

EXPERIMENTAL INVESTIGATION OF VERTICAL TAIL BUFFETING ON A TRIPLE-DELTA-WING CONFIGURATION IN TRANSONIC FLOWS

Patrick Hartl¹, Thomas G. Schmidt¹, Anna Altkuckatz¹, Lukas Koida¹, Charlotte Hanke¹, Thomas Büte¹, Holger Ernst¹, Heiko Böhlken¹, Marc Braune¹

¹German Aerospace Center (DLR), Institute of Aeroelasticity,
Bunsenstrasse 10, 37073 Göttingen, Germany
patrick.hartl@dlr.de

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Abstract: Modern high-agility aircraft are often subjected to buffeting phenomena at subsonic and transonic Mach numbers and high angles of attack. This study investigates vertical tail buffeting on the DLR-F23-T triple-delta-wing configuration at Mach numbers representative of flight conditions. Wind tunnel experiments were performed in the DNW-TWG to analyze aerodynamic characteristics, surface pressure distributions, pressure fluctuations, structural response, and quasi-steady hysteresis effects. In addition, an experimental modal analysis was conducted to characterize the structural dynamics of the investigated configuration. The results show that buffet onset shifts from $\alpha = 21^\circ$ at $Ma = 0.55$ to $\alpha = 19^\circ$ at $Ma = 0.85$, indicating an increasing influence of compressibility effects on the vortex-dominated flow field. Spectral analyses identify a dominant buffet-related peak at a reduced frequency close to $k \approx 1$ for both Mach numbers. Furthermore, pronounced hysteresis effects in lift and pitching moment indicate significant nonlinear aerodynamic phenomena associated with the vortex-dominated flow field.

1 INTRODUCTION

The performance of modern high-agility aircraft is significantly affected by vertical tail buffeting at high subsonic and transonic Mach numbers and at medium to high angles of attack (AoA). Such configurations are typically characterized by low aspect-ratio wings with moderate to high sweep angles. In particular, multi-delta wing configurations exhibit enhanced high-AoA maneuverability due to nonlinear vortex-induced lift. At low angles of attack, the boundary layer at the leading edge interacts with the surrounding flow, leading to the formation of a large-scale leading-edge vortex. As the angle of attack increases, the vortex core flow becomes unstable, which is indicated by strong fluctuations in axial velocity and the presence of an adverse axial pressure gradient over the wing [1]. Beyond a critical AoA, the vortices exhibit a structural change leading to the onset of vortex breakdown, which is characterized by a highly turbulent flow field downstream of the breakdown position. The vortex breakdown induces significant pressure fluctuations, resulting in severe structural vibrations of the vertical tail. This aeroelastic phenomenon, known as tail buffeting [2], degrades the flight performance of high-agility configurations and generates unsteady loads that excite the vertical tail at its natural frequencies, leading to increased fatigue, reduced service life, and higher maintenance costs.

Due to these complex flow–structure interactions, the accurate prediction of buffeting phenomena remains a key challenge in the structural design of modern aircraft, as it directly affects dynamic loading and fatigue behavior in both civil and military applications. In recent years, significant progress has been made in the numerical simulation of buffeting, driven by advances in computational capabilities. Nevertheless, purely numerical approaches are not sufficient on their own and require validation against experimental data. In this context, wind tunnel experiments continue to play a crucial role. To ensure that buffeting effects can be reliably captured, experimental models must be designed with sufficient structural flexibility to exhibit measurable aeroelastic responses. In addition, an appropriate level of instrumentation is required to resolve the relevant unsteady flow-induced loads and structural vibrations. To characterize the severity of such buffeting phenomena, Mabey [2] introduced a buffet excitation parameter that relates the structural response to the underlying aerodynamic excitation.

The importance of wind tunnel testing for buffet prediction has been recognized since early studies. Initial investigations examined the capability of wind tunnel testing to predict buffet loads and the transferability to flight conditions, as demonstrated by Davis and Huston [3]. Complementary experimental work by Rainey and Igoe [4] provided detailed insight into unsteady aerodynamic forces through wind tunnel measurements on a scaled X-1E configuration. Subsequent investigations focused specifically on vertical tail buffeting, for example in the work of Triplett [5], who provided detailed insight into the aerodynamic loading through pressure measurements on twin vertical tails in buffeting flow, revealing highly unsteady and spatially varying pressure fields. The relevance of vertical tail buffeting is well illustrated by high-agility aircraft configurations with twin vertical tails, such as the F/A-18, which has served as a key reference. Extensive wind tunnel and flight test studies have provided detailed insight into unsteady pressure distributions and structural loading of the vertical tail, with reported local acceleration peaks of up to approximately 450 g measured at the vertical tail tip at high angles of attack [6–9].

Recent research has led to an improved understanding of vortex-dominated buffeting phenomena in more complex configurations. In particular, Katzenmeier et al. [10] investigated unsteady vortex flow on a generic double-delta wing configuration (AWTM), highlighting the complex interaction of multiple vortex systems and their influence on unsteady aerodynamic loading and aeroelastic response. Stegmüller et al. [11] further developed the AWTM configuration into an aeroelastic full-span double-delta configuration (AWTMF), enabling detailed experimental investigations of vortex-induced fluid–structure interaction under subsonic flow conditions. Hartl et al. [12] and Stegmüller et al. [13] conducted experimental investigations on the AWTMF, analyzing the interaction between unsteady vortex-induced pressure fluctuations and the resulting structural response using pressure and acceleration measurements.

While experimental studies have investigated vertical tail buffeting primarily in low-speed wind tunnels, experimental data for multi-delta-wing configurations under flight-relevant conditions remain scarce. The present study addresses this gap by investigating the aeroelastic response of the vertical tail of the DLR-F23 triple-delta wing configuration at Mach numbers representative of flight conditions. Experiments are conducted over a wide range of flow conditions, including subsonic and transonic regimes and varying angles of attack, with a focus on the buffeting-induced excitation. Although the overall experimental campaign comprised multiple vertical tail configurations and structural layouts, the present paper focuses on the detailed investigation of the quasi-rigid QR-28 configuration for two representative Mach numbers. In addition, nonlinear aerodynamic effects are assessed through the analysis of observed quasi-static hysteresis in lift and pitching moment. The paper is structured as follows: Section 2 describes the experimental setup and test conditions. Section 3 presents the experimental modal analysis

of the DLR-F23-T model. Section 4 addresses the aerodynamic behavior of the configuration through the analysis of lift and pitching moment characteristics, surface pressure distributions, surface pressure fluctuations, and the spectral characteristics of the pressure fluctuations measured at the vertical tail. Section 5 investigates the structural dynamics of the vertical tail under buffet excitation. Section 6 presents the quasi-steady hysteresis characteristics of the lift and pitching moment coefficients and discusses the associated nonlinear aerodynamic effects of the vortex-dominated flow field. Finally, Section 7 summarizes the findings and provides concluding remarks and perspectives.

2 EXPERIMENTAL SETUP AND TEST CONDITIONS

2.1 Experimental facility

The experimental study is conducted at the Transonic Wind Tunnel Göttingen (DNW-TWG), see Fig. 1, administrated by the German-Dutch Wind Tunnels (DNW). The DNW-TWG is a Göttingen Type, closed circuit, continuous wind tunnel whose test section has dimensions of 1.0 m (W) x 1.0 m (H) x 4.5 m (L). The wind tunnel employs perforated walls specifically designed to reach high transonic flow regimes. This particular test section can achieve Mach numbers of $Ma = 0.50$ to 1.20 , with the higher Mach numbers reached by additional suction through the perforated walls. In addition, the test section is enclosed in a pressurized chamber, allowing the pressure and Reynolds number to be adjusted independently of the Mach number, thereby enabling a total pressure range of $p_{tot} = 30$ kPa to 150kPa. The turbulence level inside the test section varies between 0.10 % and 0.25 %, depending on the flow conditions.

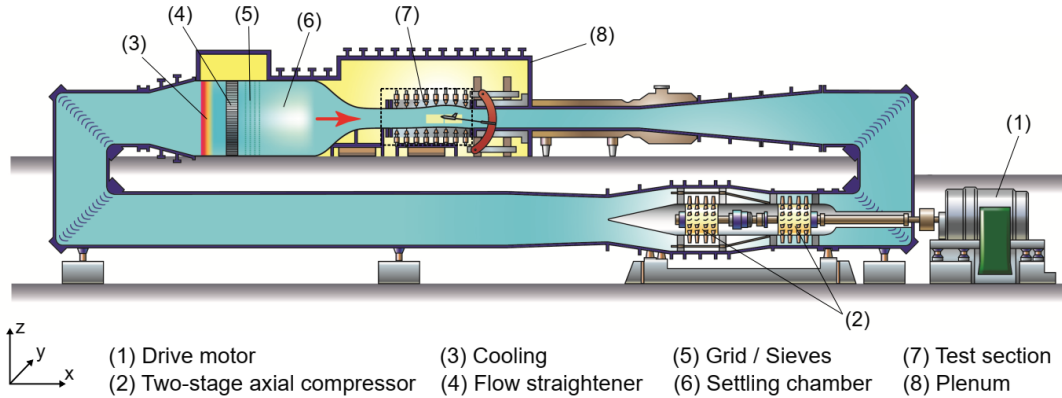


Figure 1: Schematic of the Transonic Wind Tunnel Göttingen (DNW-TWG).

2.2 Triple-delta-wing configuration - the DLR-F23-T

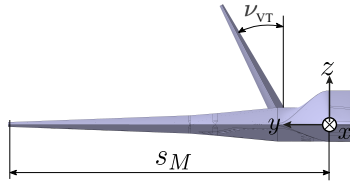
The DLR-F23-T configuration investigated in this study is a generic triple-delta-wing half-span wind tunnel model with an ogival cosine-chined forebody and a vertical tail (see Fig. 2). The model features a peniche to minimize measurement bias arising from the wind tunnel boundary layer. The specific dimensions of the model can be found in Table 1. The wing consists of three main sections, the so-called leading-edge vortex controller (LEVCON), the strake, and the main wing, with leading-edge sweep angles of $\varphi_{W,1} = 45^\circ$, $\varphi_{W,2} = 75^\circ$, and $\varphi_{W,3} = 45^\circ$, respectively. The model consists of elliptic airfoils for each wing section that taper into a sharp trailing edge. The leading edge of each wing segment has a constant radius of $r_{LE} = 0.50$ mm ($r_{LE}/c_{r,W} < 0.001$). The wind tunnel model is further defined by three characteristic lengths, the wing root chord $c_{r,W} = 0.575$ m, the total length $l = 0.862$ m, and its half span $s = 0.420$ m, cf. Fig. 2. For the definition of the wing reference length and reference area, a simplified reference geometry is used, which is indicated by dashed lines in Fig. 2. The wing reference

area is $A_{\text{ref}} = 0.133 \text{ m}^2$, while the reference length is $l_\mu = 0.382 \text{ m}$. In addition, the moment reference point (MRP) is located at $x_{\text{MRP}} = 0.515 \text{ m}$ ($x_{\text{MRP}}/l_M = 0.60$) downstream of the origin at $y = z = 0 \text{ m}$. The DLR-F23-T model features a vertical tail (VT), which can be changed to allow different configurations. A quasi-rigid VT configuration enables a detailed flow-physical analysis of the vortex system and the associated aerodynamic excitation, whereas a flexible VT configuration allows for the investigation of the aeroelastic structural response. The quasi-rigid (QR) vertical tail is manufactured from steel (Ramax HH), while the flexible (FL) vertical tail is 3D-printed from polyamide (PA12). Two vertical-tail dihedral angles of $\nu_{VT,1} = 28^\circ$ and $\nu_{VT,2} = 45^\circ$ were investigated for each configuration, resulting in four model variants, hereafter denoted as QR-28, QR-45, FL-28, and FL-45. The vertical tail is designed as a V-tail and has a span of $b_{VT} = 0.157 \text{ m}$, with a root chord of $c_{r,VT} = 0.200 \text{ m}$ and a tip chord of $c_{t,VT} = 0.036 \text{ m}$. The VT has a leading-edge sweep of $\varphi_{VT,LE} = 45^\circ$ and a trailing-edge sweep of $\varphi_{VT,TE} = -2.2^\circ$. The center of the symmetry line at the root of the VT is located at $x/l_M = 0.935$ and $y/s_M = 0.160$ with respect to the origin.

Table 1: Dimensions of the DLR-F23-T configuration.

Wing/Fuselage		Vertical Tail (VT)	
l	0.862 m	b_{VT}	0.157 m
s	0.420 m	$c_{r,VT}$	0.200 m
$c_{r,W}$	0.575 m	$c_{t,VT}$	0.036 m
$\varphi_{W,1}/\varphi_{W,2}/\varphi_{W,3}$	$45^\circ/75^\circ/45^\circ$	$\varphi_{VT,LE}/\varphi_{VT,TE}$	$45^\circ/-2.2^\circ$
l_μ	0.382 m	$\nu_{VT,1}/\nu_{VT,2}$	$28^\circ/45^\circ$
A_{ref}	0.133 m^2	A_{VT}	0.019 m^2

Configuration 1: VT 28°



Configuration 2: VT 45°

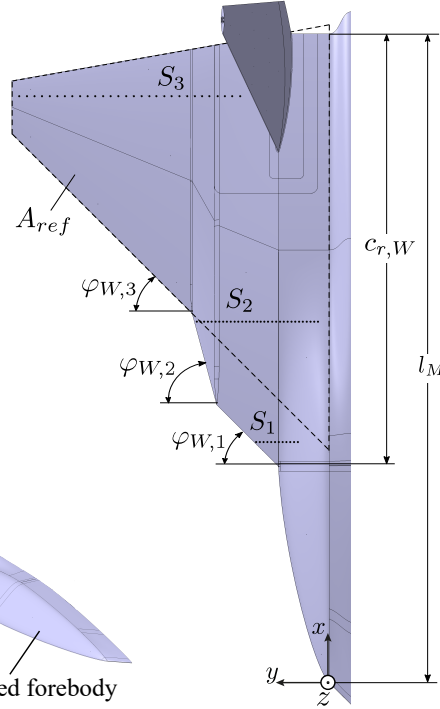
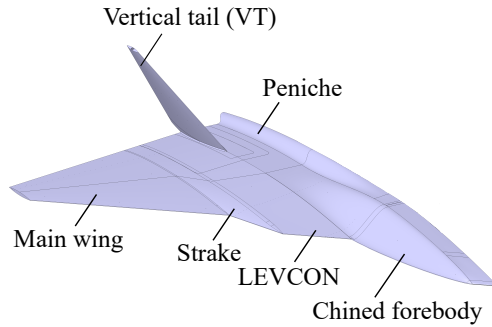
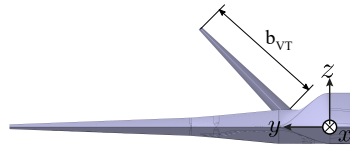


Figure 2: Geometry of the DLR-F23-T wind tunnel model.

2.3 Dynamic pitch test rig

The DLR-F23-T model with the peniche is mounted on the rotatable disk of the dynamic pitch test rig in the test section with perforated walls of the DNW-TWG (see Fig. 3). The actuation from a rotational hydraulic cylinder, located outside the wind tunnel test section, is transmitted via a bellows coupling and a shaft. The test rig is used to set discrete angles of attack for the acquisition of steady polars, to obtain quasi-steady polars at constant pitch rates, and to perform dynamic pitch-up maneuvers as well as controlled pitch oscillations. The angle of attack (AoA) is determined based on vertical distance measurements from two laser triangulators positioned upstream and downstream of the rotation axis below the model. Furthermore, a piezoelectric six-component balance is installed between the model mounting plate and the dynamic pitch actuator. Consequently, the measured forces and moments are unaffected by the disk and represent only the loads acting on the wind tunnel model. A more detailed description of the test rig used for this experiment is given in Wiggen and Voß [14].

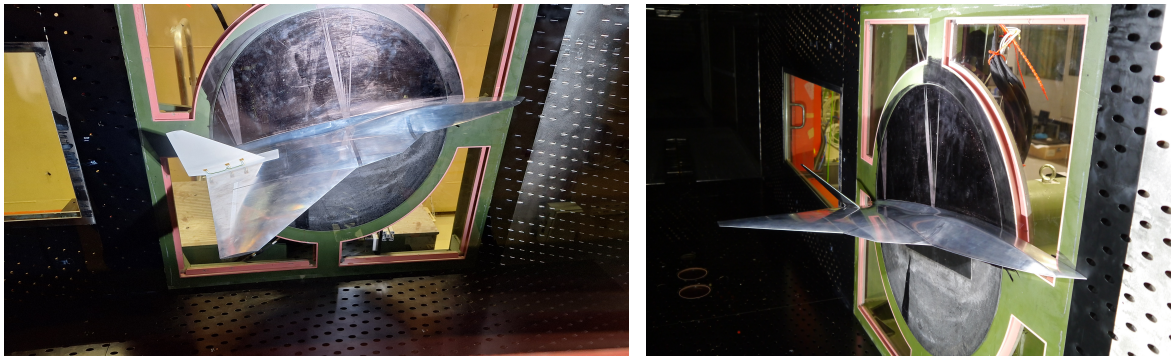


Figure 3: DLR-F23-T wind tunnel model mounted on the dynamic pitch test rig in the perforated test section of the DNW-TWG (left: side view; right: front view).

2.4 Model Instrumentation and Test Conditions

The upper wing surface of the wind tunnel model is equipped with 71 unsteady surface pressure transducers, arranged in three spanwise-aligned pressure sections (S1 to S3), see Section 2.2. On the vertical tail, 26 transducers of the same type are installed. To assess structural excitation due to buffeting, the model is instrumented with four uniaxial accelerometers, including three sensors mounted on the wing and one sensor located on the tip of the vertical tail. The experimental investigations are performed within a Mach number range from $Ma_\infty = 0.50$ to 1.15, with a Mach number increment of 0.1. The Reynolds number based on the mean aerodynamic chord ranges from 2.35×10^6 to 3.27×10^6 . All measurements are performed at a constant total pressure of 60 kPa. The measurements are conducted over an angle-of-attack range of $\alpha = 0^\circ$ to 30° at Mach numbers between $Ma_\infty = 0.50$ and 0.85. At higher Mach numbers, the maximum angle of attack is reduced due to increased aerodynamic loads. For the present model configuration, the maximum wind tunnel blockage of 10 % is reached at an AoA of $\alpha = 32.7^\circ$. All measurement conditions for the experimental investigation conducted in the DNW-TWG are summarized in Table 2.

3 EXPERIMENTAL MODAL ANALYSIS

To characterize the structural properties of the DLR-F23-T configuration and to identify its eigenmodes and corresponding eigenfrequencies, an experimental modal analysis was conducted in the test section of the DNW-TWG. The modal tests were performed on all four vertical tail (VT) configurations described in Section 2.2, representing quasi-rigid and flexible vertical

Table 2: Wind tunnel measurement conditions.

Parameter	Value
Ma	0.50 - 1.15
$Re_{l_\mu} = (\rho_\infty U_\infty l_\mu) / \mu$	$2.35 \cdot 10^6 - 3.27 \cdot 10^6$
p_{tot}	60 kPa
	$0^\circ - 30^\circ$ ($0.50 \leq Ma \leq 0.85$)
α	$0^\circ - 25^\circ$ ($Ma = 0.95$)
	$0^\circ - 20^\circ$ ($Ma \geq 1.05$)

tails. The experimental setup for the modal analysis is shown in Fig. 4. The structure was excited using an impulse hammer, and the dynamic response was measured using a total of 27 accelerometers, including 14 triaxial accelerometers on the wing and 13 uniaxial accelerometers on the VT. The excitation was applied at selected locations to adequately excite the relevant structural modes.

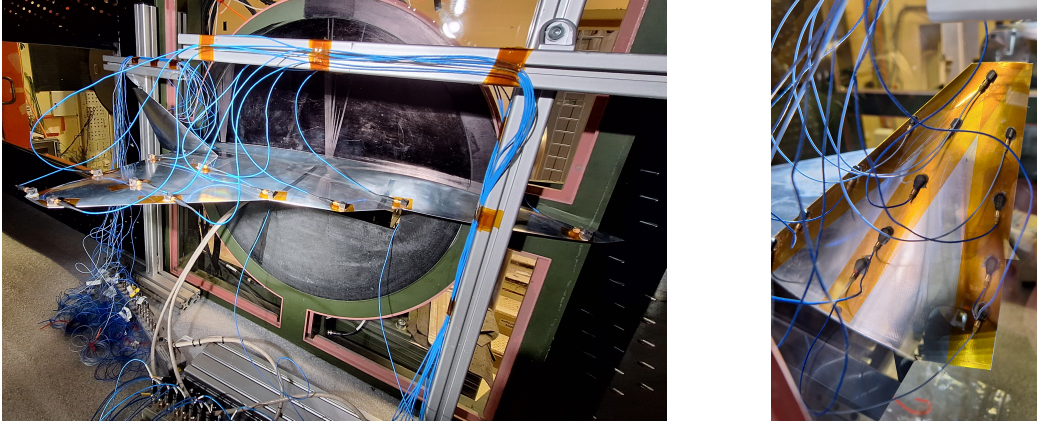


Figure 4: Experimental setup of the modal analysis in the perforated test section of the DNW-TWG (left: wing instrumentation; right: vertical-tail instrumentation).

The measured time signals were evaluated in the frequency domain using power spectral density (PSD) estimation based on Welch's method, and the eigenfrequencies were identified from the spectral peaks of the response signals. The corresponding mode shapes were determined from the spatial distribution of the measured responses. For the triple-delta-wing configuration, no distinct separation between bending and torsional modes is observed, in contrast to the behavior typically found in high-aspect-ratio wing structures. Instead, the low aspect ratio results in strongly coupled mode shapes involving both bending and torsional components.

The power spectral density for the quasi-rigid vertical tail configurations QR-28 and QR-45 is shown in Fig. 5. The QR-28 configuration is analyzed first and serves as the reference case for the modal analysis. The first peak at $f_\alpha = 30.98$ Hz corresponds to a rigid-body pitch mode (RBM) about the rotational axis of the dynamic pitch test rig. A second rigid-body mode is observed at $f_h = 91.25$ Hz and is associated with a heave motion, corresponding to a vertical translation of the complete model. The first elastic mode of the QR-28 configuration occurs at $f_{s2} = 161.90$ Hz and corresponds to the first bending mode (BM), characterized by an in-phase bending motion of the wing and the vertical tail. A coupled bending mode is identified at $f_{s3} = 203.25$ Hz, characterized by out-of-phase bending of the wing and vertical tail. At higher frequencies, the structural response becomes increasingly coupled. A coupled bending-torsion mode of the wing is observed at $f_{s4} = 323.45$ Hz, dominated by bending with a superimposed torsional component. A vertical-tail-dominated bending mode occurs at $f_{s5} = 349.73$ Hz, ac-

companied by a coupled bending–torsion response of the wing. At $f_{s6} = 353.45$ Hz, a similar deformation pattern is observed for the wing, while the response of the vertical tail is significantly reduced. Finally, at $f_{s7} = 407.87$ Hz, a higher-order coupled mode is identified, characterized by axial deformation of the forebody and a coupled bending–torsion response of the wing. The same modal characteristics are observed for the QR-45 configuration, see Fig. 5, although with reduced amplitudes and slight frequency shifts. The corresponding eigenfrequencies are summarized in Table 3. Reduced amplitudes are evident for the rigid-body modes as well as for the first two elastic modes up to approximately 250 Hz. In particular, the closely spaced modes around 350 Hz are less pronounced compared to the reference configuration.

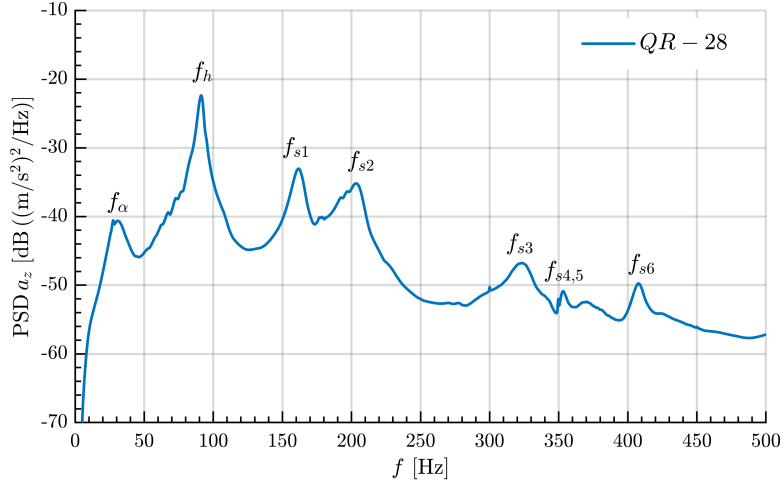


Figure 5: Power spectral density (PSD) with identified eigenfrequencies of the quasi-rigid vertical tail configurations with dihedral angles of 28° (QR-28) and 45° (QR-45).

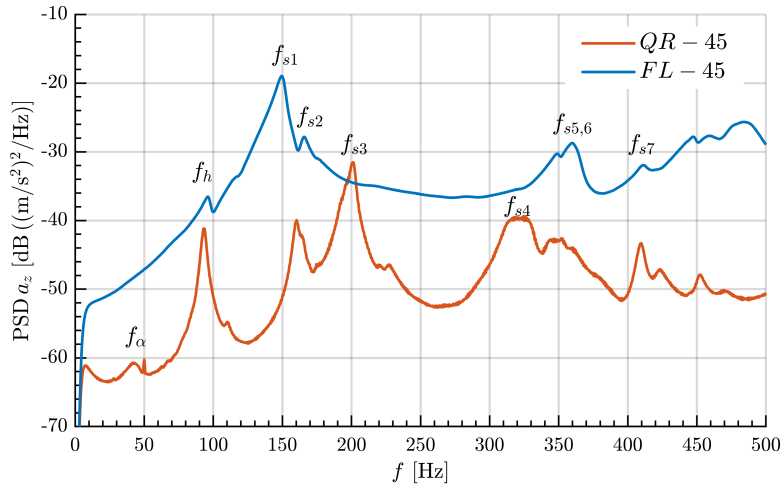


Figure 6: Power spectral density (PSD) comparison of the quasi-rigid and flexible vertical tail configurations at a dihedral angle of 45° (QR-45 and FL-45).

Figure 6 compares the power spectral densities of the QR-45 and FL-45 configurations. In general, both configurations exhibit similar modal characteristics, with the dominant structural modes occurring at comparable frequencies. However, noticeable differences in the spectral amplitudes and the distinctness of individual modes are observed. Compared to the quasi-rigid QR-45 configuration, the flexible FL-45 configuration exhibits an additional pronounced peak at $f_{s1} = 149.54$ Hz, corresponding to the first bending mode of the flexible vertical tail. In contrast, no distinct peaks corresponding to the out-of-phase wing–vertical-tail bending mode at f_{s3} and the coupled bending–torsion mode at f_{s4} can be identified for the FL-45 configuration.

Moreover, the higher-order modes above approximately 350 Hz are more clearly distinguishable for the flexible configuration, accompanied by slight frequency shifts caused by differences in structural stiffness. All identified modes and the corresponding eigenfrequencies of the FL-45 configuration are summarized in Table 3.

Table 3: Eigenmodes and eigenfrequencies of the DLR-F23-T configuration.

Eigenmode	Eigenfrequency		
	QR-28 f , Hz	QR-45 f , Hz	FL-45 f , Hz
RBM (Pitch, f_α)	30.98	-	-
RBM (Heave, f_h)	91.25	93.69	96.13
1st BM VT (f_{s1})	-	-	149.54
1st BM wing-VT (in-phase, f_{s2})	161.90	160.22	166.02
1st BM wing-VT (out-of-phase, f_{s3})	203.25	201.42	-
Coupled BM-TM (f_{s4})	323.50	324.71	-
VT BM (wing-coupled, f_{s5})	349.73	347.90	348.82
Wing TM (VT coupling, f_{s6})	353.45	351.85	359.50
Higher-order Wing BM-TM (f_{s7})	407.87	409.85	411.07

4 AERODYNAMIC LOADS AND BUFFET CHARACTERISTICS

The following section analyzes the aerodynamic load characteristics and the associated buffet behavior of the investigated configurations for Mach numbers of 0.55 and 0.85. The analysis focuses on lift and pitching moment coefficients, unsteady pressure fluctuations, and the identification of buffet onset under representative transonic flow conditions.

4.1 Lift and Pitching Moment Characteristics

The lift and pitching moment characteristics of the investigated DLR-F23-T quasi-rigid QR-28 configuration at a Mach number of $Ma = 0.55$ are shown in Fig. 7. The error bars indicate the corresponding standard deviations of the measured signals. The lift coefficient increases approximately linearly up to $\alpha = 17^\circ$, indicating stable vortex-dominated flow conditions. A local maximum in lift coefficient is observed at $\alpha = 21^\circ$. Beyond this angle of attack, a reduction in lift is observed, which is attributed to the onset of vortex breakdown over the wing, resulting in a reduction of vortex-induced lift. At $\alpha = 21^\circ$, a pronounced increase in the standard deviations is observed, indicating the onset of significant unsteady aerodynamic loading associated with buffet, which is further confirmed by the RMS analysis shown in Fig. 8. In particular, a distinct local peak in $C_{L,rms}$ is identified at $\alpha = 22^\circ$. The pitching moment coefficient shows a significant increase between $\alpha = 21^\circ$ and $\alpha = 22^\circ$ indicating the buffet onset at $\alpha_B = 21^\circ$. The buffet onset corresponds to the transition from a stable vortex-dominated flow regime to increasingly unsteady flow conditions associated with vortex breakdown and enhanced aerodynamic load fluctuations. For higher angles of attack above approximately $\alpha = 24^\circ$, the lift coefficient increases moderately again and reaches values close to $C_L \approx 0.9$ at $\alpha = 30^\circ$, while the RMS values continue to rise, indicating unsteady aerodynamic load fluctuations. This behavior indicates that, despite the onset of vortex breakdown, separated vortex-dominated flow structures continue to contribute to the aerodynamic lift generation in the post-stall regime.

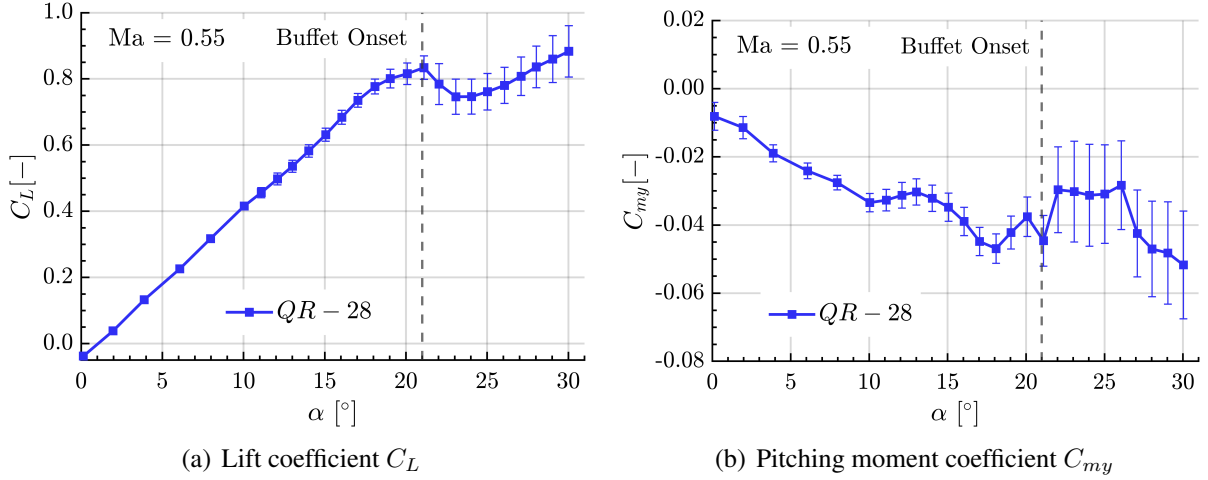


Figure 7: Lift coefficient C_L (left) and pitching moment coefficient C_{my} (right) for the DLR-F23-T QR-28 configuration (quasi-rigid) at $Ma = 0.55$ and $Re_{l_\mu} = 2.31 \cdot 10^6$.

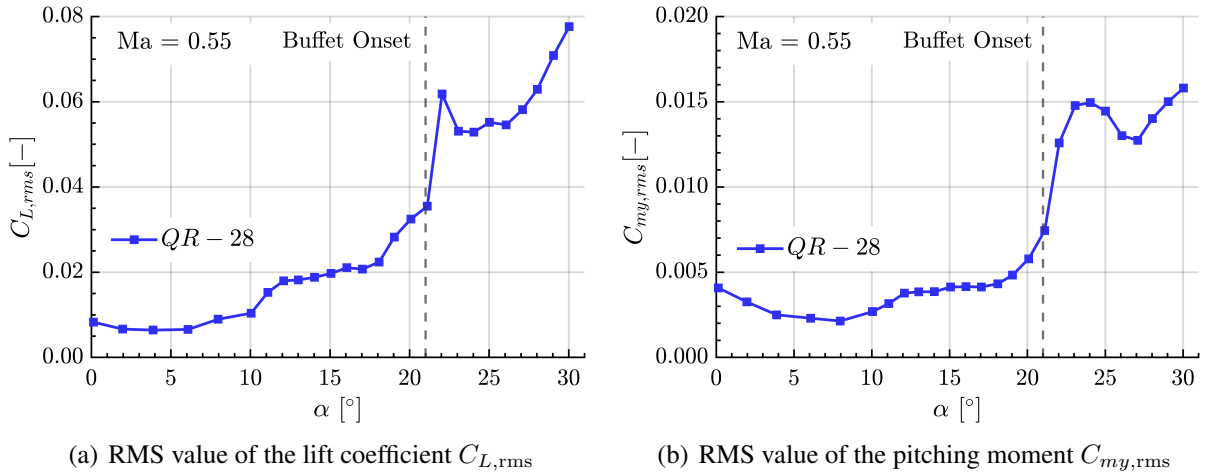


Figure 8: RMS values of the lift coefficient $C_{L,rms}$ (left) and the pitching moment coefficient $C_{my,rms}$ (right) for the DLR-F23-T QR-28 configuration (quasi-rigid) at $Ma = 0.55$ and $Re_{l_\mu} = 2.31 \cdot 10^6$.

The lift and pitching moment characteristics of the quasi-rigid QR-28 configuration at a Mach number of $Ma = 0.85$ are shown in Fig. 9. At low angles of attack, the lift coefficient increases continuously with increasing α , indicating the development of a stable vortex-dominated flow regime. Simultaneously, the pitching moment coefficient decreases gradually with increasing α , indicating an increasing nose-down pitching tendency associated with the strengthening and downstream movement of the vortex system. A first noticeable change in lift-curve slope is observed at $\alpha = 8^\circ$. This kink may be associated with an interaction of the leading-edge vortices generated by the different triple-delta wing segments, resulting in a redistribution of the pressure field and a modified pitching moment characteristic. Beyond $\alpha = 10^\circ$, the lift coefficient continues to increase steadily and reaches a local maximum of $C_L = 0.93$ at $\alpha = 19^\circ$. Following this local maximum, a distinct reduction in lift coefficient is observed. At this angle of attack, significantly increased fluctuations are observed, suggesting enhanced aerodynamic unsteadiness potentially related to shock-vortex interaction, shock-induced separation, and vortex breakdown effects in the transonic flow regime. A pronounced change in pitching moment behavior is observed between $\alpha = 19^\circ$ and 20° , where the pitching moment coefficient abruptly shifts toward less negative values. In combination with the significantly increased aerodynamic fluctuations, represented as RMS values in Fig. 10, these observations suggest the onset of buf-

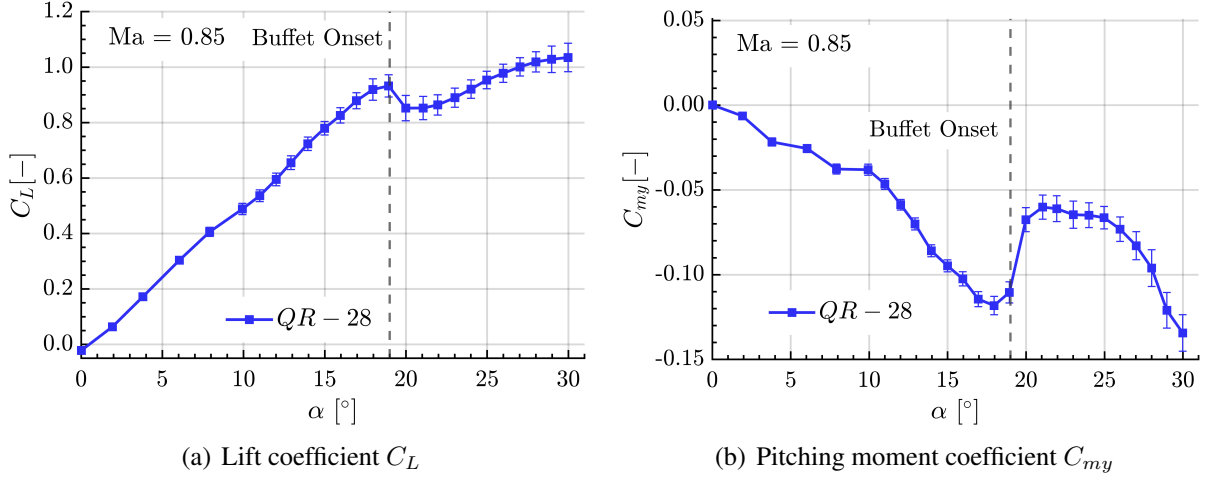


Figure 9: Lift coefficient C_L (left) and pitching moment coefficient C_{my} (right) for the DLR-F23-T QR-28 configuration (quasi-rigid) at $Ma = 0.85$ and $Re_{l\mu} = 3.02 \cdot 10^6$.

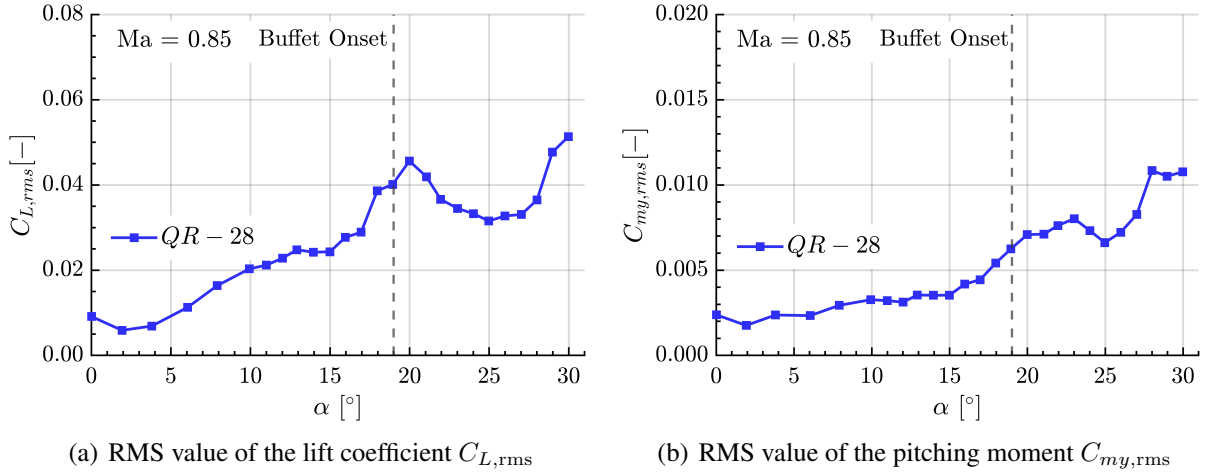


Figure 10: RMS values of the lift coefficient $C_{L,rms}$ (left) and the pitching moment coefficient $C_{my,rms}$ (right) for the DLR-F23-T QR-28 configuration (quasi-rigid) at $Ma = 0.85$ and $Re_{l\mu} = 3.02 \cdot 10^6$.

fet at $\alpha = 19^\circ$. For angles of attack beyond $\alpha = 20^\circ$, the lift coefficient increases moderately again and reaches values above $C_L \approx 1.0$ at $\alpha = 30^\circ$, while the RMS values remain elevated. This behavior indicates the persistence of highly unsteady vortex-dominated flow structures in the post-buffet regime, which continue to contribute to aerodynamic lift generation despite the onset of vortex breakdown.

The comparison of the investigated Mach number cases shows that buffet onset shifts from $\alpha = 21^\circ$ at $Ma = 0.55$ to $\alpha = 19^\circ$ at $Ma = 0.85$. This shift indicates the increasing influence of compressibility effects and transonic shock-related flow instabilities at higher Mach numbers. The earlier onset of buffet is likely associated with enhanced shock-vortex interaction and earlier shock-induced separation, which destabilize the vortex-dominated flow field and promote vortex breakdown at lower angles of attack.

Figure 11 shows the comparison of the lift coefficient C_L and the pitching moment coefficient C_{my} for $Ma = 0.55$ and $Ma = 0.85$, highlighting the Mach number effects on the nonlinear lift increase and the nose-down pitching trend associated with the vortex-dominated flow. The lift coefficient C_L for both Mach numbers exhibits the characteristic nonlinear increase associated with the formation of leading-edge vortices on the triple-delta wing. At low angles of attack,

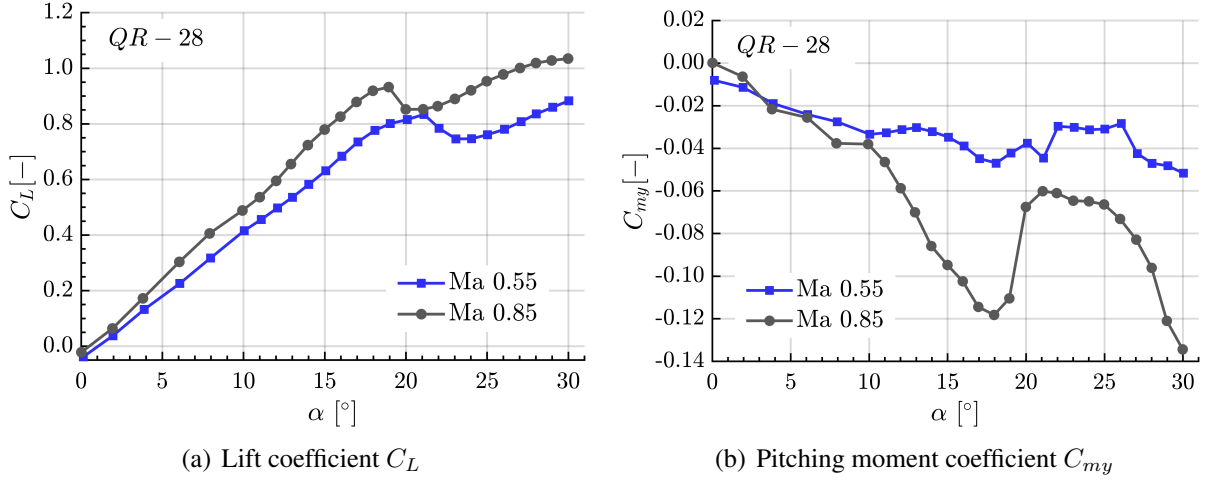


Figure 11: Comparison of the lift coefficient C_L (left) and the pitching moment coefficient C_{my} (right) for the quasi-rigid QR-28 configuration of the DLR-F23-T model for $Ma = 0.55$ and $Ma = 0.85$.

the lift coefficient shows a larger gradient for $Ma = 0.85$ compared to $Ma = 0.55$, indicating a stronger initial vortex-induced lift contribution at the higher Mach number. At $Ma = 0.85$, C_L reaches a local maximum at a lower angle of attack, highlighting the earlier breakdown of the vortex system and the increased unsteadiness of the flow. The pitching moment coefficient C_{my} shows a pronounced nose-down trend at small angles of attack for both Mach numbers. At $Ma = 0.85$, a distinct kink towards more negative pitching moment is observed at $\alpha = 10^\circ$. This negative gradient reflects the strengthening of the vortex system behind the aerodynamic center, which generates additional lift and induces a nose-down pitching tendency. At $\alpha = 18^\circ$, a distinct positive gradient is observed for both Mach numbers. The pronounced increase in C_{my} starts at $\alpha = 19^\circ$ and is considerably more pronounced for $Ma = 0.85$. At $Ma = 0.55$, a distinct increase in C_{my} is observed from $\alpha = 21^\circ$.

Overall, the comparison of both coefficients demonstrates that increasing Mach number leads to an earlier onset of buffet and a stronger rise in the pitching moment, while also amplifying the nonlinear aerodynamic response. These effects are consistent with the enhanced compressibility and transonic shock-vortex interactions observed at higher Mach numbers.

4.2 Surface Pressure Distributions

Figure 12(a) shows the surface pressure coefficient distributions at the pressure section S_1 ($x/l = 0.371$), located at the LEVCON described in Section 2.2, for the quasi-rigid QR-28 configuration at $Ma = 0.55$ and selected angles of attack. Distinct suction peaks associated with the leading-edge vortex system are clearly identified along the spanwise direction. The inboard vortex (IBV) is observed at $y/s = 0.122$ as a local suction peak, while the midboard vortex (MBV) is identified at $y/s = 0.205$. With increasing angle of attack, the magnitude of the vortex-induced suction peaks increases, reflecting the strengthening of the vortex system at the LEVCON. Even after the buffet onset at $\alpha = 21^\circ$, the MBV-induced suction peak remains largely unaffected, indicating that the vortex system at the LEVCON retains a stable structure despite increasingly unsteady flow conditions.

Figure 12(b) shows the pressure coefficient distributions at the pressure section S_2 ($x/l = 0.556$), located in the rear strake region near the kink connecting the strake and the main wing. At $\alpha = 15^\circ$, distinct suction peaks associated with the inboard vortex (IBV) and the midboard vortex (MBV) are observed at $y/s = 0.227$ and $y/s = 0.346$, respectively, indicating stable vortex structures. At the buffet onset condition of $\alpha = 21^\circ$, the IBV suction peak remains lo-

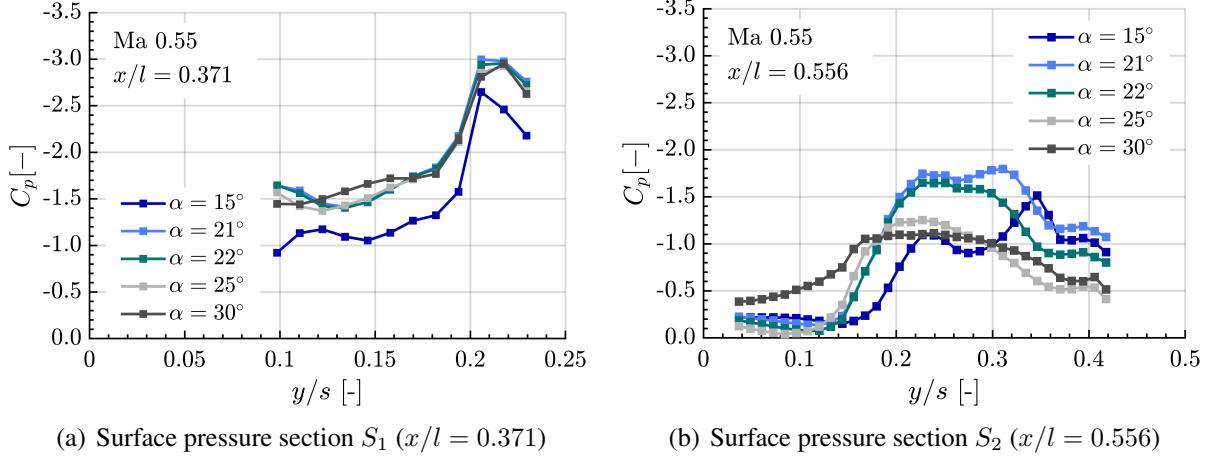


Figure 12: Mean surface pressure coefficient distributions C_p for the quasi-rigid QR-28 configuration of the DLR-F23-T model at $Ma = 0.55$ for selected angles of attack.

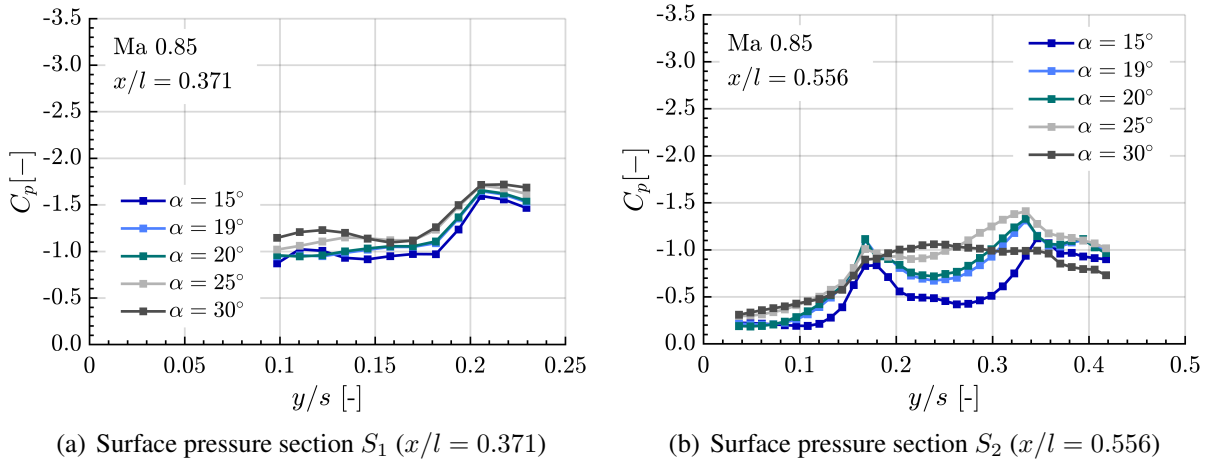


Figure 13: Mean surface pressure coefficient distributions C_p for the quasi-rigid QR-28 configuration of the DLR-F23-T model at $Ma = 0.85$ for selected angles of attack.

cated at approximately the same spanwise position, while the MBV suction peak shifts inboard to $y/s = 0.310$. This inboard displacement indicates a modification of the vortex trajectory associated with the onset of increasingly unsteady flow conditions. For $\alpha = 22^\circ$, after the buffet onset, the IBV suction peak remains clearly visible at nearly the same location. In contrast, the MBV no longer exhibits a distinct suction peak, indicating the onset of vortex breakdown within the investigated pressure section. At higher angles of attack of $\alpha = 25^\circ$ and $\alpha = 30^\circ$, no pronounced vortex-induced suction peaks are observed. Instead, the pressure distributions exhibit a significantly smoother behavior, indicating the breakdown and subsequent loss of coherence of the vortex structures in the rear strake region.

Figure 13(a) shows the pressure coefficient distributions at the pressure section S_1 ($x/l = 0.371$) at the LEVCON at $Ma = 0.85$. At $\alpha = 15^\circ$, distinct suction peaks associated with the inboard vortex (IBV) and the midboard vortex (MBV) are identified at $y/s = 0.110$ and $y/s = 0.206$, respectively, indicating coherent vortex structures. At the buffet onset condition of $\alpha = 19^\circ$, no pronounced IBV-induced suction peak can be identified. In contrast, the MBV suction peak remains nearly unchanged at $y/s = 0.206$, indicating that the MBV structure remains stable despite the onset of buffet. A very similar pressure distribution is observed at $\alpha = 20^\circ$, beyond the buffet onset condition. At higher angles of attack of $\alpha = 25^\circ$ and $\alpha = 30^\circ$, the MBV-induced

suction peak persists, indicating that the vortex structure at the LEVCON retains a stable behavior even under increasingly unsteady flow conditions.

Figure 13(b) shows the pressure coefficient distributions at the pressure section S_2 ($x/l = 0.556$) at $Ma = 0.85$. At $\alpha = 15^\circ$, distinct suction peaks associated with the IBV and the MBV are observed at $y/s = 0.170$ and $y/s = 0.346$, respectively, indicating stable vortex structures in the rear strake region. With increasing angle of attack toward the buffet onset condition at $\alpha = 19^\circ$, the suction peaks associated with both the IBV and the MBV become more pronounced. In addition, the MBV suction peak shifts further inboard to $y/s = 0.335$, indicating a modification of the vortex trajectory with increasing angle of attack. Immediately beyond the buffet onset at $\alpha = 20^\circ$, the pressure distribution remains largely unchanged compared to the buffet onset condition, indicating that the vortex structures are still coherent in the investigated pressure section. At $\alpha = 25^\circ$ the IBV-induced suction peak remains identifiable, whereas the MBV suction peak becomes broader and less pronounced. At $\alpha = 30^\circ$, the pressure distribution no longer exhibits distinct vortex-induced suction peaks, indicating a substantial loss of vortex structures.

4.3 Surface Pressure Fluctuations

Figure 14(a) shows the RMS values of the surface pressure coefficient fluctuations $C_{p,rms}$ at selected sensor positions of pressure section S_1 ($x/l = 0.371$) at $Ma = 0.55$. For all investigated sensor positions, comparatively low RMS values are observed in the low-angle-of-attack regime up to approximately $\alpha = 20^\circ$, indicating predominantly stable flow conditions with only minor pressure fluctuations. At the buffet onset condition of $\alpha = 21^\circ$, a distinct increase in $C_{p,rms}$ is observed at all sensor locations, indicating the onset of significant unsteady pressure fluctuations associated with buffet. Beyond the buffet onset, the RMS levels remain approximately constant up to angles of attack of $\alpha = 25^\circ$. For higher angles of attack above $\alpha = 26^\circ$, a pronounced increase in the RMS values is observed, particularly for the sensor locations at larger spanwise positions.

Figure 14(b) shows the $C_{p,rms}$ values at selected sensor positions of pressure section S_2 ($x/l = 0.556$) for the quasi-rigid configuration at $Ma = 0.55$. For low angles of attack up to $\alpha = 10^\circ$, comparatively low RMS values are observed at all sensor locations, indicating stable flow conditions with only minor pressure fluctuations. With increasing angle of attack, a gradual increase in $C_{p,rms}$ is observed, particularly for the sensor positions located near the IBV and MBV trajectories (see Section 4.2). At the buffet onset condition of $\alpha = 21^\circ$, a pronounced increase in the RMS values occurs at all investigated sensor locations. The strongest increase is observed for the sensor position at $y/s = 0.311$, where a distinct peak in $C_{p,rms}$ is reached after the buffet onset. This behavior indicates strongly intensified unsteady flow phenomena associated with the onset of vortex breakdown in the rear strake section. For higher angles of attack above $\alpha = 24^\circ$, the RMS levels remain elevated for all sensor positions.

Figure 15(a) shows the $C_{p,rms}$ values of pressure section S_1 ($x/l = 0.371$) for the quasi-rigid configuration at $Ma = 0.85$. In contrast to the corresponding results at $Ma = 0.55$, comparatively low RMS levels are observed over the entire investigated angle-of-attack range for all sensor positions, indicating only minor unsteady pressure fluctuations. A moderate increase in $C_{p,rms}$ is observed for the sensor position at $y/s = 0.194$ in the angle-of-attack range between $\alpha = 21^\circ$ and $\alpha = 25^\circ$. The results indicate that the vortex system at the LEVCON remains stable at $Ma = 0.85$, with only weak pressure fluctuations and no significant buffet-induced unsteadiness.

Figure 15(b) presents the $C_{p,rms}$ values of pressure section S_2 ($x/l = 0.556$) for the quasi-rigid configuration at $Ma = 0.85$. For low angles of attack up to $\alpha = 18^\circ$, comparatively low RMS

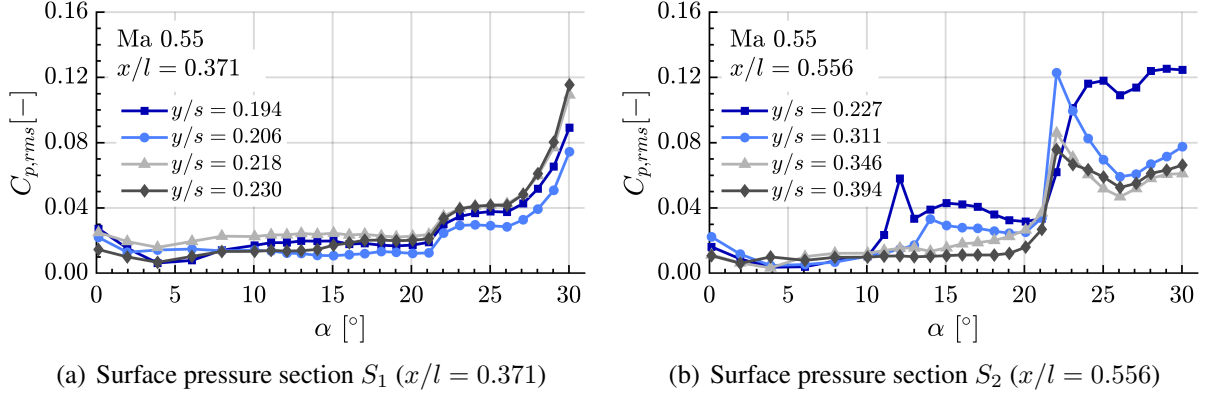


Figure 14: RMS values of the surface pressure coefficient $C_{p,rms}$ for selected pressure sensors of the quasi-rigid QR-28 configuration of the DLR-F23-T model at $Ma = 0.55$ as a function of angle of attack.

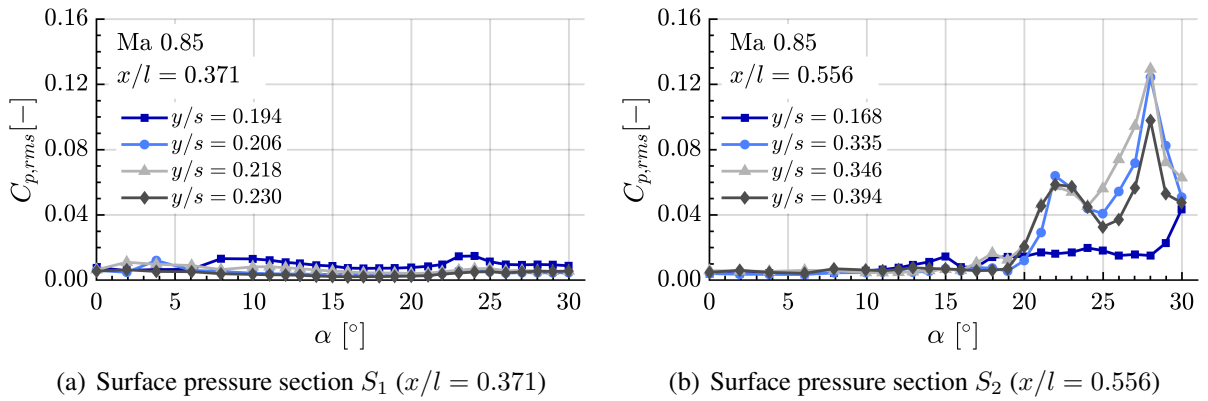


Figure 15: RMS values of the surface pressure coefficient $C_{p,rms}$ for selected pressure sensors of the quasi-rigid QR-28 configuration of the DLR-F23-T model at $Ma = 0.85$ as a function of angle of attack.

values are observed at all investigated sensor positions, indicating steady flow conditions with only minor pressure fluctuations. At angles of attack exceeding $\alpha = 20^\circ$, a pronounced increase in $C_{p,rms}$ is observed for the sensor positions located near the MBV trajectory, particularly at $y/s = 0.335$, $y/s = 0.346$, and $y/s = 0.394$. For the three previously mentioned sensor positions, a local maximum in $C_{p,rms}$ is observed at $\alpha = 23^\circ$. At angles of attack above $\alpha = 25^\circ$, the RMS values increase again and reach their maximum at $\alpha = 28^\circ$. In contrast, no pronounced increase in $C_{p,rms}$ is observed for the more inboard sensor position at $y/s = 0.168$. Overall, the results suggest that the onset of pronounced pressure fluctuations is closely associated with the progressive destabilization of the MBV-dominated flow structures in the rear strake region.

4.4 Spectral Analysis of Pressure Fluctuations at the Vertical Tail

Figure 16 shows the power spectral density (PSD) of the surface pressure fluctuations c'_p measured at the inboard side (Kulite 1) of the rigid vertical tail (QR-28) for selected angles of attack at $M = 0.55$. At the pre-buffet condition of $\alpha = 15^\circ$, comparatively low PSD levels are observed over the entire investigated frequency range, indicating only minor unsteady pressure fluctuations at the vertical tail. At the buffet onset condition of $\alpha = 21^\circ$, a noticeable increase in the PSD levels is observed, particularly in the intermediate frequency range. At $\alpha = 22^\circ$, following the buffet onset, the PSD amplitudes increase significantly over a broad frequency range, indicating strongly intensified buffet-induced flow unsteadiness. A pronounced broadband spectral peak is identified at $f = 447$ Hz, corresponding to a reduced frequency of $k = 0.92$. The occurrence of this dominant buffet peak indicates the presence of characteristic unsteady

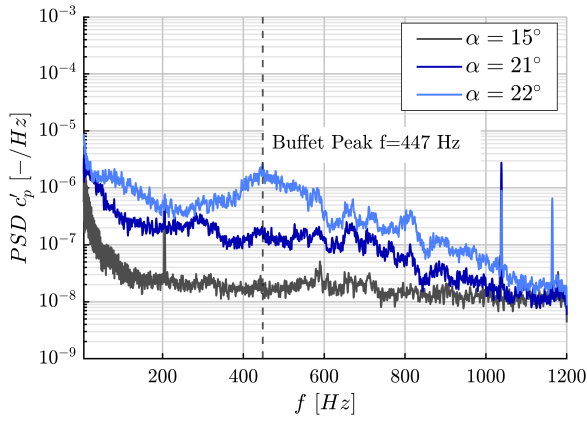
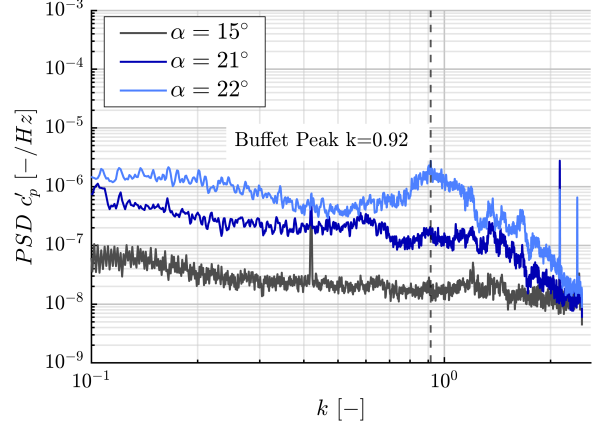
(a) Kulite 1 VT inboard ($x/l = 0.943$)(b) Kulite 1 VT inboard ($x/l = 0.943$)

Figure 16: Power spectral density (PSD) of the surface pressure fluctuations c'_p at the inboard side of the rigid vertical tail (QR-28) for selected angles of attack at $Ma = 0.55$.

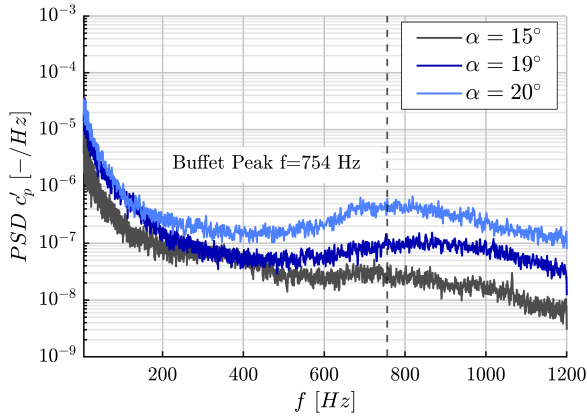
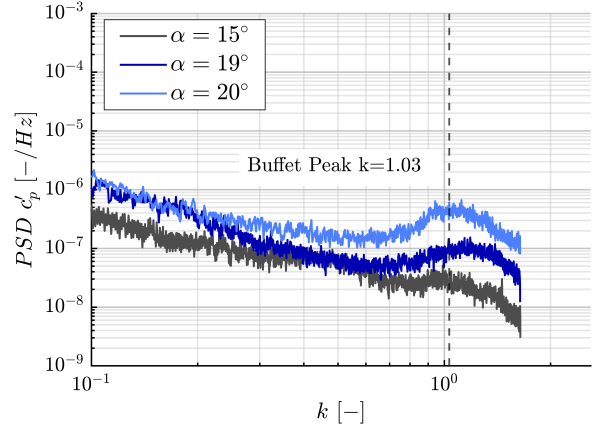
(a) Kulite 26 VT outboard ($x/l = 1.012$)(b) Kulite 26 VT outboard ($x/l = 1.012$)

Figure 17: Power spectral density (PSD) of the surface pressure fluctuations c'_p at the outboard side of the rigid vertical tail (QR-28) for selected angles of attack at $Ma = 0.85$.

flow structures associated with vortex breakdown and buffet-induced unsteady flow phenomena. Overall, the PSD analysis indicates a significant amplification of buffet-induced pressure fluctuations at the vertical tail after the buffet onset, consistent with the increased flow unsteadiness identified in the RMS analysis (see Section 4.3). Figure 17 shows the power spectral density (PSD) of the surface pressure fluctuations c'_p measured at the outboard side (Kulite 25) of the rigid vertical tail (QR-28) for selected angles of attack at $Ma = 0.85$. At the pre-buffet condition of $\alpha = 15^\circ$, comparatively low PSD levels are observed over the entire investigated frequency range, indicating only minor unsteady pressure fluctuations at the vertical tail. At the buffet onset condition of $\alpha = 19^\circ$, the PSD levels increase noticeably over a broad frequency range, indicating the onset of intensified buffet-induced flow unsteadiness. A further increase in the PSD amplitudes is observed at $\alpha = 20^\circ$, immediately beyond the buffet onset condition, particularly in the frequency range associated with the dominant buffet-related spectral peak. A pronounced broadband spectral peak is identified at $f = 754$ Hz, corresponding to a reduced frequency of $k = 1.03$. The occurrence of this dominant buffet peak indicates characteristic unsteady flow phenomena associated with vortex breakdown and shock-vortex interaction in the transonic flow regime, resulting in intensified buffet-induced pressure fluctuations acting on the vertical tail. Although the investigated flow conditions differ significantly between $Ma = 0.55$

and $Ma = 0.85$, the dominant buffet-related spectral peak occurs in both cases at a reduced frequency close to $k = 1$. This suggests a similar non-dimensional scaling behavior of the dominant buffet dynamics on the vertical tail and indicates that the characteristic unsteady flow phenomena evolve on comparable normalized time scales.

5 STRUCTURAL RESPONSE ANALYSIS TO BUFFET EXCITATION

Figure 18 presents the dimensionless RMS values of the structural acceleration response measured at selected accelerometer positions at the wing and the vertical tail of the QR-28 configuration for $Ma = 0.55$ and $Ma = 0.85$ as a function of angle of attack. For both Mach numbers, the structural acceleration response remains at a very low level up to approximately $\alpha = 10^\circ$, indicating steady aerodynamic flow conditions with only minor structural excitation. At angles of attack above approximately $\alpha = 10^\circ$, an initial increase in the RMS acceleration levels is observed for both Mach numbers. At $Ma = 0.55$, a pronounced increase in the RMS acceleration levels occurs at $\alpha = 20^\circ$. The strongest response at $\alpha = 22^\circ$ is observed at the vertical tail accelerometer (ACC VT), indicating significant buffet-induced structural excitation of the VT. In addition, the sensor position ACC Wing 3 exhibits a noticeable increase in the RMS levels, whereas the responses at ACC Wing 1 and ACC Wing 2 remain comparatively low over the investigated angle-of-attack range. Beyond the peak at $\alpha = 22^\circ$, the RMS acceleration levels at the vertical tail continue to increase toward higher angles of attack, indicating intensified unsteady aerodynamic excitation associated with vortex breakdown and separated flow phenomena.

For $Ma = 0.85$, the structural response exhibits a similar overall behavior, although the onset of intensified structural excitation occurs at lower angles of attack. A pronounced increase in the RMS acceleration levels is observed at $\alpha = 18^\circ$ to $\alpha = 20^\circ$, again corresponding closely to the buffet onset condition identified from the aerodynamic analyses (see Section 4.1). The largest structural response is observed at the vertical tail accelerometer, where a distinct local maximum occurs at $\alpha = 20^\circ$. Compared to the subsonic case at $Ma = 0.55$, the transonic condition at $Ma = 0.85$ exhibits stronger structural excitation at lower angles of attack, which is likely associated with additional shock-induced unsteady flow phenomena and shock-vortex interaction effects. Overall, the acceleration measurements demonstrate a strong coupling between the buffet-induced aerodynamic unsteadiness and the structural response of the model, with the vertical tail exhibiting the highest sensitivity to the unsteady aerodynamic loading.

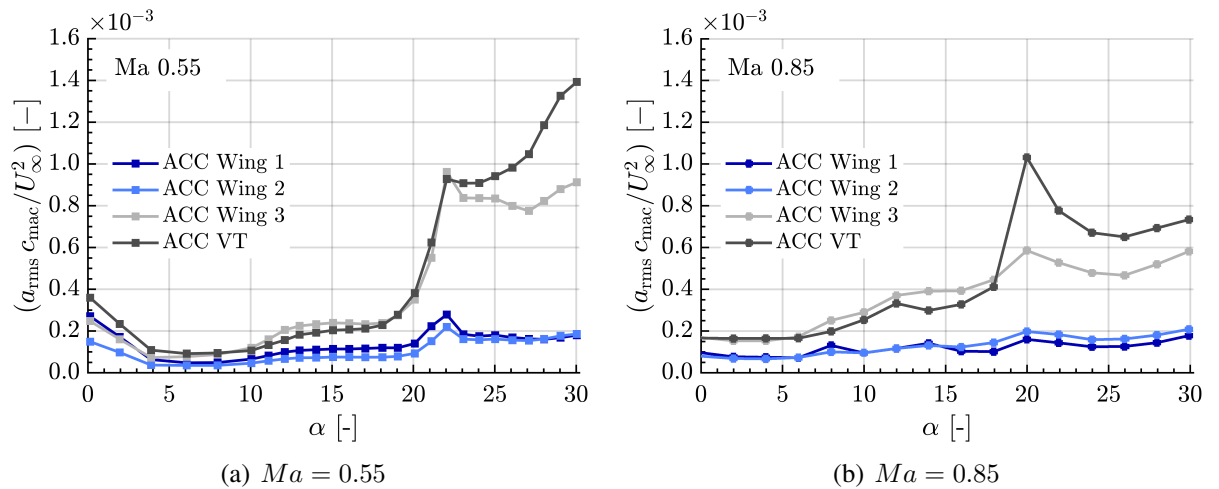


Figure 18: Dimensionless RMS values of the buffet-induced structural acceleration response measured at selected accelerometer positions of the QR-28 configuration as a function of angle of attack.

6 LIFT AND PITCHING MOMENT HYSTERESIS

To investigate nonlinear aerodynamic effects induced by the vortex-dominated flow field, quasi-steady angle-of-attack sweeps with different sweep rates ($0.10^\circ/\text{s}$, $0.25^\circ/\text{s}$, and $0.50^\circ/\text{s}$) were performed under both subsonic and transonic flow conditions. Figures 19 and 20 show the resulting hysteresis characteristics of the lift coefficient C_L and the pitching moment coefficient C_{my} for the quasi-rigid QR-28 configuration at $Ma = 0.55$ and $Ma = 0.85$, respectively. At $Ma = 0.55$, the lift coefficient exhibits pronounced hysteresis characteristics at higher angles of attack. Up to $\alpha = 10^\circ$, only small deviations between the upstroke and downstroke sweeps are observed. With increasing angle of attack, the hysteresis becomes more pronounced. The largest deviations occur between $\alpha = 18^\circ$ and $\alpha = 24^\circ$, where significant differences in lift level are observed. These hysteresis effects may be associated with delayed vortex breakdown, vortex interaction, and vortex merging processes within the complex vortex-dominated flow field. A comparable hysteresis behavior is observed for the pitching moment coefficient C_{my} . In particular, pronounced differences between the upstroke and downstroke sweeps are observed in the medium and high angle-of-attack range, indicating significant nonlinear variations in the aerodynamic loading and center-of-pressure position.

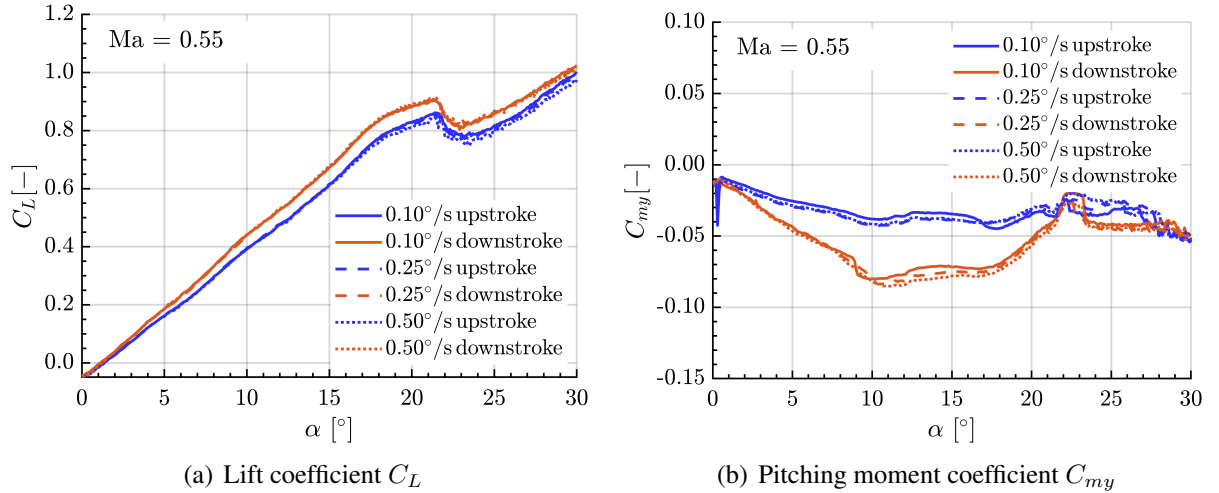


Figure 19: Quasi-steady lift coefficient C_L (left) and pitching moment coefficient C_{my} (right) hysteresis characteristics of the DLR-F23-T QR-28 quasi-rigid configuration at $Ma = 0.55$ and $Re_{l\mu} = 2.31 \times 10^6$.

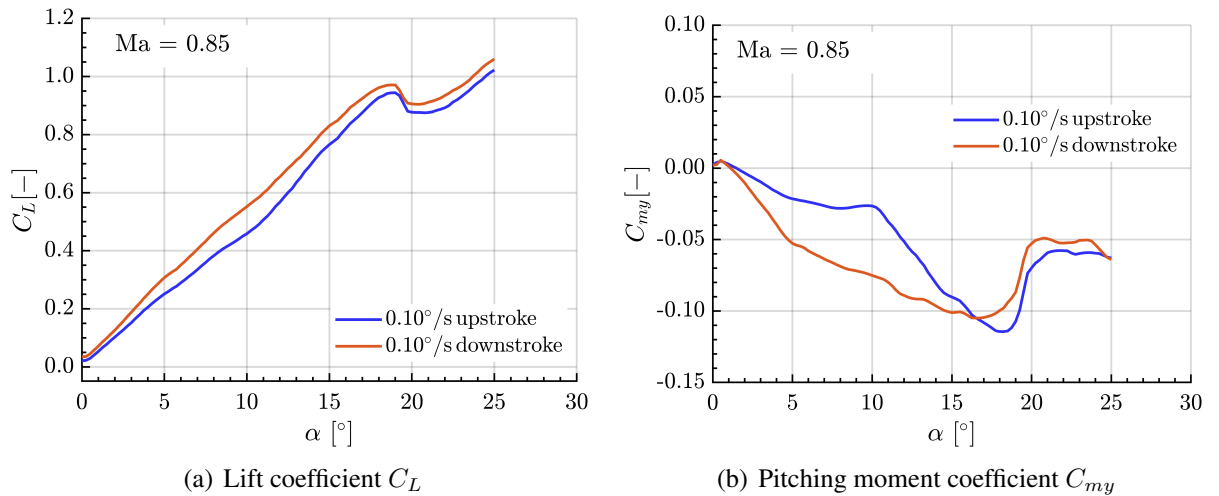


Figure 20: Quasi-steady lift coefficient C_L (left) and pitching moment coefficient C_{my} (right) hysteresis characteristics of the DLR-F23-T QR-28 quasi-rigid configuration at $Ma = 0.85$ and $Re_{l\mu} = 3.02 \times 10^6$.

At $Ma = 0.85$, both the lift coefficient C_L and the pitching moment coefficient C_{my} exhibit noticeable hysteresis characteristics. For the lift coefficient, only minor deviations between the upstroke and downstroke sweeps are observed at low angles of attack. With increasing angle of attack, the hysteresis effects become more pronounced, particularly between approximately $\alpha = 10^\circ$ and $\alpha = 20^\circ$. In this range, the downstroke sweep exhibits consistently higher lift levels compared to the upstroke sweep. Around $\alpha = 19^\circ$ to $\alpha = 20^\circ$, a distinct local reduction in lift is observed for both sweep directions, which is associated with the onset of vortex breakdown and additional shock-induced flow separation effects in the transonic flow regime. The pitching moment coefficient exhibits even more pronounced hysteresis characteristics. Significant differences between the upstroke and downstroke sweeps are observed over a wide angle-of-attack range, indicating strong nonlinear variations in the aerodynamic loading and center-of-pressure position. In particular, the downstroke sweep is characterized by considerably stronger nose-down pitching moment levels up to $\alpha = 16^\circ$. Beyond $\alpha = 20^\circ$, both sweep directions exhibit a rapid recovery toward less negative pitching moment values. Compared to the subsonic case at $Ma = 0.55$, the transonic condition at $Ma = 0.85$ exhibits additional nonlinear aerodynamic effects likely associated with shock-vortex interaction and shock-induced separation phenomena.

7 CONCLUSION

In this study, vertical tail buffeting on the DLR-F23-T triple-delta-wing configuration was investigated for the quasi-rigid QR-28 configuration at representative subsonic and transonic Mach numbers, with particular emphasis on the identification of buffet onset and the resulting aerodynamic and structural response of the vertical tail. Aerodynamic loads, surface pressure fluctuations, structural response characteristics, and quasi-steady hysteresis effects were analyzed to improve the understanding of the buffet-induced aerodynamic and structural behavior of the vertical tail.

The experimental modal analysis identified the dominant structural modes and corresponding eigenfrequencies of the investigated DLR-F23-T configuration. The results revealed strong coupling between bending and torsional modes, which is characteristic of low-aspect-ratio triple-delta-wing configurations. While the two quasi-rigid configurations exhibited largely similar modal characteristics, the flexible configuration showed a distinct modification of the structural dynamics, demonstrating the significant influence of structural flexibility on the dynamic response of the vertical tail. The aerodynamic analysis highlighted the nonlinear lift and pitching moment characteristics of the triple-delta-wing configuration. Buffet onset was determined from the evaluation of the lift and pitching moment characteristics and the corresponding aerodynamic load fluctuations. The buffet onset shifted from $\alpha = 21^\circ$ at $Ma = 0.55$ to $\alpha = 19^\circ$ at $Ma = 0.85$, indicating an increasing influence of compressibility effects on the stability of the vortex system. Furthermore, the transonic flow condition exhibited a stronger nonlinear aerodynamic response and increased aerodynamic load fluctuations, which are likely associated with vortex-shock interactions and shock-induced vortex breakdown. The surface pressure distributions provided detailed insight into the evolution of the vortex-dominated flow field and the associated buffet mechanisms. While the vortex structures in the LEVCON region remained largely coherent beyond buffet onset, significant changes in the rear strake region indicated the onset of vortex breakdown and the progressive loss of vortex coherence. The surface pressure fluctuation analysis demonstrated that buffet onset is accompanied by a significant increase in unsteady pressure fluctuations, particularly in the rear strake region, where the destabilization of the dominant vortex structures was observed. The spectral analysis of the pressure fluctuations at the vertical tail revealed a pronounced increase in buffet-induced unsteadiness beyond

buffet onset. For both Mach numbers, a dominant buffet-related spectral peak was identified at a reduced frequency close to $k \approx 1$, indicating a similar non-dimensional scaling of the dominant buffet phenomenon. The structural response analysis demonstrated a significant increase in buffet-induced structural excitation beyond buffet onset. The strongest response was consistently observed at the vertical tail, demonstrating its high sensitivity to unsteady aerodynamic flow. In addition, the transonic condition exhibited an earlier onset of structural excitation, consistent with the aerodynamic buffet characteristics. The quasi-steady hysteresis investigations revealed pronounced hysteresis effects in both the lift and pitching moment characteristics, indicating significant nonlinear aerodynamic responses to changes in angle of attack. These effects are likely associated with vortex breakdown, vortex interaction, and vortex merging processes, while additional nonlinearities were observed under transonic flow conditions due to shock-related flow phenomena.

Future work will focus on the investigation of the flexible DLR-F23-T vertical-tail configurations and the associated aeroelastic response under buffet excitation. Particular attention will be given to the interaction between vortex-dominated flow phenomena and structural dynamics under transonic flow conditions. In addition, ongoing unsteady pressure-sensitive paint measurements will provide further insight into the observed lift and pitching moment hysteresis characteristics and the vortex-dominated flow phenomena responsible for these nonlinear aerodynamic effects.

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