

Investigation of time- and spatially-resolved surface pressures on an aeroelastically scaled aircraft model in low-speed, high-angle-of-attack conditions

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ABSTRACT

This study investigates the unsteady aerodynamic surface pressures on a full-span, aeroelastically scaled, flexible aircraft model of double delta wing type focusing on low-speed, high-angle-of-attack conditions. Experiments were conducted in the TUM-AER wind tunnel at $Ma_\infty = 0.15$ using a synchronized measurement setup featuring fast-response pressure-sensitive paint and high-speed photogrammetry sampled at 5000 Hz. This work utilizes a sting-mounted full model, including fuselage, wings, horizontal tailplanes, and vertical fins, to capture flow phenomena associated with leading-edge vortex bursting and structural dynamics interactions. Comparisons between rigid and aeroelastically scaled configurations reveal distinct differences in flow topology; specifically, the rigid configuration exhibits a vortex breakdown location further upstream compared to the flexible case. The findings in this work highlight the critical role of fluid-structure interaction in determining buffet loads.

1. Introduction

The flow field around modern, high-agility aircraft configurations is characterized by the formation of complex vortical flow structures and large regions of flow separation at low subsonic speeds and medium to high angles of attack. Depending on the configuration, the vortices reach an unstable state at a certain angle of attack, which is known as vortex-bursting and results in higher turbulence intensities downstream of the breakdown (Breitsamter, 2008). Furthermore, burst frequency content at specific bandwidths occurs. Flow separation, especially associated with leading-edge vortices, in the higher angle of attack range leads to structural excitation at the wing as well as at downstream located elements such as tail planes. The structural response to the excitation through the unsteady flow field is commonly referred to as buffeting (Mabey, 1988). This can result in severe structural damage and deterioration of handling qualities. Due to its criticality and complexity, buffeting has

long been the subject of both numerical and experimental research. For the experimental analysis of buffeting effects, an aeroelastic full-span wind tunnel model (AWTMF) of double delta wing type was developed at the Chair of Aerodynamics and Fluid Mechanics of the Technical University of Munich (TUM) and features quasi-rigid components as well as elements scaled according to structural elasticity and dynamic similarity laws (cf. Stegmüller et al., 2022, 2025, 2026). The full model was developed based on the experiences obtained from the investigations with an aeroelastic half model (Katzenmeier et al., 2021). To provide structural elasticity, the $76^\circ/40^\circ$ double-delta wings, the horizontal tail planes (HTPs) and the vertical tail planes (fins) are 3D-printed from polylactide (PLA). As reference cases, aluminium wings, HTPs and fins can be mounted on the modular wind tunnel model. The modular concept is illustrated in Fig. 1, where the rigid lifting surfaces are shown on the left-hand side and the aeroelastically scaled (AES), flexible components on the right-hand side. This paper presents the first application of the previously validated pressure-sensitive paint

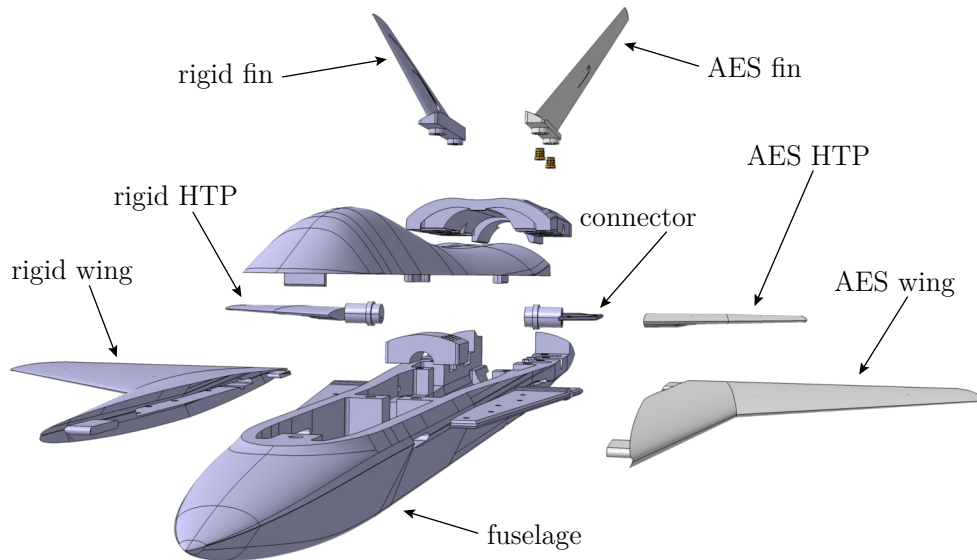


Figure 1. Modular concept of the wind tunnel model Stegmüller et al. (2026).

(PSP) and synchronized photogrammetry setup (cf. Katzenmeier et al., 2023) to a full-span aircraft model with rigid and flexible wing, HTP, and fin configurations. The study aims to characterize unsteady pressure footprints of vortex breakdown at low-speed flow conditions ($Ma_\infty = 0.15$). Building on the previously validated measurement approach for a flexible half-model configuration (cf. Katzenmeier et al., 2023), we successfully applied the PSP measurement methodology to the present full-model configuration in order to resolve surface pressures with high spatio-temporal resolution. In contrast to the earlier half-model study, the present work additionally includes the vertical fin and considers vortex systems interactions between starboard and port sides. Finally, by comparing the flexible and rigid configurations, this study investigates how wing and tail flexibility influences the overall vortex dynamics. The post-processing tool chain from Katzenmeier et al. (2023) is extended and optimized by implementing snapshot Proper Orthogonal Decomposition, improving the alignment of flexible components affected by vibration and deformation, and applying optimized spatial filtering and optimized temporal detrending. The measurements are performed

in the Göttingen-type TUM-AER wind tunnel A at a Reynolds number of $Re_{1/m} = 3.20 \times 10^6$, which corresponds to a Mach number of $Ma_\infty = 0.15$ and a freestream velocity of $U_\infty = 51$ m/s.

The present paper is structured as follows. Section 2 describes the flow field classification, including the vortex topology of the $76^\circ/40^\circ$ double-delta wing and the buffet-relevant flow mechanisms. Section 3 presents the experimental methodology, including the fast-response PSP technique, the measurement setup, the data analysis toolchain, and the validation of the unsteady PSP measurements against Kulite reference signals. In Section 4, the results of the wind tunnel experiments are analyzed and discussed with a focus on the comparison between the rigid and AES configurations. First, the surface pressure fluctuations are examined based on the $c_{p,rms}$ maps on the wing and HTP. Subsequently, the spectral content of the pressure fluctuations is analyzed at selected measurement positions using the power spectral density (PSD) distributions of c'_p , with particular focus on the helical mode instability (HMI) of the inboard vortex (IBV), midboard vortex (MBV), and horizontal-tailplane vortex (HTPV), as well as their possible coupling with structural eigenmodes. Section 5 summarizes the findings and provides an outlook.

2. Flow field classification

At the investigated flow conditions, two primary vortices develop along the wing leading edge. Even at a low angle of attack, the flow around the highly swept strake leading edge ($\varphi_{W,1} = 76^\circ$) can no longer remain attached to the wing contour, resulting in the formation of a large-scale leading-edge vortex. The IBV develops from the apex region and rolls up along the strake leading edge. A second primary vortex, referred to as the MBV, originates at the leading-edge kink and follows the 40° sweep of the outboard wing section. Fully developed leading-edge vortices are characterized by high axial core velocities, low static pressure, and high dissipation rates. The associated overspeeds on the wing upper surface increase the suction level and produce the nonlinear lift contribution typical of delta wings (Breitsamter, 2008). Due to the low static pressure in both vortex cores, the IBV and MBV move toward each other and begin to interact (Verhaagen et al., 1995). A simplified illustration of the vortex topology and vortex bursting locations on a $76^\circ/40^\circ$ double-delta wing at $\alpha = 20^\circ$ is shown in Fig. 2a (Verhaagen, 1983). Vortex bursting is marked by an abrupt divergence of the vortex streamlines and a sudden increase in vortex diameter (Gursul, 1995). Downstream of the bursting location, the flow field is dominated by large-scale turbulent structures, which subsequently break down into smaller vortices and dissipate.

With increasing angle of attack, the vortex bursting location moves upstream, causing a progressively larger portion of the wing to be exposed to the turbulent post-breakdown flow, which results in reduced lift (Breitsamter, 2008). For a $76^\circ/40^\circ$ double-delta wing, the MBV generally bursts at a lower angle of attack than the IBV (Verhaagen, 1983). This behavior is consistent with the influence of leading-edge sweep, since larger sweep angles stabilize leading-edge vortices and delay vortex breakdown, whereas lower sweep angles reduce vortex stability (Hitzel et al., 2020).

Unsteady phenomena in vortex-dominated flows strongly affect the stability and control characteristics of delta-wing configurations. Downstream of leading-edge vortex breakdown, the flow field

contains high turbulence intensities and pronounced velocity and pressure fluctuations (Breitsamter, 2008). These quasi-periodic fluctuations are associated with the HMI of the breakdown flow (Gursul et al., 2005). As the angle of attack increases and the breakdown location shifts upstream, the spectra of the velocity fluctuations show a narrowband range with a dominant frequency f_{dom} , indicating a concentration of turbulent kinetic energy within a narrow frequency band (Breitsamter, 2008). The dominant reduced frequency k_{dom} can be related to wing geometry, especially the leading-edge sweep φ_W , and to the flight condition, including freestream velocity U_∞ and angle of attack (Breitsamter, 1997). The wake instability can excite wing and tail structures at their natural frequencies, particularly in the first bending and torsion modes, and thereby lead to buffeting (Breitsamter, 2008; Hirschel et al., 2021). For elastic fins, the fluid-structure interaction involves coupling between structural vibrations and several unsteady flow phenomena, as schematically illustrated in Fig. 2b (Breitsamter, 2008).

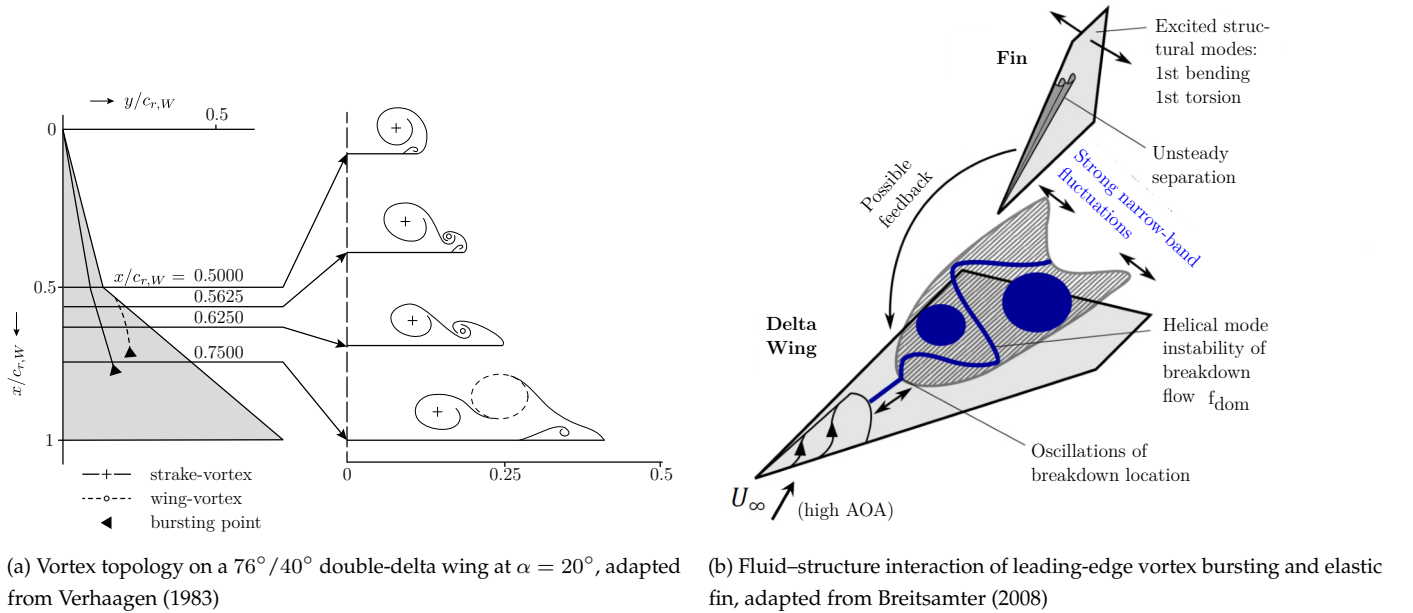


Figure 2. Flow field classification (Stegmüller et al., 2026).

3. Experimental methodology

3.1. Fast-response pressure-sensitive paint

Fast-response PSP measurements were conducted at selected angles of attack $\alpha = 20^\circ, 25^\circ, 30^\circ$, and 35° to investigate the unsteady surface pressures, including frequency content, on the wing and the HTP for the rigid and the AES configurations. As a non-intrusive optical measurement technique, PSP enables the determination of unsteady surface pressure changes with high spatial and temporal resolution (cf. Katzenmeier et al., 2023). The applied PSP was initially developed by Ponomarev & Gouterman (1998) and was further refined by Gregory et al. (2002b, 2002a, 2004). The PSP

composition applied in this work corresponds to that used for the aeroelastic half-span wind tunnel model (AWTM) measurements and is described in detail by Katzenmeier et al. (2023). Based on this reference, the following provides a brief overview. The paint was modified from the formulation of Gregory (2004) and consists of a polymer-ceramic base layer and an active layer (Gößling et al., 2020). The base-layer mixture comprises a polymer (Duromax B-1000), ceramic particles (titanium silicon oxide, TiSiO_4 , 50 nm), a dispersant (Aldrich PANA 4160029), and distilled water, whereas the active layer contains toluene and platinum(II) meso-tetrakis(pentafluorophenyl)porphyrin (PtTFPP) (Gößling et al., 2020). Figure 5 illustrates the paint composition of the polymer/ceramic type fast-response PSP. This PSP formulation has been successfully applied and validated in various studies (cf. Gößling et al., 2020, 2023; Hilfer et al., 2020, 2022; Schroll et al., 2022; Katzenmeier et al., 2023; Klein et al., 2026).

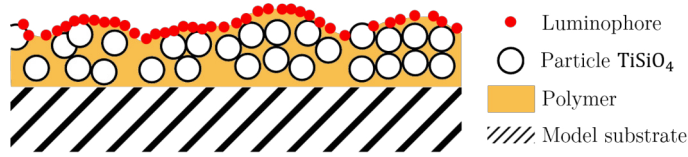


Figure 3. Polymer/ceramic type fast-response PSP based on Gößling et al. (2020).

The luminescent molecules are excited by illumination at an appropriate wavelength (i.e 395nm) and subsequently emit luminescent light at a longer wavelength (650nm), which is recorded using a camera. This signal is governed by oxygen quenching, which causes a decrease of the luminescent intensity with increasing partial pressure of oxygen, and thus with increasing air pressure. As for the half-model (cf. Katzenmeier et al., 2023), the intensity method is used to determine the unsteady pressure distribution with PSP. Based on the Stern-Volmer equation (cf. Liu et al., 2021),

$$\frac{I_{\text{ref}}}{I} = A + B \frac{p}{p_{\text{ref}}} \quad (1)$$

the relation between the luminescent intensity I and the pressure p is determined using the predetermined, temperature-dependent coefficients A and B , where I_{ref} and p_{ref} denote the luminescent intensity and the pressure at the reference condition. In wind-tunnel experiments, including the measurements presented in this work, I_{ref} is obtained from the wind-off intensity, or wind-off image, recorded under wind-off conditions (constant and known pressure on the whole surface).

Further details on the operating principle of fast-response PSP and paint compositions are provided by Liu et al. (2021) and in the review by Gregory et al. (2008).

The coating thickness is adjustable in the range 15 μm to 35 μm , and the surface roughness in the range 0.6 μm to 1.2 μm (Katzenmeier et al., 2023). For the paint used in this work, the pressure sensitivity is 77.0 %/100 kPa and the temperature sensitivity is 2.3 %/K at the reference condition $p_{\text{ref}} = 100 \text{ kPa}$ and $T_{\text{ref}} = 293 \text{ K}$ (Gößling et al., 2020). Following the first-order-system modelling of the PSP response to a sinusoidal acoustic excitation proposed by Sugimoto et al. (2017), an initial time constant of $\tau = 25 \mu\text{s}$ yields a gain change of approximately -0.1 dB at $f = 1000 \text{ Hz}$ and approximately -2.2 dB at $f = 5000 \text{ Hz}$ (Gößling et al., 2020). Since the temperature change in the

test section during the measurement is at most 1 K to 2 K and compared to the pressure changes is several orders of magnitude slower, the effects of the temperature sensitivity can be neglected for the present investigations of unsteady pressure fluctuations (cf. Gößling et al., 2020; Katzenmeier et al., 2023).

3.2. Measurement setup

The measurement setup consists of the optical system placed outside of the wind tunnel's open test section, alongside a conventional setup consisting of unsteady pressure sensors and accelerometers (ACCs) embedded inside the model surfaces. Figure 4 shows, on the left-hand side, the PSP measurement setup with 26 high-power ultraviolet (UV) light-emitting diodes (LEDs) as illumination sources and four high-speed cameras (Phantom v2640) and, on the right-hand side, the sting-mounted wind-tunnel model integrated into the test section under UV illumination.

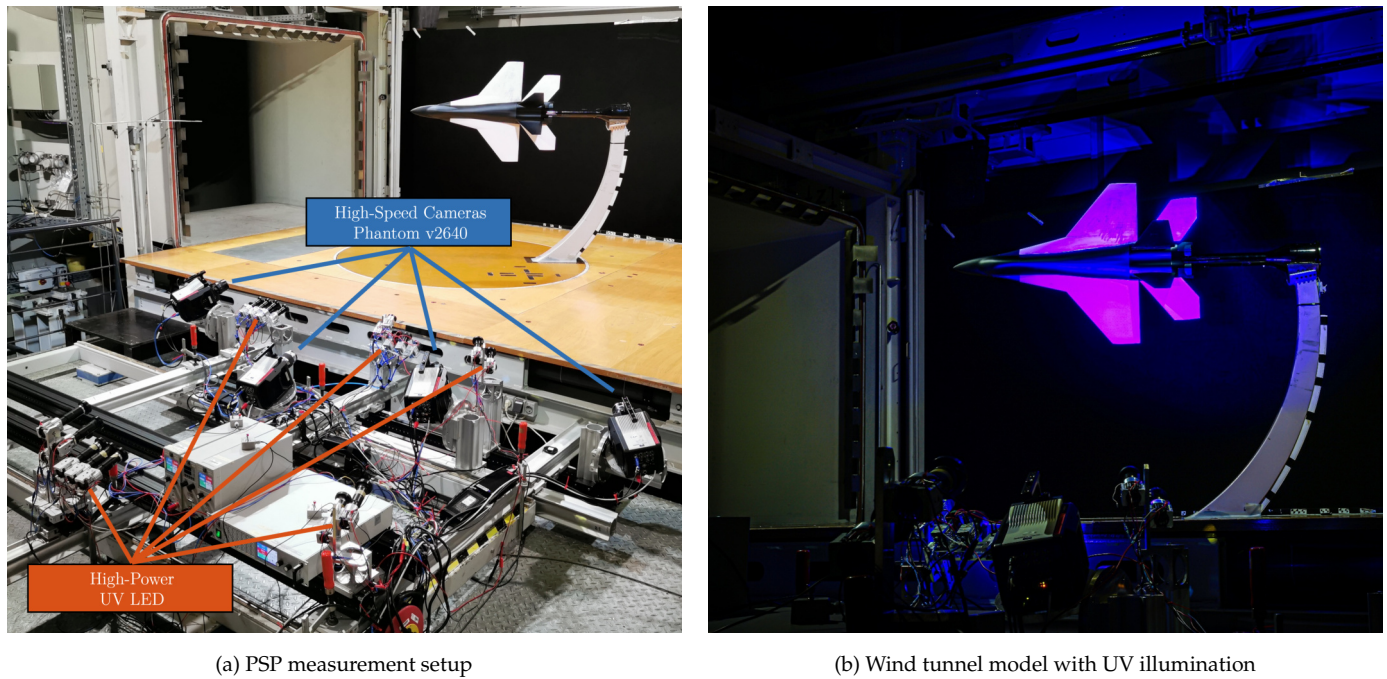


Figure 4. PSP measurement setup and UV-illuminated wind tunnel model integrated into the test section.

One camera is used as the photodetector for the PSP measurements (second camera from the left in Fig. 4a), and three cameras are used for optical deformation measurements. The PSP camera can additionally be used as a fourth camera for the deformation analysis and deformation cameras can be used as PSP photodetectors. However, the results of the simultaneous optical deformation measurements are not evaluated within the scope of this paper. The camera used for the PSP measurements is equipped with a Nikon 85 mm lens. For the deformation measurements, two cameras are equipped with a Zeiss 100 mm lenses and one camera with a Nikon 85 mm lens. Each lens is fitted with a band-pass filter (ET650m100) for wavelengths between 600 nm and 700 nm. The image resolution of the cameras is 2048×1952 pixels at a frame rate of 5000 Hz.

Figure 5 sketches the setup for the synchronized data acquisition of the PSP, optical deformation, Kulite, and ACC measurements. The measurement setup is based on experience from the half-model measurements (cf. Katzenmeier et al., 2023; Katzenmeier, 2025). The Kulite and ACC signals serve as a reference for the PSP and deformation measurements and are sampled at 25 600 Hz, with the whole measurement being triggered by the camera system, which operates at 5000 Hz. The oversampling of conventional measurements reduces the timing offset between the Kulite and ACC signals and the camera-based measurements at the trigger instant. The high-power UV LEDs (red) and the high-speed cameras (blue) are connected via LaVision's synchronizer and timing unit, PTU X, which triggers the measurements and the illumination signals and is directly connected to the CompactDAQ chassis. Data acquisition and synchronization of the optical sensors, as well as trigger generation, are implemented in software using DaVis 10 (LaVision GmbH). The camera data are stored on SSD RAID data server.

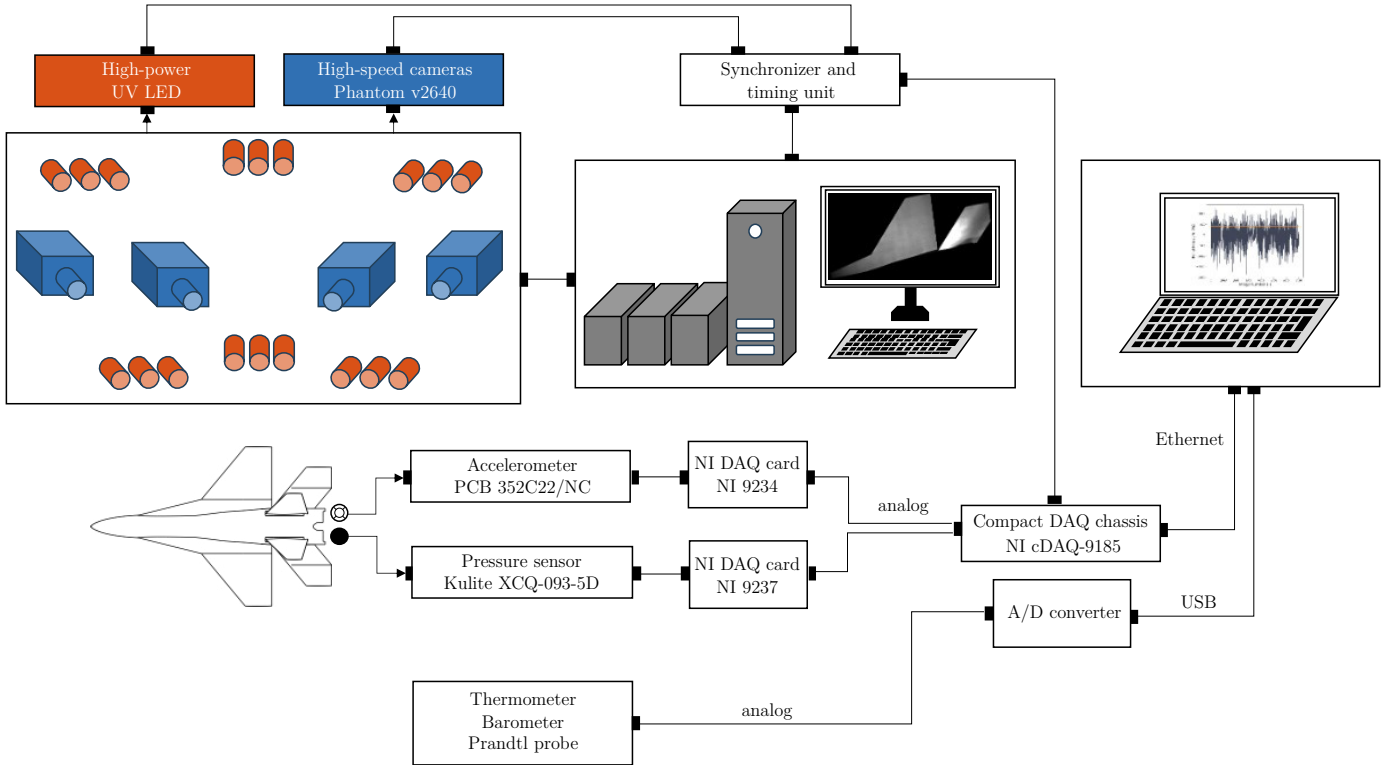


Figure 5. Measurement setup for PSP measurements.

3.3. Data analysis toolchain

Figure 6 shows the in-house signal-processing and data-analysis toolchain used to derive surface $c_{p,rms}$ maps and PSD distributions of c_p' from the PSP measurements. The procedure is based on the evaluation routine developed for the AWTM half-model by Katzenmeier et al. (2023) and was extended for the present AWTMF configuration. Newly implemented or substantially optimized

processing steps are marked in Fig. 6 with a violet dot (bullet). First, the synchronized Kulite and

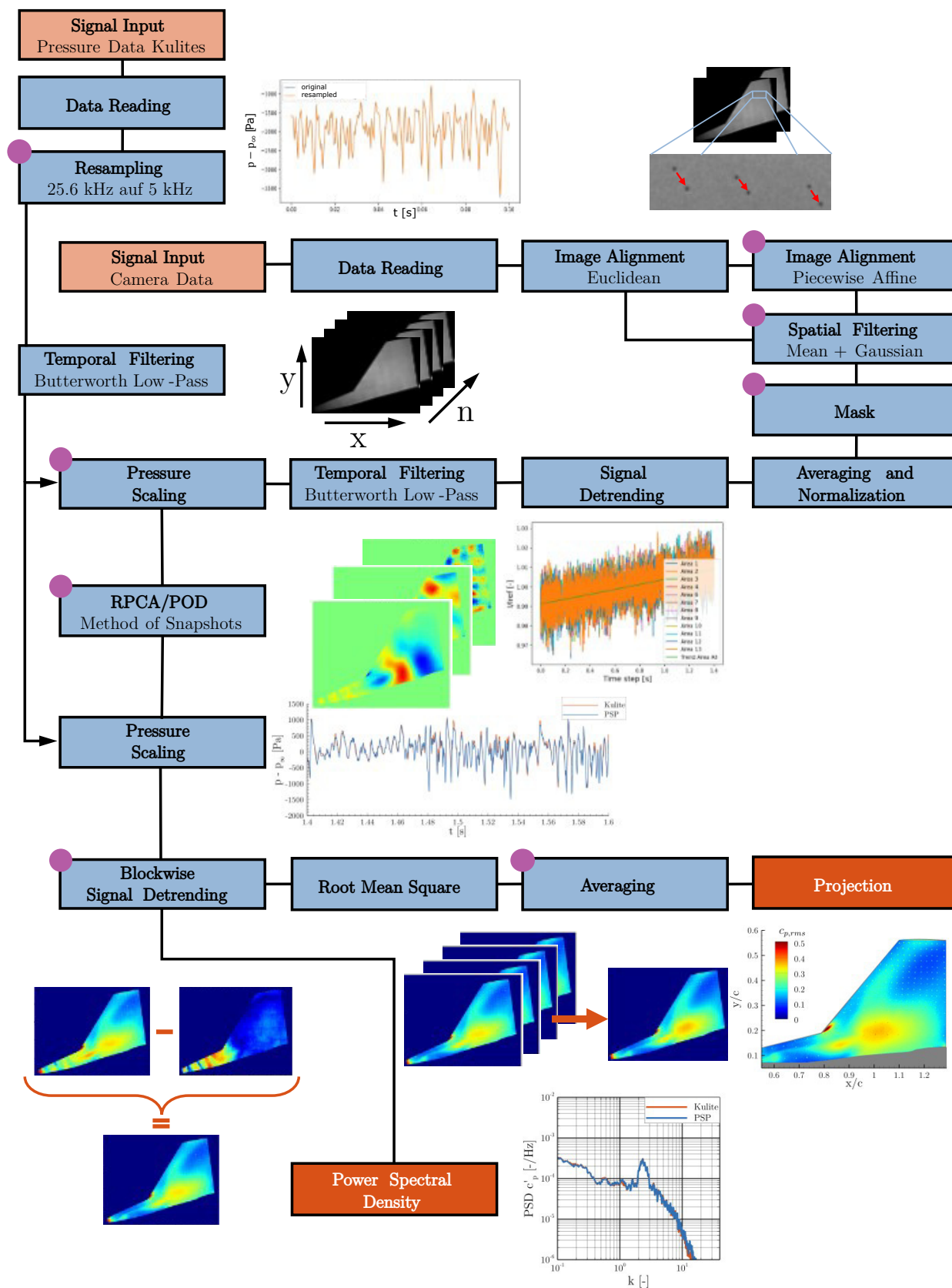


Figure 6. Signal processing and data analysis tool chain adapted and extended from Katzenmeier et al. (2023).

camera data are divided into blocks and read into the Python-based processing tool. The Kulite signals are resampled to 5 kHz to match the PSP acquisition frequency. Since the wing and HTP are recorded with the same camera, a component-specific region of interest is defined before further processing to reduce computational cost.

Geometric image misalignment caused by model vibrations, structural deformation, and motion of the measurement setup is corrected using marker-based image alignment. A Euclidean alignment is applied by translating and rotating each image relative to a reference image. For the AES components and the rigid HTP, an additional piecewise affine alignment is used to account for local deformation within the respective component. Spatial image noise and "hot pixels" are reduced by applying a 3×3 mean filter followed by a Gaussian filter with $\sigma = 1$, both without temporal smoothing.

The relevant model surface is isolated using a binary mask generated from the time-averaged image. This mask removes regions outside the component, edge regions that are sensitive to residual misalignment, reflections, and other non-relevant image areas before modal decomposition. The surface pressure fluctuations are then obtained using the intensity method, where each image is normalized by a reference image. A second-order polynomial detrending is applied to reduce nonstationary effects related to LED intensity variation.

Before pressure scaling, both the Kulite and PSP time series are low-pass filtered with a sixth-order Butterworth filter at 1500 Hz. Forward-backward filtering is used to avoid phase shifts. The PSP pressure fluctuations are scaled to physical pressure levels using the time-synchronous Kulite data. The scaling factor is determined from the ratio between the root mean square (rms) value of the Kulite pressure fluctuations and the rms value of the normalized PSP signal in the vicinity of the Kulite position.

To further reduce noise and corrupted signal components, Robust Principal Component Analysis (RPCA) followed by Proper Orthogonal Decomposition (POD) is applied to the image data. The RPCA separates the data into a low-rank component containing coherent flow structures and a sparse component containing noise and outliers (Candès et al., 2011). The Python implementation used for the RPCA is based on the open-source library `robust-pca`^{*}, which follows the method of Candès et al. (2011). The POD modes are then computed from the low-rank component using the method of snapshots (Sirovich, 1987; Taira et al., 2017), implemented based on the Python library `modred`[†] (cf. Belson et al., 2014). The data are subsequently reconstructed using only the most energetic modes, effectively filtering out the low-energy modes associated with remaining image noise.

After reconstruction of the pressure-fluctuation time series, the data are scaled again using the Kulite reference signal, since some of the energy is lost during reconstruction. A final blockwise detrending removes residual local mean offsets and slow drifts, for example due to changes in UV illumination or surface temperature.

The processed image time series finally yields temporally and spatially resolved pressure changes

^{*}Deep Ganguli, *robust-pca*, GitHub repository, <https://github.com/dganguli/robust-pca>, accessed April 11, 2026.

[†]Brandt Belson, *modred*, GitHub repository, <https://github.com/belson17/modred>, accessed April 11, 2026.

on the surface and can be used to compute surface $c_{p,rms}$ distributions and PSD distributions of c'_p at selected locations. For the $c_{p,rms}$ maps, the block-wise results are averaged and projected onto the 3D CAD surface of the wing or HTP.

For the spectral analysis on a specified location, pixels within a radius of 3 pixels around the selected point are spatially averaged, and the PSD of c'_p is computed from the resulting time signal. The spectra are denoised using a first-order one-dimensional median filter and a first-order Savitzky-Golay finite impulse response (FIR) filter with a frame length of 51 Hz.

3.4. Validation of unsteady pressure measurements with PSP

For the validation of the unsteady pressure measurements with PSP, both the Kulite signals used for pressure scaling and the signals of the second Kulite on the wing and HTP, respectively, can be used. In the case of $\alpha = 30^\circ$, the inboard Kulite is used for pressure scaling on the wing. Figures

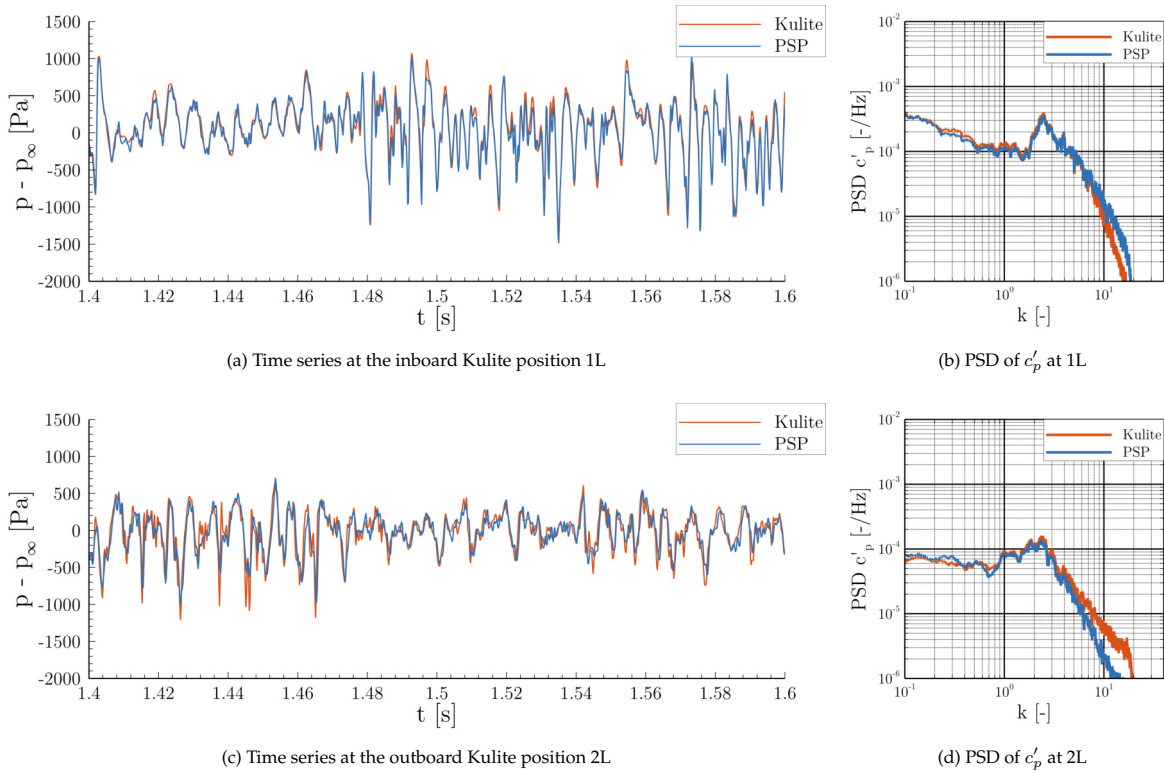


Figure 7. Comparison between the Kulite signals on the wing and the corresponding local PSP signals averaged in the vicinity of the respective Kulite positions at $\alpha = 30^\circ$ for the rigid configuration.

7 and 8 compare the pressure time series measured by the two Kulite sensors integrated into the wing with the corresponding data extracted from the PSP. The PSP time series at these locations were reconstructed by spatially averaging 12 points surrounding each respective Kulite sensor at every time step. Figure 7 shows the comparison for the rigid configuration and Figure 8 for the AES configuration with the section of the time series on the left and corresponding PSD c'_p for the whole time series on the right. For both the inboard and outboard Kulite positions, the time series data generally demonstrate strong agreement between the Kulite and PSP results. At the

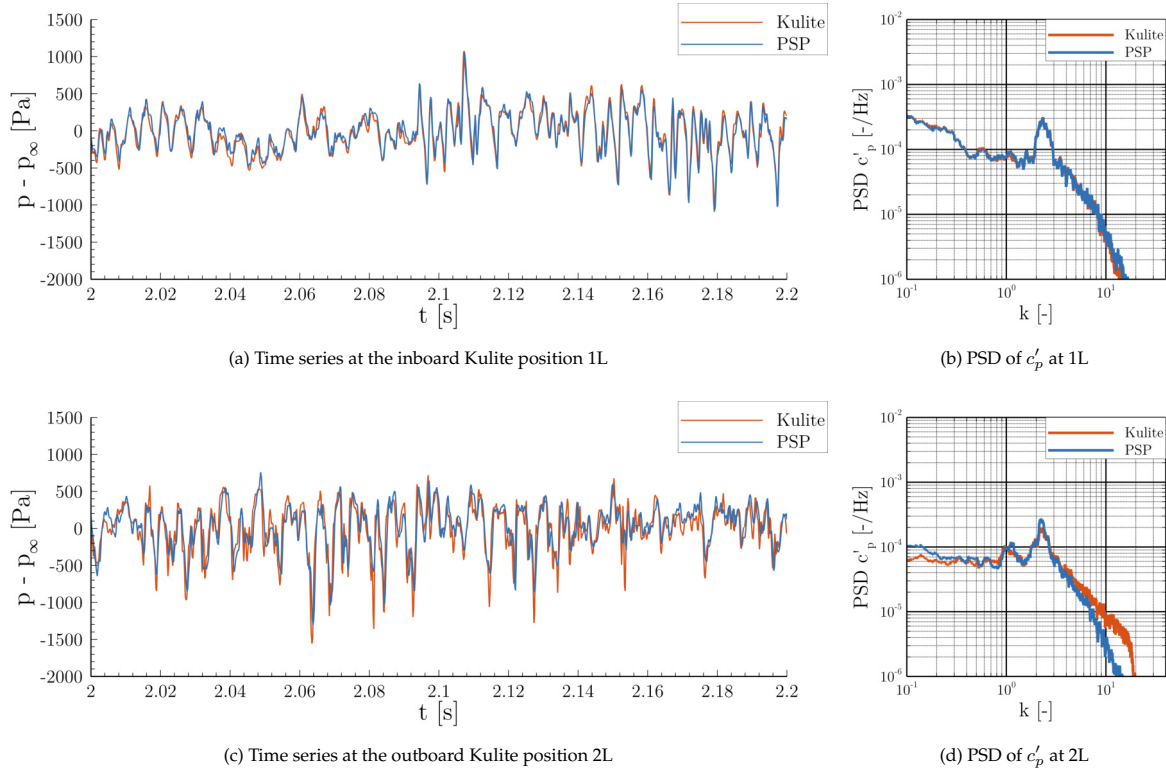


Figure 8. Comparison between the Kulite signals on the wing and the corresponding local PSP signals averaged in the vicinity of the respective Kulite positions at $\alpha = 30^\circ$ for the AES configuration.

outboard position, this agreement is slightly reduced, though still highly correlated. This minor discrepancy is primarily due to the inherently lower pressure fluctuation levels at this location. Additionally, because the Kulite sensor itself is not coated with PSP, the corresponding PSP signal must be approximated by spatially averaging 12 surrounding points. In regions with steep gradients between high and low rms values, this spatial averaging can introduce slight deviations from the precise point measurement recorded by the Kulite.

4. Results

The results are presented in two parts. First, the spatial distributions of the surface pressure fluctuations are analyzed based on the $c_{p,rms}$ maps on the wing and HTP for the rigid and AES configurations. The corresponding difference maps, $\Delta c_{p,rms} = (c_{p,rms})_{AES} - (c_{p,rms})_{rigid}$, are used to identify configuration-dependent changes in the vortex-induced pressure fluctuations. Subsequently, the PSD distributions of c'_p at selected measurement positions are examined to assess the local spectral characteristics of the IBV, MBV, and HTPV and their possible coupling with structural eigenmodes. For the wing, the spectral analysis is demonstrated at $\alpha = 30^\circ$, since the spectral contributions of the vortex systems can be clearly identified at this angle of attack. For the HTP, which is located further downstream, the spectral analysis of the pressure fluctuations is conducted at $\alpha = 20^\circ$. Due to the strong vibrations of the fin, application of the post-processing toolchain first requires an alignment based on the optical deformation measurements obtained with the

high-speed photogrammetry setup and is therefore not part of the present study.

4.1. Distribution of surface pressure fluctuations

Previous stereoscopic particle image velocimetry (Stereo-PIV) flow-field measurements (Stegmüller et al., 2025) and surface pressure measurements at Kulite locations (Stegmüller et al., 2026) on the AWTMF model indicated earlier vortex bursting in the rigid configuration. The comparison of the PSP-based wing surface pressure fluctuations between the rigid and AES configurations (Fig. 9) confirms this observation. At identical angles of attack ($\alpha = 20^\circ$ and $\alpha = 30^\circ$), the vortex-bursting location in the rigid configuration is shifted significantly further upstream, indicating a more advanced bursting stage. In the $c_{p,rms}$ maps on the wing surface, the onset of vortex bursting is indicated by an abrupt increase in the spanwise cross-sectional extent of the region of raised pressure fluctuations. The Kulite locations are indicated by black crosses. To assess the influence of the vortex system forming on the wing and on the HTP, the surface pressure fluctuations are shown on both the wing and the HTP.

Examining the $c_{p,rms}$ distributions on the wing surface at $\alpha = 20^\circ$ clearly reveals the footprint of the vortex structures. In this angle-of-attack range, the MBV trajectory moves above the IBV trajectory in the z direction before both vortices merge, beyond a distinct downstream position, into a common burst helical ring structure (cf. Stegmüller et al., 2025). The IBV core initially remains in the region of the IBV trajectory, whereas more outboard structures of the IBV are stretched toward the wing tip in the spanwise direction during the bursting process (Stegmüller et al., 2025). Correspondingly, the $c_{p,rms}$ values on the wing surface exhibit a region of high pressure fluctuations at the spanwise location of the IBV trajectory, which spreads in the spanwise direction with lower values consistent with a ring structure whose diameter increases downstream. The footprint of the ring structure associated with helical vortex bursting is particularly visible in the outboard region of the ring structure, where, near the wing root, the burst vortex helical structure intersects with the wing surface and, near the wing tip, moves away from the surface. Since the MBV moves away from the wing surface downstream (cf. Stegmüller et al., 2025), its footprint on the wing surface pressure fluctuations is primarily visible in the immediate vicinity of the kink. A spanwise more outboard band of increased pressure fluctuations indicates an oscillation of the MBV trajectory. As already shown in the flow-field analysis by Stegmüller et al. (2025) for $\alpha = 25^\circ$, the oscillation of the IBV is also evident in the $c_{p,rms}$ values on the wing surface for $\alpha = 20^\circ$ through two adjacent IBV trajectories, particularly immediately upstream of vortex bursting.

Figure 9c shows the difference in the surface pressure fluctuations $\Delta c_{p,rms} = (c_{p,rms})_{AES} - (c_{p,rms})_{rigid}$ between the AES and the rigid configurations. The region of the burst helical structure of the IBV starts further upstream in the rigid configuration, as indicated by a blue region corresponding to higher $c_{p,rms}$ values in the rigid configuration compared to the AES configuration. Further downstream, the red region, associated with higher pressure fluctuations in the AES configuration, is dominant. The MBV produces a stronger footprint on the surface pressure fluctuations in the AES configuration, which is located closer to the leading edge than in the rigid configuration.

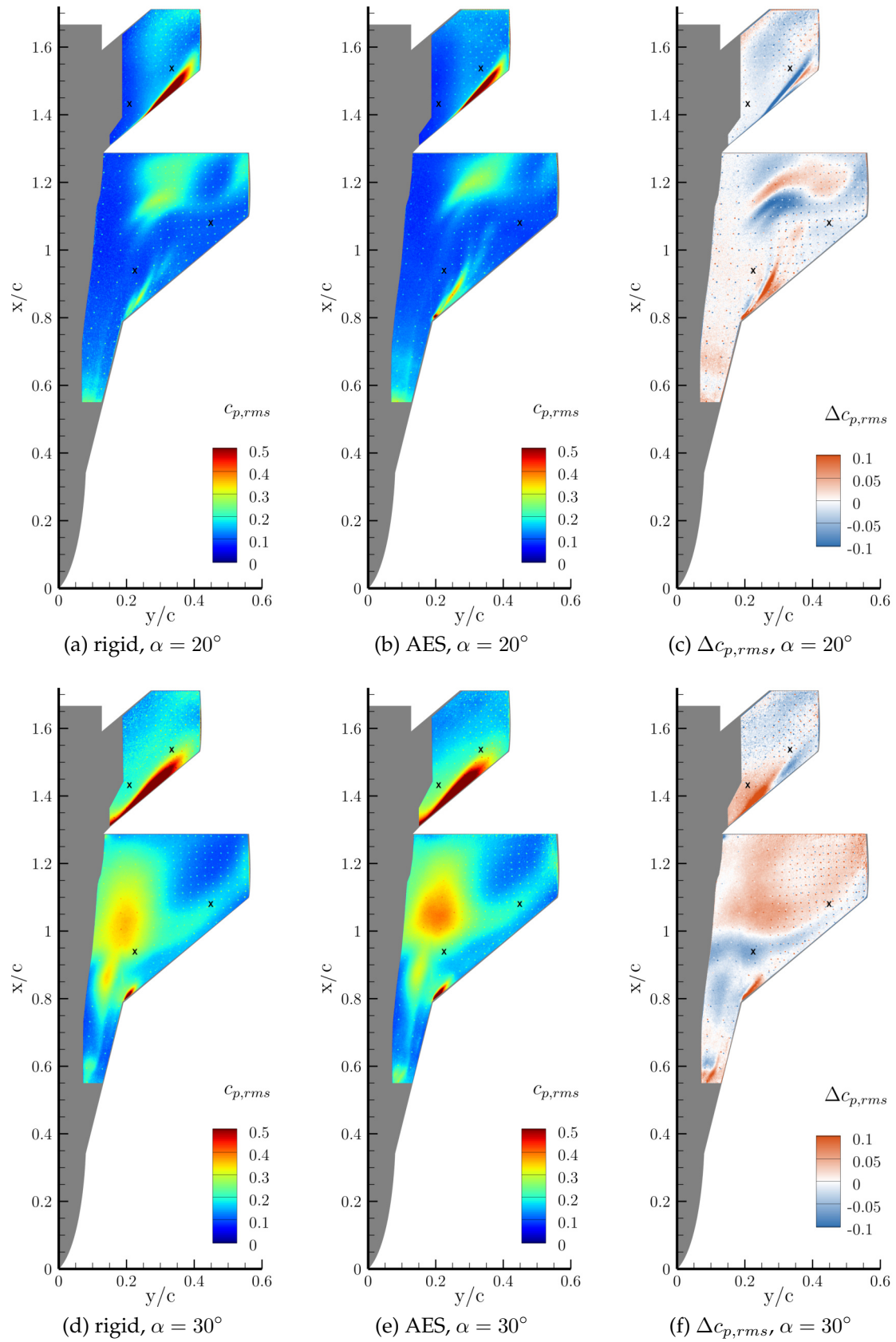


Figure 9. $c_{p,rms}$ and $\Delta c_{p,rms} = (c_{p,rms})_{AES} - (c_{p,rms})_{rigid}$ on the wing and HTP surfaces for $\alpha = 20^\circ$ and $\alpha = 30^\circ$.

The bottom row of Fig. 9 shows the $c_{p,rms}$ maps of the rigid and AES configurations and the corresponding difference map, $\Delta c_{p,rms} = (c_{p,rms})_{AES} - (c_{p,rms})_{rigid}$, on the wing and HTP surfaces for $\alpha = 30^\circ$. For both configurations, the increasingly upstream shift of the vortex-burst onset with increasing angle of attack is indicated by the upstream movement of the red-orange elliptical region of high $c_{p,rms}$ values. Compared with the rigid reference configuration, the AES configuration is associated with higher $c_{p,rms}$ values over a larger region in both the axial and lateral directions. As identified by Stegmüller et al. (2025) in the flow-field analysis above the wing for $\alpha = 25^\circ$ and $\alpha = 35^\circ$, the ring structure associated with helical vortex bursting is visible close to the wing surface through increased values of turbulent kinetic energy. This is consistent with the red-orange region of increased pressure fluctuations downstream of the vortex-burst onset near the wing-root region for $\alpha = 30^\circ$ in Fig. 9. In the spanwise direction, the footprint of the helical vortex bursting on the surface pressure fluctuations is visible as a green band that migrates towards the wing tip with increasing downstream position, due to the downstream increase in the diameter of the burst vortex ring structure.

One possible explanation for the elliptical region of concentrated high pressure fluctuations near the wing-root region is provided by the analysis of individual instantaneous snapshots of the wing surface pressures at $\alpha = 30^\circ$ in terms of the mean-subtracted c_p distributions in Fig. 10. The top and bottom rows each show three temporally consecutive instantaneous pressure distributions. A blue region downstream of the kink is visible, which further downstream splits into two smaller, approximately circular blue regions. These regions correspond to the footprint of the ring structure associated with helical vortex bursting, where, near the wing root, the helical structure intersects the wing surface and, near the leading edge, moves away from the surface. When comparing the upper and lower snapshots, it can be seen that, at the later time in Fig. 10d compared to the earlier time in Fig. 10a, the splitting of the blue region, and thus the onset of vortex bursting, occurs further downstream. The vortex-bursting location, which fluctuates primarily in the axial direction, causes locally raised pressure fluctuations on the wing surface.

For $\alpha = 30^\circ$ in Fig. 9, higher pressure fluctuations are also observed along the vortex trajectory of the stable, not yet burst, IBV in the strake region. As for $\alpha = 20^\circ$, this indicates an oscillation of the IBV trajectory. When comparing the difference map, $\Delta c_{p,rms} = (c_{p,rms})_{AES} - (c_{p,rms})_{rigid}$, on the wing, the transition from a blue to a red region, as for $\alpha = 20^\circ$, indicates an onset of vortex bursting located further upstream in the rigid configuration. The footprint of the MBV on the wing surface downstream of the kink results in higher pressure fluctuations in the AES configuration at $\alpha = 30^\circ$. As analyzed later in subsection 4.2 in Fig. 13, the red region of high $c_{p,rms}$ values near the HTP leading edge results from an oscillation of the vortex rolling up at the HTP leading edge (HTPV). With increasing angle of attack, the red region of raised pressure fluctuations migrates upstream along the leading edge towards the HTP root. Downstream of the HTPV, Fig. 9 shows qualitatively similar $c_{p,rms}$ distributions for $\alpha = 20^\circ$ and $\alpha = 30^\circ$, with a generally higher level for $\alpha = 30^\circ$. A crescent-shaped region of increased $c_{p,rms}$ values (light-green region) extends from the leading edge towards the transition from trailing edge to tip and is more pronounced in the rigid configuration than in the AES configuration, which is also visible as a blue region in the $\Delta c_{p,rms}$ maps. At $\alpha = 20^\circ$,

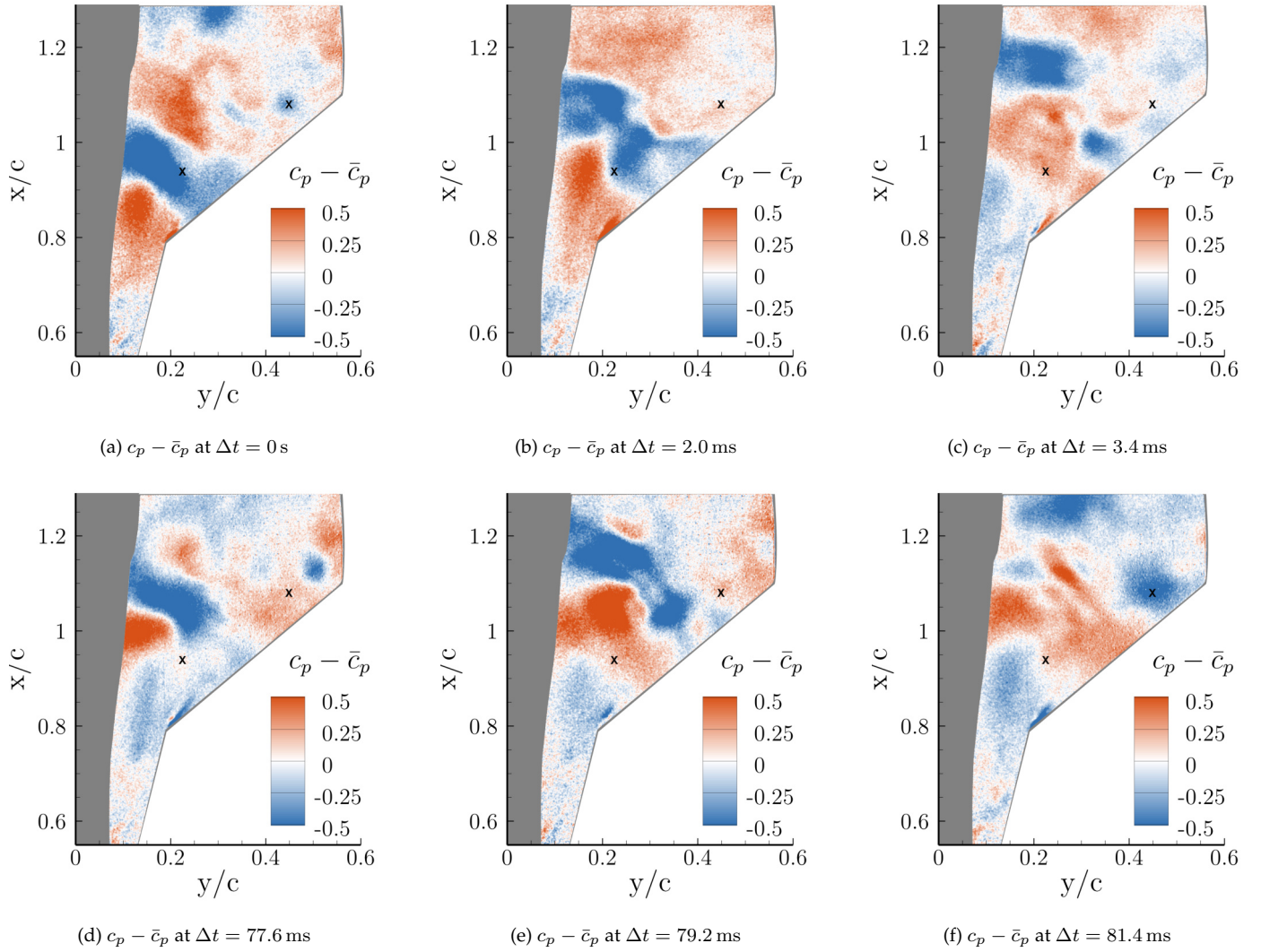


Figure 10. $c_p - \bar{c}_p$ at the wing of the AES configuration at $\alpha = 30^\circ$.

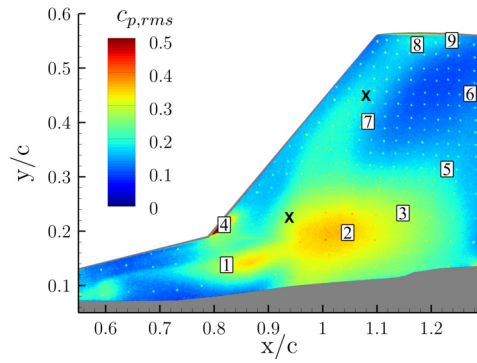
the region influenced by the HTPV oscillations extends further downstream in the axial direction in the rigid configuration and appears in the $\Delta c_{p,rms}$ maps as a blue line moving away from the leading edge. In contrast, a red region close to the leading edge indicates higher pressure fluctuations in the AES configuration, where the footprint of the HTPV oscillations is located further upstream and is clearly identifiable as a red line.

In the $c_{p,rms}$ distributions on the HTP at $\alpha = 30^\circ$, a red region of high pressure fluctuations associated with the HTPV oscillation is also visible. Overall, the rigid configuration exhibits higher $c_{p,rms}$ levels than the AES configuration, as indicated by the $\Delta c_{p,rms}$ maps. In the HTPV-influenced region close to the leading edge, the $\Delta c_{p,rms}$ maps indicate higher pressure fluctuations in the root region for the AES configuration compared to the rigid configuration. Further downstream along the leading edge, the red region in the $\Delta c_{p,rms}$ maps transitions to a blue region, indicating higher pressure fluctuations in the rigid configuration.

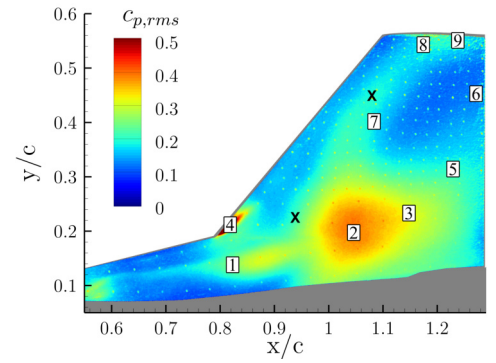
4.2. Spectral analysis of surface pressure fluctuations

To better understand the position-dependent characteristics of the buffet peaks associated with the IBV and the MBV, this subsection analyzes the spectral distribution of the pressure fluctuations at selected surface locations based on the PSP measurements, for $\alpha = 30^\circ$ in the case of the wing and for $\alpha = 20^\circ$ in the case of the HTP. The $c_{p,rms}$ maps on the wing and HTP surface for the rigid and the AES configurations serve as the basis for the interpretation.

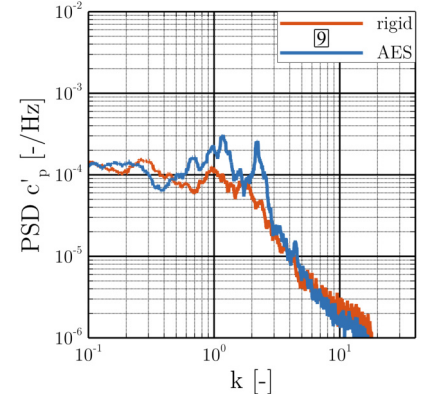
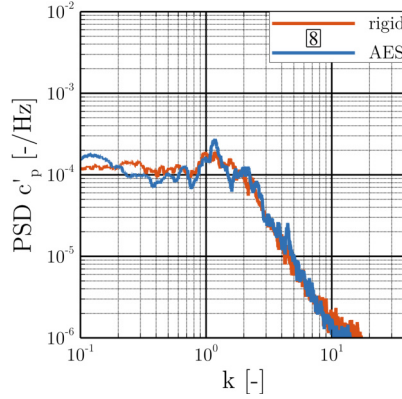
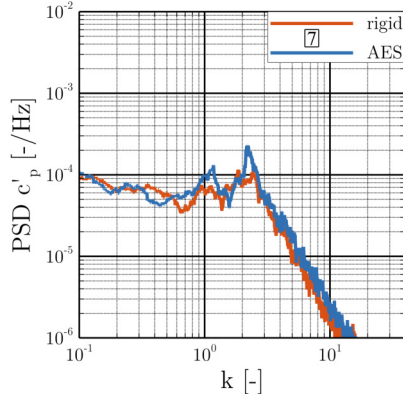
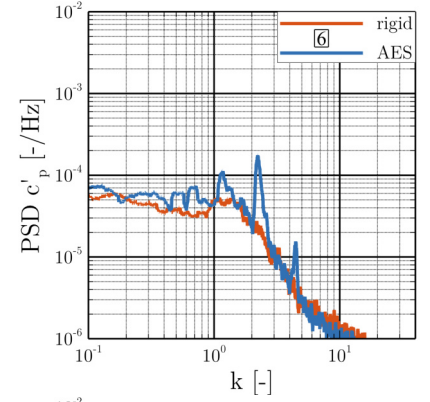
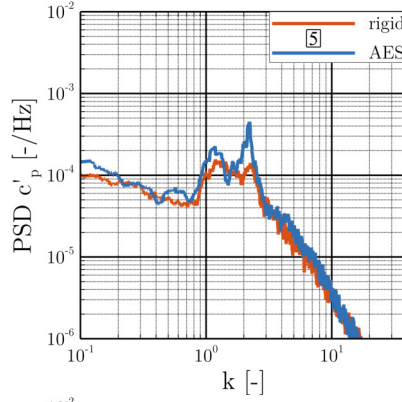
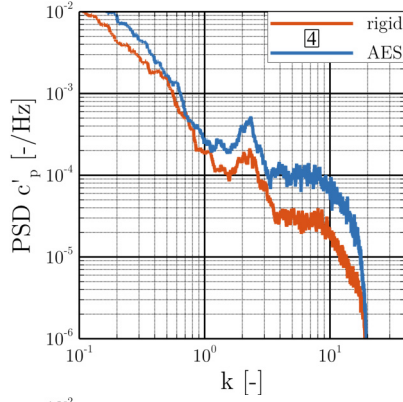
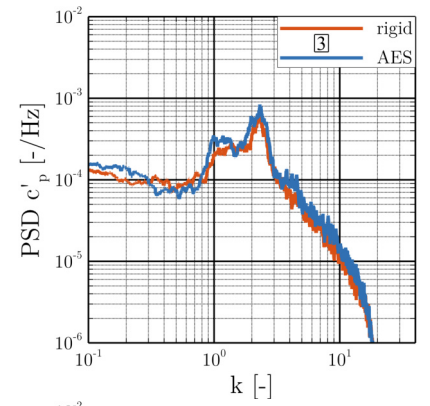
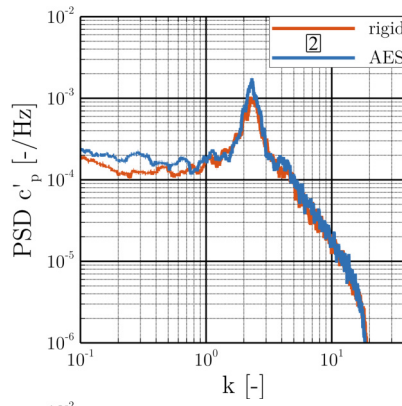
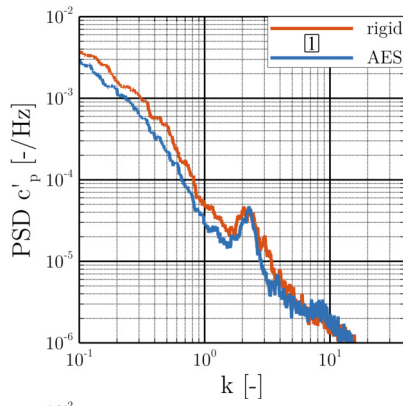
Figure 11 shows the $c_{p,rms}$ maps on the wing and the PSD values of c'_p at nine selected locations for $\alpha = 30^\circ$. Measurement position (MP) 1 is located on the vortex-core trajectory of the IBV and MP 4 on that of the MBV. Both measurement positions are located upstream of the bursting locations of the IBV and the MBV (cf. Stegmüller et al., 2025, 2026), but within regions of high $c_{p,rms}$ values resulting from the vortex footprint on the wing surface. The peaks in the PSD distributions of c'_p in Fig. 11 at MP 1 and MP 4 indicate that the HMI of the IBV and the HMI of the MBV influence the pressure fluctuations upstream of the bursting locations. In this case, the peak in the range of the reduced frequency $k \approx 1$ ($k = f \cdot c/U_\infty$) correlates with the HMI of the MBV, whereas the peak in the range around $k \approx 2$ correlates with the HMI of the IBV (cf. Stegmüller et al., 2025, 2026). At MP 1, the amplitudes of the buffet peak correlated with the HMI of the IBV are at a comparable level for the AES and rigid configurations, whereas at MP 4 the amplitude is markedly higher in the AES configuration than in the rigid configuration. As analyzed in subsection 4.1 based on the $c_{p,rms}$ maps in Fig. 9, increased pressure fluctuations along the vortex trajectory of the stable vortex indicate an oscillation of the vortex trajectory, which may result from the HMI of the IBV that bursts further downstream. At MP 2 close to the wing root, the peak correlated with the HMI of the IBV dominates the spectral distribution of the pressure fluctuations. As analyzed by Stegmüller et al. (2025) for $\alpha = 25^\circ$, and thus also for $\alpha = 20^\circ$, the bursting process of the MBV starts upstream of that of the IBV. The MBV primarily influences the flow field downstream of vortex bursting, whereas at higher angles of attack the IBV bursting location shifts upstream of that of the MBV and becomes dominant. For $\alpha = 30^\circ$, the annular structure of the burst IBV is not displaced beneath that of the MBV, as observed for $\alpha = 25^\circ$ by Stegmüller et al. (2025), and primarily governs the flow field close to the wing root and over the central region of the main wing. Further towards the wing tip, the PSD distribution of c'_p at MP 7 at $x/c = 1.08$ and $y/c = 0.40$ shows, for both configurations, a second peak at lower reduced frequencies between $k \approx 1$ and $k \approx 2$, which results from the HMI of the MBV, whose footprint is still visible in the pressure fluctuations on the wing surface. Both peaks exhibit higher amplitudes in the AES configuration. This is consistent with the location of MP 7, which, in the AES configuration, is situated within a region of higher pressure fluctuations (light-green region) compared to the rigid configuration. A similar behaviour to MP 7 is observed at MP 5, with higher amplitudes of both the peak correlated with the HMI of the IBV and the peak correlated with the HMI of the MBV in the AES configuration. From a certain downstream position onward, the annular structures of the burst IBV and the burst MBV have merged into a common annular structure (cf. Stegmüller et al., 2025), which is reflected in the spectral distribution of the pressure fluctuations. Accordingly, at MP 3 at $x/c = 1.15$ and at MP 8 at $x/c = 1.17$, as already analyzed for MP 5 and MP 7, two peaks can be identified in the PSD distributions of c'_p . Near the



(a) $c_{p,rms}$ for the rigid configuration



(b) $c_{p,rms}$ for the AES configuration



(c) PSD of c'_p for $\alpha = 30^\circ$

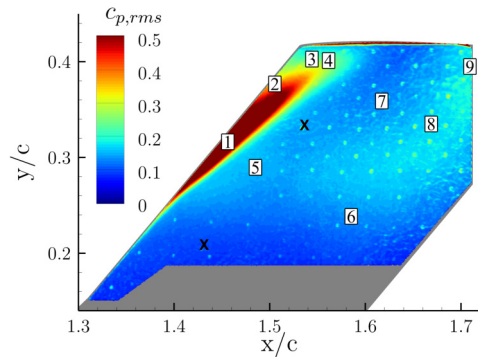
Figure 11. $c_{p,rms}$ for the rigid (left) and the AES (right) configuration and PSD of c'_p at $\alpha = 30^\circ$.

wing root at MP 3, the peak correlated with the HMI of the IBV exhibits higher amplitudes, whereas near the wing tip at MP 8 the peak correlated with the HMI of the MBV is dominant. At both measurement positions, the peak correlated with the HMI of the MBV exhibits higher amplitudes in the AES configuration than in the rigid configuration. Due to the proximity to the wing tip, the pressure-fluctuation spectra at MP 6 and MP 9 are dominated by the HMI of the MBV. In addition, further peaks are visible for the AES configuration in the frequency range of the structural modes determined via a ground vibration test (GVT) (cf. Stegmüller et al., 2026). A pronounced amplitude increase is observed at $k = 2.17$ at the 1st asymmetric (asym.) torsional mode (TM) of the wing (cf. Table 1), which is not present in the rigid configuration. This structural mode lies within the

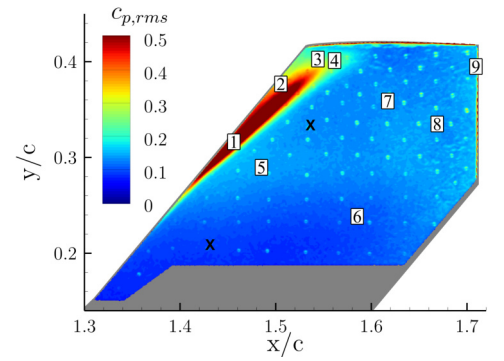
Table 1. Results of the ground vibration test at the AES configuration in terms of eigenmodes and eigenfrequencies Stegmüller et al. (2026); (BM, TM: bending, torsional mode).

	1st BM		1st TM		2nd BM		2nd TM	
	sym.	asym.	sym.	asym.	sym.	asym.	sym.	asym.
Wing k [-]	0.51	0.57	1.88	2.00	1.76	1.80	4.74	4.98
Wing f [Hz]	39.09	44.38	145.31	154.81	135.64	138.93	366.08	384.90
HTP k [-]	0.59	0.56	1.60	1.65	2.45	2.51	3.44	3.61
HTP f [Hz]	45.74	43.02	123.51	127.22	189.63	193.67	266.20	279.05
Fin k [-]	0.92	1.17	2.38	2.43	3.98	3.73	4.48	4.59
Fin f [Hz]	71.17	90.39	183.90	187.71	307.08	288.56	346.51	354.56

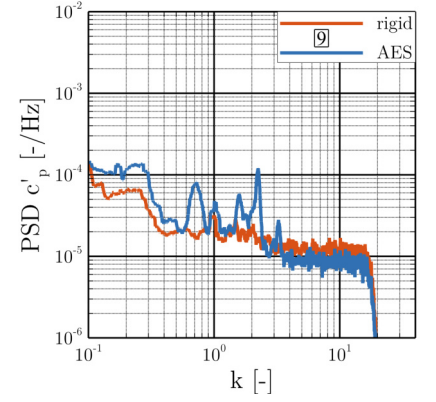
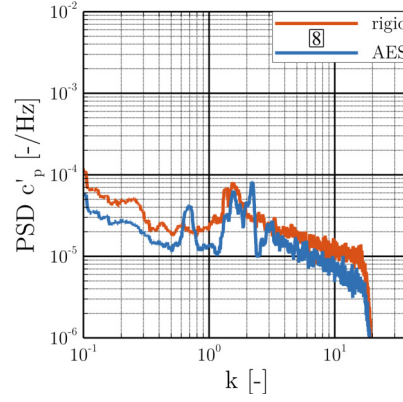
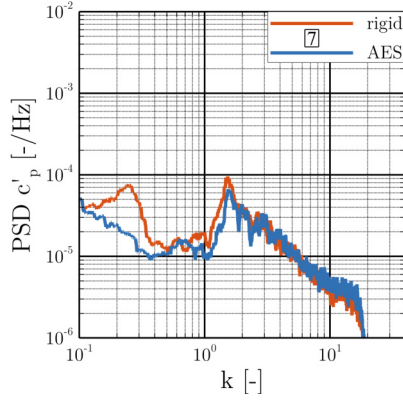
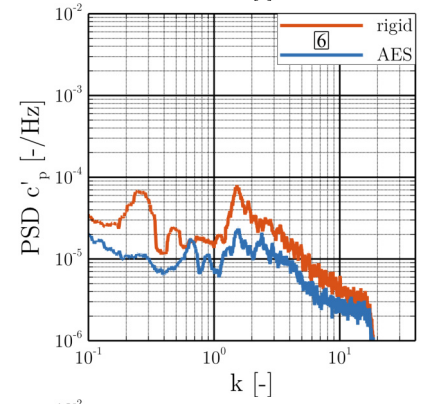
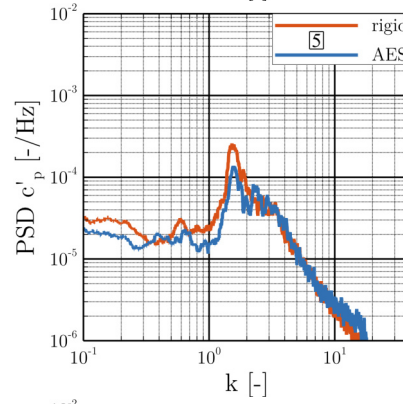
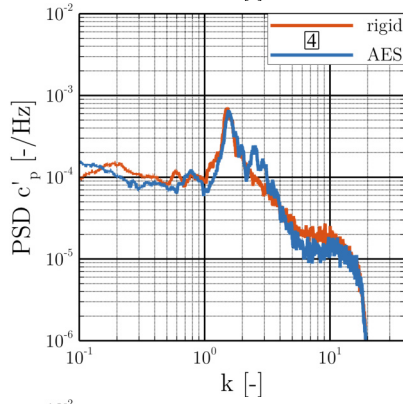
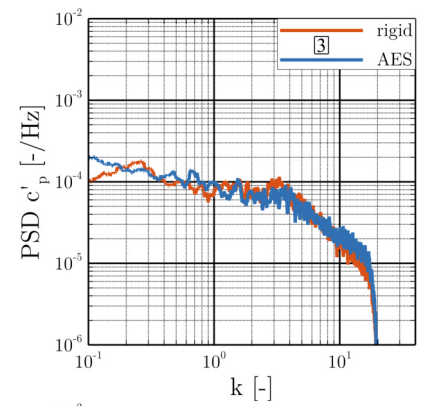
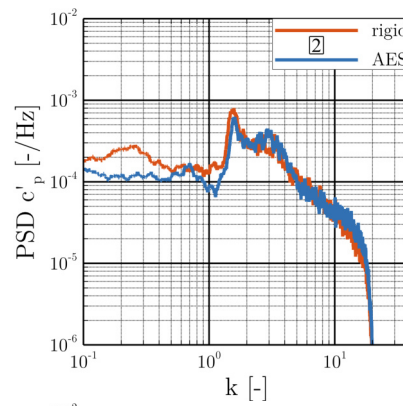
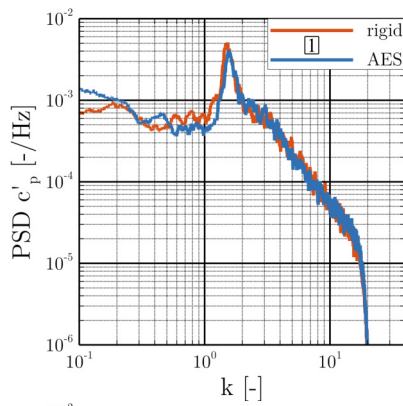
HMI range of the IBV and also appears to increase the buffet-peak level in the pressure-fluctuation spectra, and the associated potential aerodynamic excitation, at other measurement positions, for example MP 5 and MP 7. Within the HMI range of the MBV, an increase of the buffet amplitudes is also observed at MP 6 and MP 9, associated with coincidence with an eigenfrequency of a structural mode. Although no wing eigenmode is located in this reduced-frequency range, the 1st asym. bending mode (BM) of the fin is located at $k = 1.17$ and, as shown by Stegmüller et al. (2026), influences the spectral distribution of the wing-tip accelerations and is visible as a peak in the PSD distributions of a_z of the wing. This may also contribute to the higher peak amplitudes correlated with the HMI of the MBV in the PSD distributions of c'_p for the AES configuration at MP 3, MP 5, and MP 7. Another peak in the PSD distributions of c'_p is observed only for the AES configuration at $k = 4.46$ at MP 6 and MP 9. It lies within the frequency range of the 2nd symmetric (sym.) TM of the wing (cf. Table 1) and therefore appears to result from coupling with this structural mode. Figure 12 shows the $c_{p,rms}$ maps for the rigid (left) and the AES (right) configurations and the PSD values of c'_p at nine selected locations on the HTP surface for $\alpha = 20^\circ$. As analyzed in subsection 4.1 and shown in Fig. 13, the red region of high values of $c_{p,rms}$ near the HTP leading edge, including MP 1 and MP 2, results from an oscillation of the HTPV. Considering the four time steps, the displacement of the blue region of negative $c_p - \bar{c}_p$ values, in particular between $\Delta t = 1.8$ ms and $\Delta t = 3.4$ ms, illustrates the oscillation of the HTPV. The HTPV remains stable up to near the tip, as indicated in Fig. 13. The HMI of the MBV and the HMI of the IBV induce an oscillation of the HTPV rolling up at the HTP leading edge, which is clearly visible for MP 1 and MP 2 in Fig. 12. In



(a) $c_{p,rms}$ for the rigid configuration



(b) $c_{p,rms}$ for the AES configuration



(c) PSD of c'_p for $\alpha = 20^\circ$

Figure 12. $c_{p,rms}$ for the rigid (left) and the AES (right) configuration and PSD of c'_p at $\alpha = 20^\circ$.

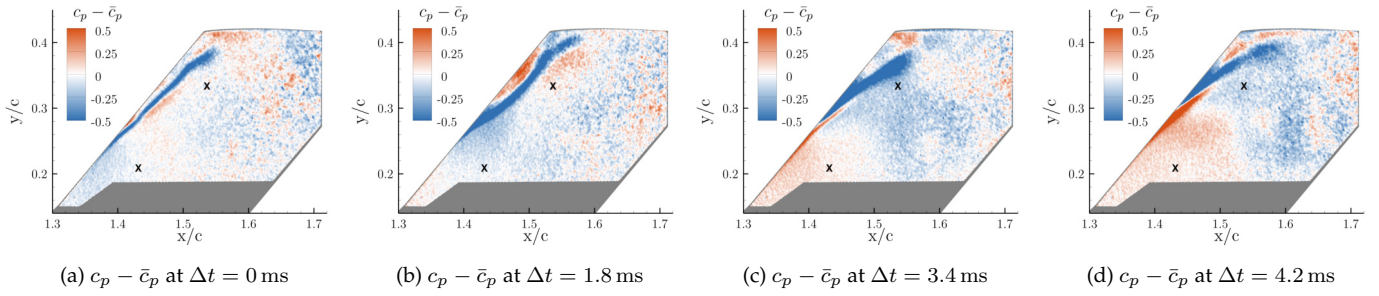


Figure 13. $c_p - \bar{c}_p$ at the HTP of the rigid configuration at $\alpha = 20^\circ$.

the angle-of-attack range of $\alpha = 25^\circ$ and below, the MBV passes above the IBV, such that the MBV dominates the flow pattern (cf. Stegmüller et al., 2025). As a result, over a large region on the HTP surface, the peak correlated with the HMI of the MBV between $k \approx 1$ and $k \approx 2$ is higher in the PSD distributions of c'_p than the peak correlated with the HMI of the IBV. The peak correlated with the HMI of the IBV between $k \approx 2$ and $k \approx 4$ is only visible as a small peak or a plateau. As already analyzed for the wing, structural modes in the PSD distributions of c'_p are most clearly visible at measurement positions with a generally lower level of pressure fluctuations, as for MP 8 and MP 9. Clearly identifiable are the 1st sym. and asym. BMs of the AES HTP and the AES wing in the range between $k \approx 0.5$ and $k \approx 1$, the 1st sym. and asym. TMs between $k \approx 1.5$ and $k \approx 2$, the 2nd sym. and asym. BMs of the AES HTP between $k \approx 2$ and $k \approx 3$ and the 2nd sym. TM of the AES HTP between $k \approx 3$ and $k \approx 3.5$ (cf. Table 1). As discussed by Stegmüller et al. (2026), eigenmodes of one component can be transmitted to another component via the fuselage. At MP 8, the peak correlated with the HMI of the MBV between $k \approx 1$ and $k \approx 2$ is visible for both configurations, whereas at MP 9 it is only visible for the AES configuration and can alternatively be associated with the 1st sym. and asym. TMs of the HTP in this reduced-frequency range. The peak correlated with the HMI of the IBV between $k \approx 3$ and $k \approx 4$ is visible only at MP 8 and MP 9 close to the trailing edge in the AES configuration and lies within the frequency range of the 2nd sym. and 2nd asym TMs of the AES HTP. However, the rigid configuration exhibits a generally higher PSD level of c'_p in this frequency range at both measurement positions, particularly at MP 8. While, at MP 3 close to the tip and leading edge and just outside the red region of increased pressure fluctuations associated with the HTPV oscillation, a generally high PSD level of c'_p is still present over a broad reduced-frequency range, the peaks correlated with the HMI of the MBV and the IBV are only weakly visible. At MP 4, located immediately downstream of MP 3, the peak correlated with the HMI of the MBV is clearly identifiable with high amplitude. The peak correlated with the HMI of the IBV between $k \approx 2$ and $k \approx 4$ exhibits higher values in the AES configuration than in the rigid configuration, in which the peak is visible only as a weaker slope and remains at a similar PSD level of c'_p as at MP 3. Coupling with the 2nd sym. and asym. BM can also explain the higher amplitudes of the peak correlated with the HMI of the IBV in the AES configuration compared to the rigid configuration, given the tip-near location. At MP 5 to MP 7, the peak correlated with the HMI of the MBV is dominant and exhibits higher amplitudes in the rigid configuration. As indicated by the $c_{p,rms}$ maps, these measurement positions are located in regions where the rigid configuration shows higher $c_{p,rms}$ values than the

AES configuration. At MP 6, the PSD level of c'_p is generally higher in the rigid configuration than in the AES configuration.

5. Conclusions and outlook

A synchronized fast-response pressure-sensitive paint measurement setup was successfully applied to the sting-mounted, aeroelastic full-span double-delta-wing model at $Ma_\infty = 0.15$ and $Re_{1/m} = 3.20 \times 10^6$ for vortex-induced buffet and buffeting analysis on wing and tailplane. Temporally and spatially resolved surface pressure fluctuations were obtained on the wing and horizontal tailplane (HTP) for the rigid reference configuration and the aeroelastically scaled (AES) configuration. Comparison with pressure transducer (Kulite) signals shows good agreement in time series and power spectral densities of pressure fluctuations (PSD of c'_p), confirming the applicability of the measurement methodology and the extended post-processing toolchain. The $c_{p,rms}$ distributions show a more advanced vortex-bursting stage in the rigid configuration at the same angle of attack. On the wing, the onset of vortex bursting is shifted further upstream for the rigid configuration, whereas higher pressure fluctuations occur further downstream for the AES configuration. The instantaneous mean-subtracted c_p distributions indicate that the region of higher pressure fluctuations near the wing root at $\alpha = 30^\circ$ is associated with axial fluctuations of the vortex-bursting location and with the footprint of the burst vortex helical structure on the wing surface. On the HTP, raised $c_{p,rms}$ values near the leading edge are associated with the oscillation of the horizontal-tailplane vortex (HTPV). At $\alpha = 20^\circ$, the HTPV-influenced region extends further downstream in the rigid configuration, whereas it remains closer to the leading edge in the AES configuration. At $\alpha = 30^\circ$, the rigid configuration exhibits generally higher $c_{p,rms}$ levels on the HTP, while locally higher values occur near the HTP root in the AES configuration. The spectral analysis shows distinct peaks in the PSD of c'_p correlated with the helical mode instability (HMI) of the inboard vortex (IBV) and the HMI of the midboard vortex (MBV). The relative PSD peaks depend on the measurement position and reflect the local influence of the respective vortex system on the surface pressure fluctuations. In the AES configuration, additional peaks occur in the frequency range of structural eigenmodes of the wing and HTP. These peaks indicate coupling between aerodynamic excitation and structural response and show that structural dynamics can be identified in the surface pressure fluctuations. The coincidence of HMI-related pressure peaks with structural eigenfrequencies implies a potential aeroelastic interaction that affects the local spectral content of the aerodynamic excitation. The results demonstrate that fast-response PSP is suitable for analyzing distributed unsteady surface pressure fluctuations on an aeroelastic wind tunnel model at vortex-dominated flow conditions. Future work will include the evaluation of the synchronized optical deformation measurements obtained with the high-speed photogrammetry setup and the extension of the analysis to the fin surfaces in order to relate the distributed aerodynamic excitation to the dynamic structural response relevant to tail buffeting.

Acknowledgments

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Nomenclature

A	Stern-Volmer coefficient
ACC	Accelerometer
AES	Aeroelastically scaled
AWTM	Aeroelastic half-span wind tunnel model
AWTMF	Aeroelastic full-span wind tunnel model
BM	Bending mode
c	Chord length
$\bar{c}_p$	Time-averaged pressure coefficient
c_p	Pressure coefficient
c'_p	Pressure coefficient fluctuation
$c_{p,rms}$	Root mean square of pressure coefficient
CMOS	Complementary metal-oxide semiconductor
FIR	Finite impulse response
f	Frequency
f_{dom}	Dominant frequency
FSI	Fluid-structure interaction
GVT	Ground vibration test
HMI	Helical mode instability
HTP	Horizontal tailplane
HTPV	Horizontal-tailplane vortex
I	Luminescent intensity
I_{ref}	Reference luminescent intensity
IBV	Inboard vortex
k	Reduced frequency
k_{dom}	Dominant reduced frequency
Ma_∞	Freestream Mach number
MBV	Midboard vortex
MP	Measurement position
p	Pressure
p_{ref}	Reference pressure
PIV	Particle image velocimetry

PLA	Poly lactide
POD	Proper orthogonal decomposition
PSD	Power spectral density
PSP	Pressure sensitive paint
PtTFPP	Platinum(II) meso-tetrakis(pentafluorophenyl)porphyrin
$Re_{1/m}$	Reynolds number
ROI	Region of interest
RPCA	Robust principal component analysis
t	Time
T_{ref}	Reference temperature
TiSiO ₄	Titanium silicon oxide
TM	Torsional mode
U_{∞}	Freestream velocity
α	Angle of attack
φ_W	Wing leading-edge sweep angle

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