the fuselage in the steady and dynamic measurement campaigns, respectively. For reference, the test condition - at which dynamic pitch oscillations are investigated in this work - is highlighted (square marker).

For the steady measurements capturing the wing and fuselage, the bending and twist distributions over the model span for the mean incidence of $\bar{\alpha} = 1^\circ$ obtained from the displacement of the SPT markers are shown in Fig. 4(a) and its structural behavior at the wing tip is provided in Fig. 4(b). The wing exhibits a rather typical bending distribution, with its z displacement increasing over the span and a maximum being reached at the wing tip. The twist, on the other hand, is seen to increase over the mid-span of the wing, plateauing towards the tip at approximately 80% span. The maximum deformations in bending and twist linearly increase when the model's incidence is set from low (negative) to high (positive) angles of attack. For further details on the steady characteristics of the NLF-ECOWING-FSW model across various Mach numbers, the reader is referred to a previous publication by the present authors [6].

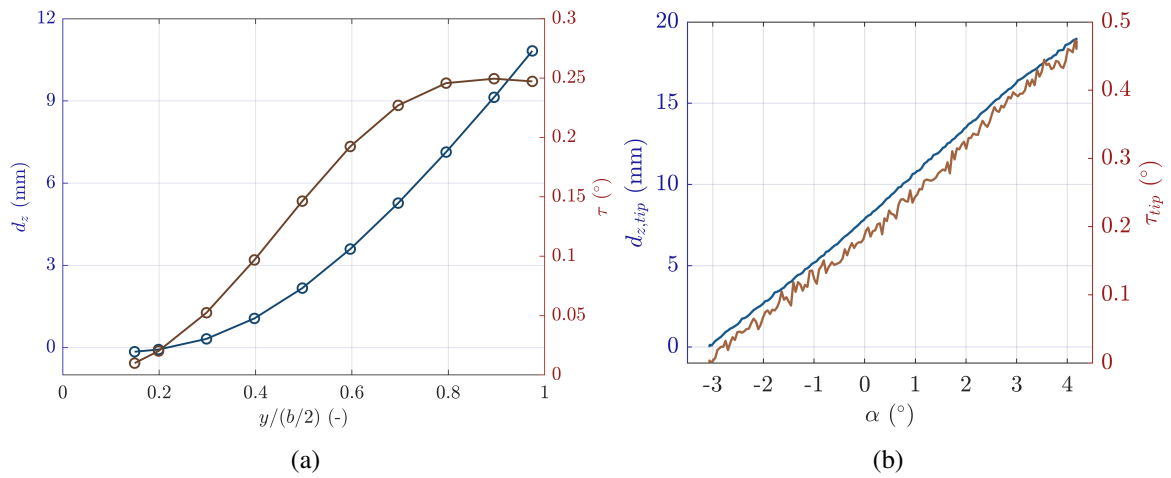


Figure 4: Bending and twist distributions over the wing span, as obtained at a mean incidence of $\bar{\alpha} = 1^\circ$ (left). Tip deflection and twist as a function of the angle of attack (right). Flow conditions: $M = 0.78$, $Re_c = 16 \times 10^6$.

For reference, the structural characteristics - i.e., the model's eigenfrequencies and structural modes - were identified prior to the test campaigns. Table 1 summarizes these structural characteristics of the model, as obtained when the piezoelectric balance is turned off and the brakes for the turntable and pitch oscillator are respectively engaged and open - so as to match the conditions during the wind tunnel tests as closely as possible.

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	First bending	25.02
2	Second bending	115.66
3	First torsion	273.74

2.3 Pitch Oscillator

To investigate the dynamic behavior of the wing model, the ETW required a device to induce dynamic excitations. This is achieved together with the Institute of Aeroelasticity at DLR by developing a novel pitch oscillator, which is mounted on the test section ceiling and to which the wing model root is connected - as shown in Fig. 5. Due to the cryogenic environmental conditions in the ETW, this pitch oscillator is fully encapsulated in a thermally regulated housing. This thermal enclosure box is heated to maintain a constant ambient temperature regardless of the cryogenic temperatures, at which the wind tunnel model is tested. Within this thermal enclosure box, the drivetrain unit of the pitch oscillator is placed, including a piezoelectric 6-component load balance for measuring dynamic model loads and moments. More specifically, the pitch oscillator consists of four main assembly units: the angle-of-attack mechanism, the pitching drive system, an active bending compensation, and the piezoelectric load balance. The angle-of-attack mechanism enables a range of -20° to $+20^\circ$. The pitching drive system features a motor with a rated torque of 2400 N m, which is capable of inducing pitch oscillations of up to 100 Hz. Besides, the active bending compensation is implemented to decouple the bending response of the wing model onto the drivetrain. For instance, laboratory tests revealed that this active bending compensation reduces the decay duration by a factor of 10, when the drive shaft experiences an impact excitation of comparable magnitude and frequency. The piezoelectric load balance consists of four triaxial force sensors (brand Kistler) with integrated charge amplifiers. It is necessary to integrate the charge amplifiers in the balance due to two main reasons: firstly, they need to be placed in the heated environment. Secondly, the sensitive charge cables cannot be routed next to the torque motor due to interference effects.

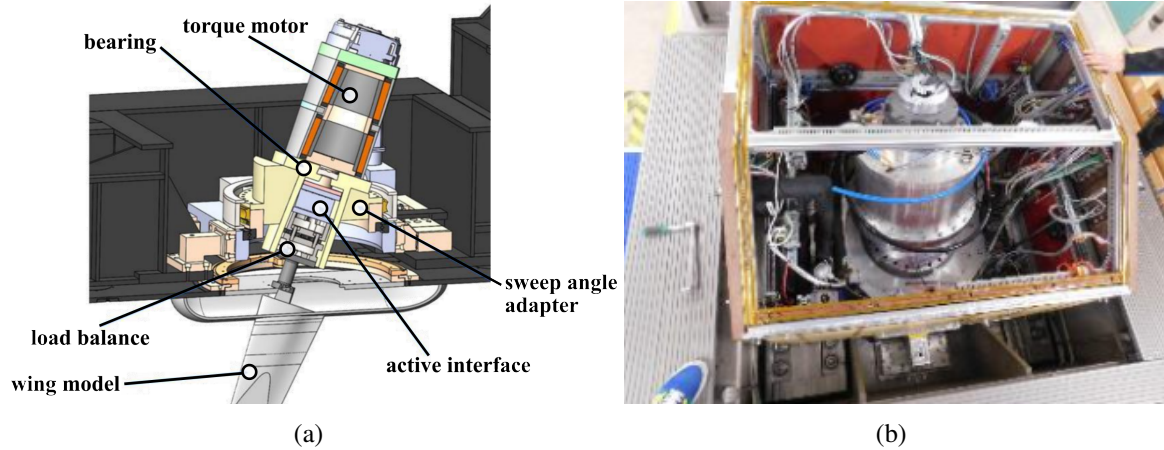


Figure 5: Sectional CAD view (left) and photograph (right) of the assembled pitch oscillator.

During the test campaign, the wind tunnel model is pitched dynamically for given set of amplitude and frequency using the pitch oscillator, thereby exploring the unsteady aerodynamic and aeroelastic response of the wing model. To give an overview of the technical capabilities of the pitch oscillator, Table 2 summarizes the range of test parameters that can be enforced.

Table 2: Technical capabilities of the pitch oscillator

Parameter	Range
Angle of attack, α ($^\circ$)	± 20
Excitation amplitude, A ($^\circ$)	± 0.5
Excitation frequency, f (Hz)	0 – 100
Reduced frequency, k (-)	0 – 0.4

As an example, sinusoidal pitch excitations generated by the pitch oscillator are depicted in Figs. 6(a) and 6(b), demonstrating various types of pitch oscillations with varying amplitudes and frequencies. For comparison purposes, varying-amplitude results are plotted as concatenated snapshots of the time signals, while varying-frequency results are shown as superimposed frequency spectra. As can be seen in Fig. 6(a), the pitch oscillator enforces a repetitive, clean sinusoidal excitation signal, no matter the amplitude. Notably, similar observations have been made for when the wing model is pitched around different mean incidences (e.g., $\bar{\alpha} = -3.5^\circ$ and $\bar{\alpha} = 0^\circ$), which is however not shown here for the sake of conciseness. When comparing varying pitch oscillation frequencies (cf. Fig. 6(b)), it can be observed how the most dominant peak occurs at the excitation frequency - as one would expect. This shows that the pitch oscillator is capable to maintain constant and repetitive oscillation characteristics, allowing to excite the wing model at specific, predefined frequencies (e.g., the model's structural eigenfrequencies), which is of particular relevance for aeroelastic investigations.

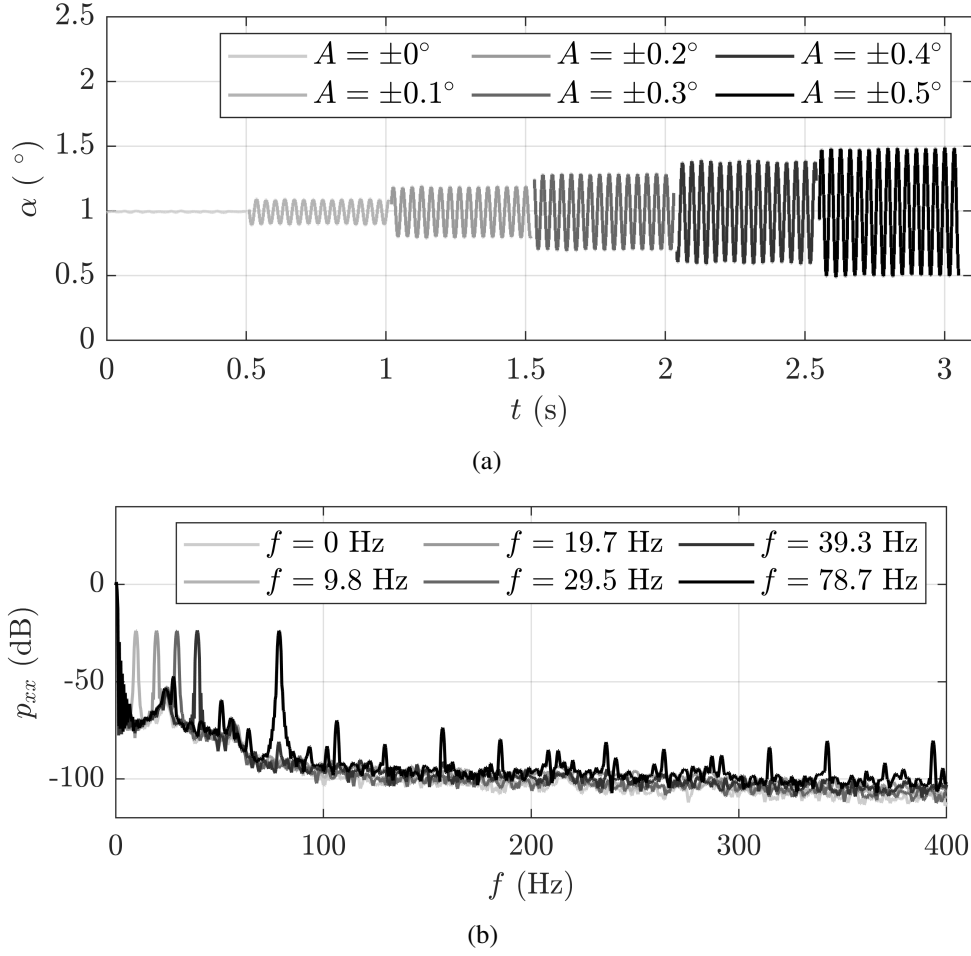


Figure 6: Concatenated dynamic angle-of-attack signals in time domain, as generated from sinusoidal pitch oscillations of varying amplitudes $\pm 0^\circ$ to $\pm 0.5^\circ$ at a frequency of 34.6 Hz (a). Dynamic angle-of-attack signal with varying frequencies 0 Hz to 78.7 Hz at an amplitude of $\pm 0.1^\circ$ (except for the highest frequency at amplitude of $\pm 0.05^\circ$) are shown in frequency domain (b).

2.4 Experimental Matrix

During the dynamic wind tunnel tests a wide range of flow conditions, including - but not limited to - various Mach numbers, total temperatures and pressures, and thus several chord-based Reynolds numbers are explored. More importantly, the addition of the pitch oscillator allows for testing various dynamic conditions by varying the pitch amplitude and frequency around a mean angle of attack. A summary of the conditions tested in the dynamic measurement campaign is provided in Table 3. For the sake of conciseness, this paper will only discuss some of the dynamic test cases.

Table 3: Summary of experimental test conditions covered in the dynamic measurement campaigns.

Parameter	Range
Mach number, Ma	0.20 to 0.78
Chord-based Reynolds number, Re_c	0.8 to 16×10^6
Mean angle of attack, $\bar{\alpha}$	-4.2 to 4.2°
Oscillation amplitude, A_{osc}	± 0.05 to $\pm 0.5^\circ$
Oscillation frequency, f_{osc}	0 to 92.1 Hz
Non-dimensional oscillation frequency, k	0 to 0.4

3 Dynamic Measurement Results

This section presents experimental test results from the dynamic wind tunnel campaigns, including unsteady pressure data and model accelerations that strongly vary depending on the dynamic pitch excitation.

3.1 Unsteady Pressure Characteristics

Figure 7 depicts the mean pressure coefficients over the wing chord at four spanwise sections (from in- to outboard, S_1 to S_4), with error bars indicating the standard deviations of the pressure coefficients at each sensor location. As can be inferred by the pressure coefficients dropping below their critical counterpart (i.e., $C_{p,crit}$), a shock occurs on the model suction side. At the shock locations, the pressure fluctuations also become more prominent, as can be seen by the larger error bars. This behavior is observed for when the model being steadily held at the mean incidence as well as for when it is dynamically pitched. Nonetheless, the pressure fluctuations appear to be slightly more pronounced when the model undergoes a dynamic pitch excitation. That being said, these effects seem to be rather small.

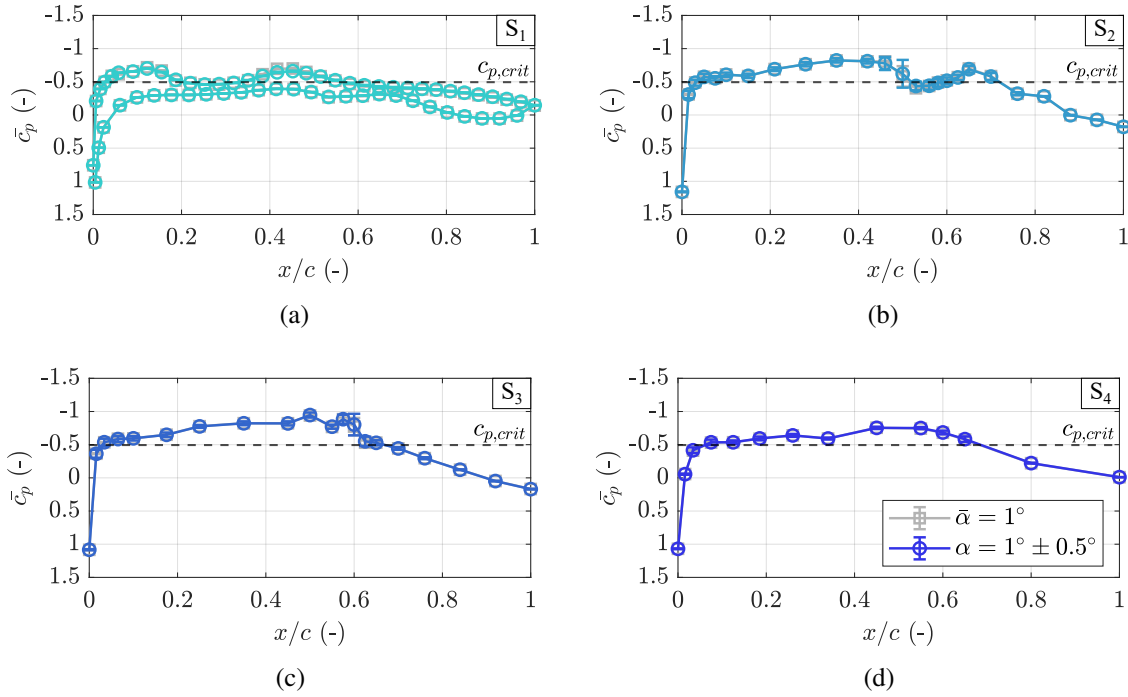


Figure 7: Mean pressure coefficients over the wing chord at four spanwise positions, from inboard (a) to outboard (d), when the model is set at a mean incidence of $\bar{\alpha} = 1^\circ$ without and with dynamic pitching oscillations of $A = \pm 0.5^\circ$ applied. Standard deviations indicating unsteady pressure fluctuations are shown using error bars.

3.2 Model Accelerations

To further investigate the dynamic response of the wing model with respect to the enforced pitch oscillations, the acceleration sensor data is looked upon. As an illustration, Fig. 8 depicts the time-history data of the most outboard acceleration sensor near the wing's trailing-edge. As expected, the model accelerations are significantly increased when the wing is pitched dynamically. This behavior is observed to depend on the pitch amplitude and frequency - i.e., becoming more prominent as either parameter is increased. While the most pronounced excitation is found

at the pitch oscillation frequency (here 29.5 Hz), the structural eigenfrequencies retrieved prior to the wind tunnel tests (cf. Table 1) can be recovered. For instance, the first and second bending as well as the first torsion mode seem to be found at $f = 24.3$ Hz, $f = 118.9$ Hz, and $f = 286$ Hz, respectively. Even though these values differ slightly from the eigenfrequencies identified in the structural impact tests, these differences are associated with the aerodynamic effects induced at a flow of Mach number $M = 0.78$.

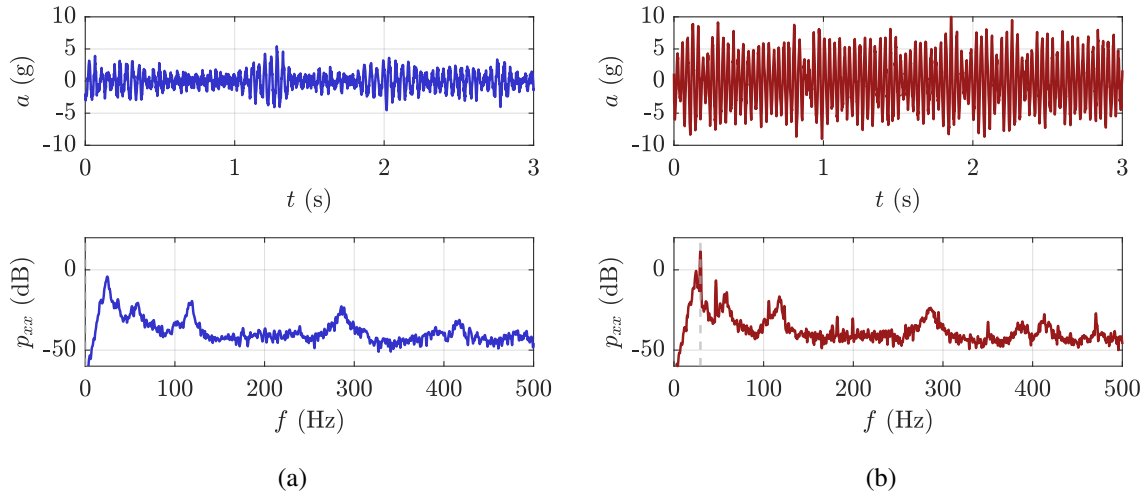


Figure 8: Time-history results of the most outboard acceleration sensor installed close the wing trailing-edge, as obtained for when the model is held steady at a mean incidence of $\bar{\alpha} = 1^\circ$ (left) or pitched dynamically at a frequency of 29.5 Hz with an amplitude of $\pm 0.5^\circ$ (right). The pitch excitation frequency is annotated by a dashed grey line.

As was seen in Fig. 8, the accelerations considerably increase when comparing outboard to in-board sensors. Aside from that, the model's dynamic response is also expected to significantly increase with a larger pitch oscillation amplitude and/or frequency. To explore this, Fig. 9 compares the standard deviations obtained from the acceleration data for all sensor locations and for varying pitch amplitudes and frequencies - see Fig. 9(a) and Fig. 9(b), respectively. Most notably, it can be seen how an increase in both, pitch amplitude and frequency exacerbates the model accelerations' standard deviations across all sensors. When comparing which parameter is more potent, it appears that increasing the pitch amplitude results in even larger standard deviations. Interestingly, the acceleration sensors placed closer to the trailing-edge are found to exhibit higher accelerations compared to their leading-edge counterpart - at least for what concerns the varying-amplitude results in Fig. 9(a). From the varying-frequency results in Fig. 9(b) it is more difficult to derive such a trend.

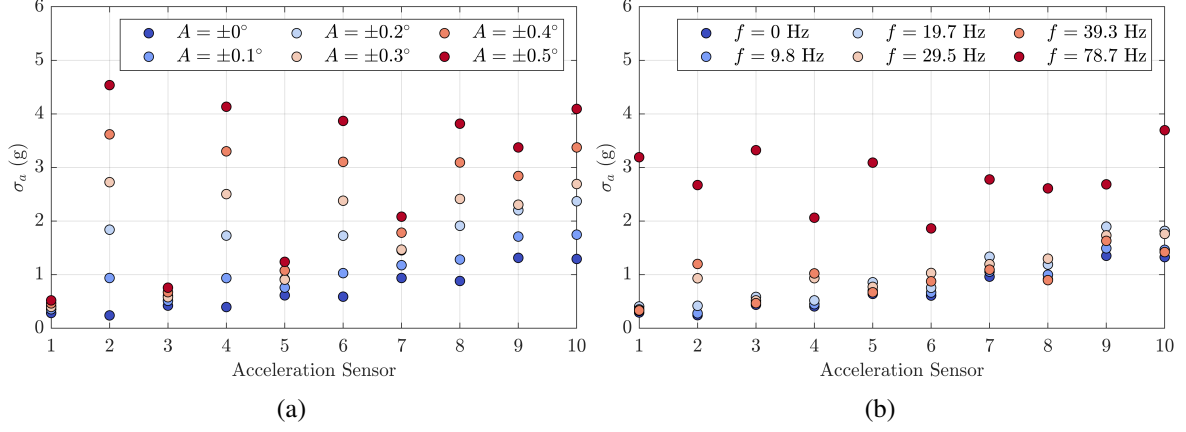


Figure 9: Standard deviations of the model accelerations across all 10 sensor positions, as obtained for varying pitch amplitudes of $\pm 0^\circ$ to 0.5° at a fixed frequency of 29.5 Hz (left) as well as for varying oscillation frequencies of 0 Hz to 78.7 Hz with a fixed amplitude ($\pm 0.1^\circ$), except for the highest frequency where only $\pm 0.05^\circ$ could be reached (right).

4 Conclusion

The present paper discussed the dynamic wind tunnel measurements performed within the DLR projects ECOWING and ULTIMATE, on a forward-swept semi-span wing with natural laminar flow technology. Specific focus was put on the dynamic test capabilities developed for these tests, in the form of a novel pitch oscillator to dynamically excite the wing model. A wide range of flow conditions were explored; In particular, the results presented in this work investigated the effects of varying the pitch oscillation amplitude and frequency.

To explore the dynamic characteristics of the wing model, unsteady data from pressure and acceleration sensors were analyzed. Results revealed that unsteady pressure fluctuations, specifically around the shock locations, are almost similarly found for a pitching wing, as for the model being held steady at a mean incidence. Standard deviations were only slightly increased in the dynamic test cases. In contrast, when looking at the acceleration data, the dynamic response of the wing model was more pronounced. It was observed that the wing accelerations are significantly increased for both, when the model is pitched with larger amplitudes and at higher frequencies. Notably, the model accelerations obtained from the sensors close to the wing trailing-edge were larger compared to their leading-edge counterparts.

From the dynamic measurement data presented in this work it becomes clear how important dynamic test capabilities are to explore aeroelastic characteristics of modern wing models. With the development of this novel pitch oscillator, conducting unsteady wind tunnel tests of both aerodynamic and aeroelastic nature become feasible in the European Transonic Wind Tunnel, which represents an important resource towards properly validating numerical models and simulations at realistic flight conditions.

5 References

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