

Time-resolved PIV and IPCT measurements of fluid-structure interaction of the flap seal of a two-element high-lift wing

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ABSTRACT

The fluid-structure acoustic interaction of a flap cover seal on a two-element 2D wing is investigated. Time-resolved velocity measurements were conducted at the inflow into the flap cove just downstream of the flap cover seal and on the suction side of the flap starting just upstream of the trailing edge of the main wing and including the outlet of the flap cove by means of Particle Image Velocimetry (PIV). Furthermore, simultaneously time-resolved deformation measurements of the seal were performed by means of Image Pattern Correlation Technique (IPCT). The Fluid-Structure Acoustic Interaction of the seal is investigated for two conditions of the seal: bent seal and excited seal. This variation was achieved by changing the thickness of the seal and adapting the flow speed. The periodic motion of the seal was self-excited by the FSI. The spectral analysis of the seal deformation successfully identified several characteristic frequencies in the range of 60 Hz to 400 Hz for the excited seal, which result in tones due to the fluid-structure interaction of the seal. These frequencies are also found in the spectral analysis of the flow field. For the seal that is only bent by the aerodynamic forces only a single weak FSI mode is detected in the deformation and velocity results. These deformation and velocity data for the FSI tones enhance the findings of the acoustic measurements conducted during the same test campaign. For the bent seal characteristic frequencies are found in the spectral analysis with large amplitudes at 576 Hz and its first harmonic. These modes are caused by the Rossiter effect show significantly different dispersion compared to the FSI tones.

1. Introduction

Fluid-structure interaction (FSI) deals with the interaction of three disciplines: dynamics, solid mechanics and aerodynamics. Thus, it is the mutual influence of a flow field and a deforming or moving body. This interaction is most commonly described as the Collar's triangle (Dowell et al.,

1995). Fluid–structure interaction (FSI) significantly influences engineering design, as it is often undesirable due to its impact on reliability and efficiency, for example in aeroelastic effects observed in bridges and wind turbines. (Hansen et al., 2006). The relevance of fluid-structure interaction experimental and computational work in aviation is increasing due to the required reduction of aircraft structural weight, fuel consumption and related noise. Aircraft structures affected by FSI are for example static and dynamic aeroelasticity of wings, flutter of control surfaces, structural vibrations and noise generation of landing gear bays (Nilsson et al., 2022).

The interaction of the inertial, elastic and aerodynamic forces, as described by the collar triangle, requires simultaneous information about the unsteady flow field structures, and model surface dynamics. These requirements make time-resolved Particle Image Velocimetry (PIV) (Raffel et al., 2018) and Image Pattern Correlation Technique (IPCT) (Kirmse et al., 2013) deformation measurements key experimental capabilities. These measurements enable to correlate optical measurements of time-resolved flow fields with the dynamics of surface movements or deformations. Thus, it becomes possible to derive a comprehensive understanding of unsteady flow phenomena that can be exploited in the analysis of the given aerodynamic and aeroelastic configuration designs.

One of the goals of the FALCON project (Foreseeing the next generation of Aircraft – Fluid/structure interActions using Lattice-Boltzmann COupliNg) is to create test cases to validate numerical and modelling challenges raised by FSI in realistic conditions. One of the three test cases with industrial relevance is the investigation of a flap cover seal. The flap cover seal is installed to cover the gap between the main wing and flap of the high lift system in the retracted position. When the flap is extended, it is exposed to the strong unsteady loads from turbulent flow passing through the flap cove. The combination of FSI affecting the seal and flow over a cavity, which can cause Rossiter tones (Rossiter, 1964), results in a multidisciplinary design task for aerodynamics, FSI, and aeroacoustics (Jente et al., 2026). In the present paper, we consider a more general and complex geometry by studying the two-dimensional, self-excited periodic motion of an elastic, free vibrating structure.

2. Experimental setup and procedure

The Aeroacoustic Wind Tunnel Braunschweig (AWB) The experiments were conducted in the AWB of the Technical Acoustics department of the German Aerospace Center (DLR) (Pott-Pollenske & Delfs, 2008). The Göttingen-type wind tunnel has an open test section of circa 3.6 m length, which is in a semianechoic measurement room. The nozzle of the open test section has a cross section of 0.8 m in horizontal and 1.2 m in vertical direction. The vertical position of the collector can be adapted to compensate for larger flow deflection caused by high-lift configurations.

The DLR-F15LSmod wind tunnel model. The DLR-F15LS is a 2D wind tunnel model of a two-element high-lift wing of a transport aircraft (Pott-Pollenske et al., 2013). It features a large flap cove suitable for the integration of a seal holder and differently sized seals. The existing model required a re-design of the leading edge to accommodate the large-scale wind tunnel model in the open test section of the AWB. The numerical re-design process resulted in a shorter chord length of $c = 700.8$ mm with limited flow deflection suitable for the AWB open test section and seal and flap cove geometries relevant for full-scale transport aircraft (Jente et al., 2026). Despite the reduced chord length the new leading edge geometry provides representative flow through the flap cove to trigger FSI characteristic for full-scale application. The flow through the flap cove can be altered by changing the flap deflection angle δ_F , flap position (gap and overlap), length l of the seal, and the thickness of the seal t . Boundary layer fences with a spanwise distance of 610 mm were installed to ensure a 2D flow around the model and through the flap cove. The boundary layer fences were made of polycarbonate to provide optical access, especially into the flap cove, for the PIV measurements.

Table 1. DLR-F15LSmod wind tunnel model configuration during the PIV and IPCT test campaign of the FALCON benchmark test.

Config.	α_{geo} [°]	δ_F [°]	gap [mm]	overlap [mm]	L [mm]	t [mm]
flap	1	8	29.6	91	80	0.1
					80	0.2
					-	-
no flap	1	-	-	-	80	0.1
					80	0.2
					80	0.5
					-	-

The DLR-F15LSmod setup model configuration parameters for PIV and IPCT measurements in the FALCON benchmark test are summarized in Table 1 for both model configurations, i.e., without flap and with flap. The configuration with flap is presented in Fig. 1 with the relevant geometry parameter. During the PIV test campaign the model was tested with seals of 80 mm free length L and a thickness t of 0.1 mm, 0.2 mm, and 0.5 mm. The seals were made of stainless steel (1.4310) and were screwed to the seal holder by ultra low flat head screws, see Fig. 2. The FSI of the seals was solely dynamically excited. Furthermore, tests without any seal were conducted.

Besides to IPCT and PIV measurement techniques, the wind tunnel model was additionally instrumented with 32 pressure taps in one section and six surface pressure sensors for acoustic analysis (Jente et al., 2026). Furthermore, one microphone was placed outside of the flow.

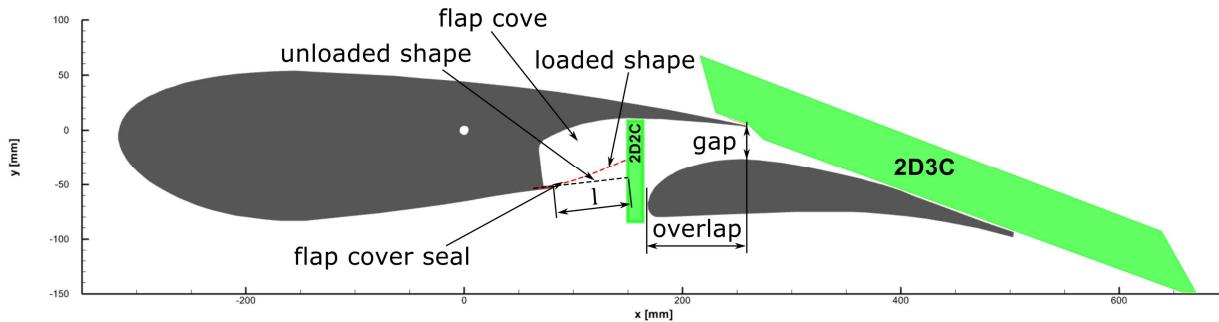


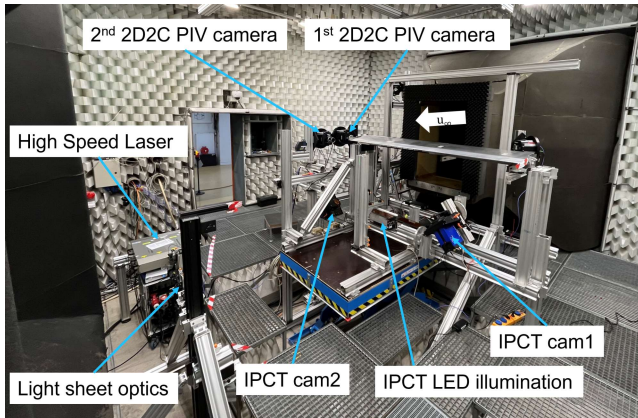
Figure 1. DLR-F15LSmod wind tunnel model with annotated geometry parameter and PIV measurement locations.

IPCT setup. The IPCT setup consisted of a high-speed stereo-camera system (two PCO.dimax) and two high-power LED arrays (HARDsoft) installed below the model, see Fig. 3a and Fig. 4a. The white-light high-power LEDs and the cameras were equipped with optical band-pass filters to separate the light for the IPCT measurement from the PIV measurement. The installed setup resulted in a common field of view (FOV) of approximately 450 mm in spanwise direction with a vector spacing of approximately 3.5 mm, which results from a final window size of 16 px and 50 % overlap. An irregular white dot pattern (diameter of 0.9 mm) on black background was applied by screen printing directly onto the seals for the dynamic 3D surface deformation measurement, see Fig. 2. The IPCT camera and illumination setup remained unchanged for both model configurations, because the position of the main wing and the seal is identical for both configurations.

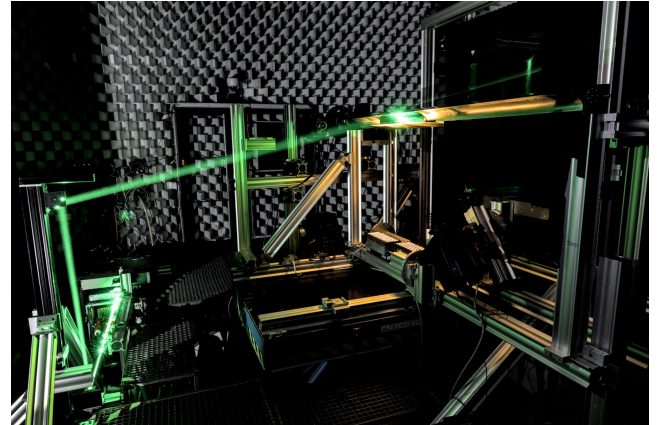


Figure 2. Stainless steel seal with printed IPCT pattern.

PIV setup without flap. The PIV setup for the configuration without flap consists of two high-speed cameras (Phantom V2640 CMOS cameras) for 2D2C PIV measurements in the flap cove (1st 2D2C PIV camera) and of a larger field of view (2nd 2D2C PIV camera) downstream of the aforementioned camera in the wake of the airfoil, see Fig. 3a. The downstream camera acquires the upper side of the airfoil and partially the wake of the airfoil. Both 2D2C cameras were setup to acquire the flow velocity in flow direction and in vertical direction. A high-speed laser (Photonics DM 150) was used to illuminate the particles during image acquisition. The available laser power and light sheet optics resulted in a light sheet dimension of approximately 90 mm height and 2 mm to 3 mm thickness. Fig. 3b shows the laser light sheet, which is in the center plane of AWB, and its orientation with respect to the model for the configuration without flap.



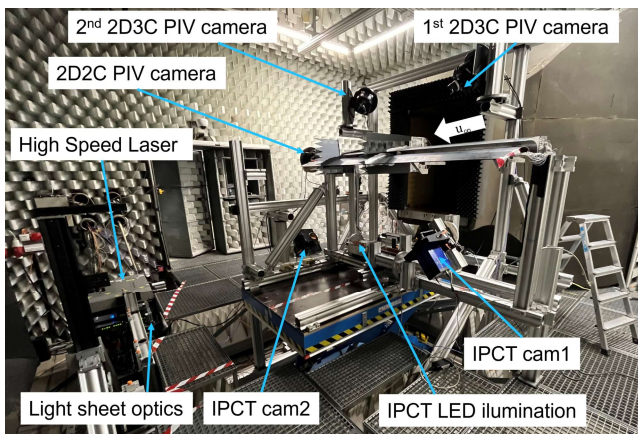
(a) Modified DLR-F15LS model without flap, boundary layer fences, and PIV and IPCT light sources and cameras



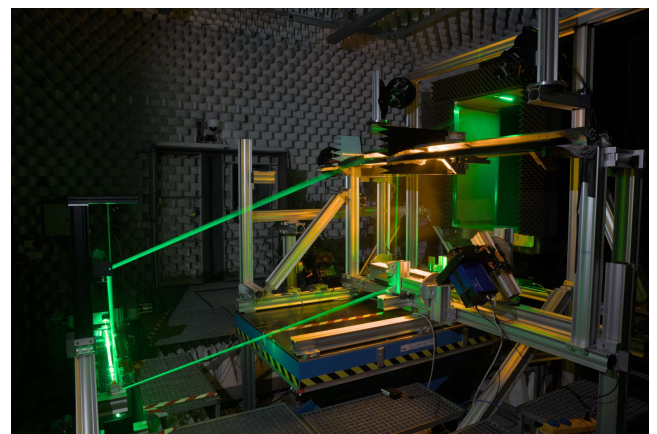
(b) Laser light sheet (green) for particle illumination and LED illumination (yellow) for IPCT pattern illumination.

Figure 3. Experimental setup of the configuration without flap in the open test section of the AWB in the semianechoic room.

PIV setup with flap. The camera setup of the configuration with flap consists of three high-speed cameras (Phantom V2640 CMOS cameras), which are arranged for a 2D2C PIV measurement in the flap cove and a stereo or 2D3C PIV measurement on the upper side of the flap, see Fig. 1 and Fig. 4a. The field of view includes also the gap flow and partially the flow from the wing's suction side. The setup required a more complex light sheet setup in order to partially illuminate also the flap cove with a laser light sheet from below. This was achieved by separating a part from the light sheet as presented in Fig. 4b.



(a) Modified DLR-F15LS model with flap, boundary layer fences, and PIV and IPCT light sources and cameras



(b) Laser light sheet (green) for particle illumination and LED illumination (yellow) for IPCT pattern illumination.

Figure 4. Experimental setup of the configuration with flap in the open test section of the AWB in the semianechoic room.

DEHS seeding of $1\text{ }\mu\text{m}$ diameter was injected downstream of the test section into the flow. PIV double images and IPCT images were acquired for approximately 3.9 s (limited by the camera's

RAM capacity) with 5 kHz and 2.5 kHz, respectively. Thus, for every second PIV velocity vector field information on the shape of the seal is available. These measurements were repeated 10 times to acquire sufficient independent vector fields to achieve meaningful statistical results in the evaluation.

3. Results

From the parameter set of the PIV and IPCT test campaign in the TC2 benchmark test, see Table 1, results are presented here only for the condition with flap and two seal of 80 mm free length with a thicknesses t of 0.1 mm and 0.2 mm, see Table 2. Criteria for the seal excitation were derived from the analysis of the acoustic measurements of the TC2 benchmark test: a flap cove duct inlet-to-outlet area ratio $AR_0 < 1$ and a dimensionless bending compliance $C_B^* > 18$ (Jente et al., 2026). The seal starts curving from $C_B^* > 2$. Thus, the presented results show an excited seal and a bent seal close to being excited.

The flap cove duct inlet-to-outlet area ratio is defined as the free cross sectional area between the seal trailing edge (*SealTE*) and the flap leading edge (*FlapLE*) normalized by the flap gap, see Eq. 1 and Fig. 1. The size of the inlet area was derived from the measured average shape of the deformed seal.

$$AR_0 = \frac{A_{inlet}}{A_{outlet}} = \frac{\Delta(SealTE - FlapLE)}{Gap} \quad (1)$$

The dimensionless bending compliance C_B^* is the inverse of the dimensionless bending stiffness Duan & Wang (2021); thus, the ratio of fluid inertial force and plate bending force:

$$C_B^* = \varrho_\infty U_\infty^2 \frac{12(1 - \nu^2) L^3}{E t^3} \quad (2)$$

The fluid inertial forces are included by the aerodynamic parameter of the fluid density ϱ_∞ and flow speed U_∞ . The plate bending force is represented by the Poisson ratio (steel $\nu = 0.29$), Young's modulus of elasticity ($E = 185$ GPa) and the seal geometry. The coating from the screen printing of the dot pattern for the IPCT is neglected up to now.

First the statistical results of the velocity field and the dynamic deformation measurement are presented in Fig. 5 for the configuration with flap and an excited seal ($L = 80$ mm, $t = 0.1$ mm, $U_\infty = 34.3$ m/s). The IPCT result clearly shows that the seal is deflected from its wind-off shape (gray line) to a curved shape (red line) due to the aerodynamic forces. The flow leads to a bending of the seal up to 17 mm at the trailing edge upwards altering the gap to the flap remarkably compared to the wind-off state. In this side view of the seal shape over the entire IPCT measurement field of 450 mm the deviations from the ideal 2D seal contour are visible as an irregularly shaped red line.

Table 2. Experimental parameter of the wind tunnel test and derived dimensionless bending compliance parameter C_B^* and flap cove duct inlet-to-outlet area ratio AR_0 .

DPN	Configuration	t [mm]	L [mm]	U_∞ [m/s]	C_B^*	AR_0
TC2-3	flap	0.1	80.0	34.3	43.8	0.76
TC2-2	flap	0.2	80.0	60.0	16.8	0.74

From the IPCT time series an amplitude of approximately 2 mm is detected for the tip oscillation. The flow into the flap cove has high flow speed and follows the contour of the seal, but inside of the flap cove above the seal barely any fluid motion is detected, see Fig. 5a and Fig. 5b. The root-mean square (rms) of the shown velocity components show increased levels in extrapolation of the seal shape and thus provide an indication of the seal movement, see Fig. 5c and Fig. 5d. The flow field above the flap clearly shows the shear layers of the wing's suction side, the shear layer of main wing leaving the flap cove, and the shear layer of the flap. At the bottom right corner flow from the pressure side of the flap is also included in the FOV. The rms of the velocity components (Fig. 5c and Fig. 5d) show that the flow from the gap is to a large extent characterized by increased levels of u_{rms} and v_{rms} , which spreads over the flap into the flaps wake.

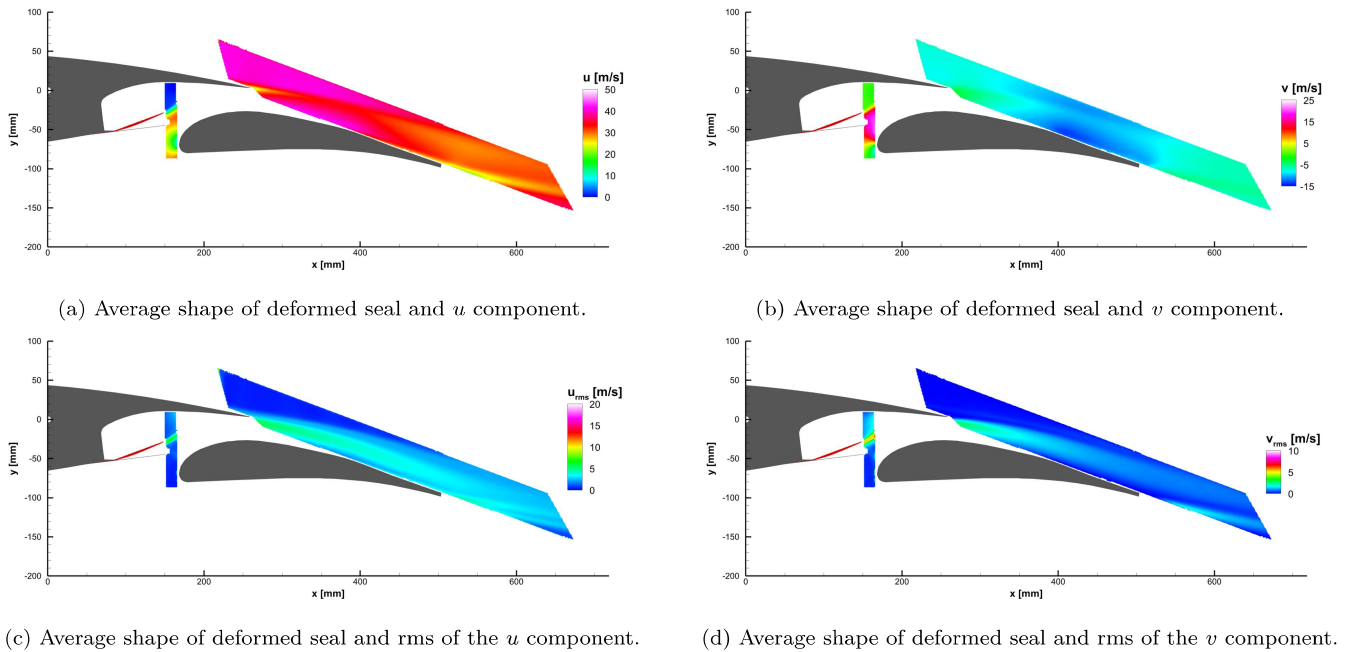


Figure 5. IPCT and PIV result for TC2-3 (excited seal, $L = 80$ mm, $t = 0.1$ mm, $U_\infty = 34.3$ m/s). Average shape of the seal under aerodynamic load (red line) and the seal shape when not loaded by aerodynamic forces (gray line). Average and rms of the flow field into the flap cove (2D2C) and on the upper side of the flap (2D3C).

The statistical results of the velocity field and the dynamic deformation measurement are presented in Fig. 6 for TC2-2 (not excited, $L = 80$ mm, $t = 0.2$ mm, $U_\infty = 60.0$ m/s). The seal is bent by

14 mm with an amplitude of the seal vibration of below 0.2 mm. The observations made for TC2-3 (Fig. 5) and TC2-2 are to a large extent quite similar. But due to the seal being deflected but not vibrating the turbulence entering the flap cove is much smaller and limited spatially. This is also observed for the flow leaving the gap, where the wall normal extent of turbulence is smaller and further away from the flap's suction side compared to the flow when the seal is excited, compare Fig. 5c and Fig. 6c.

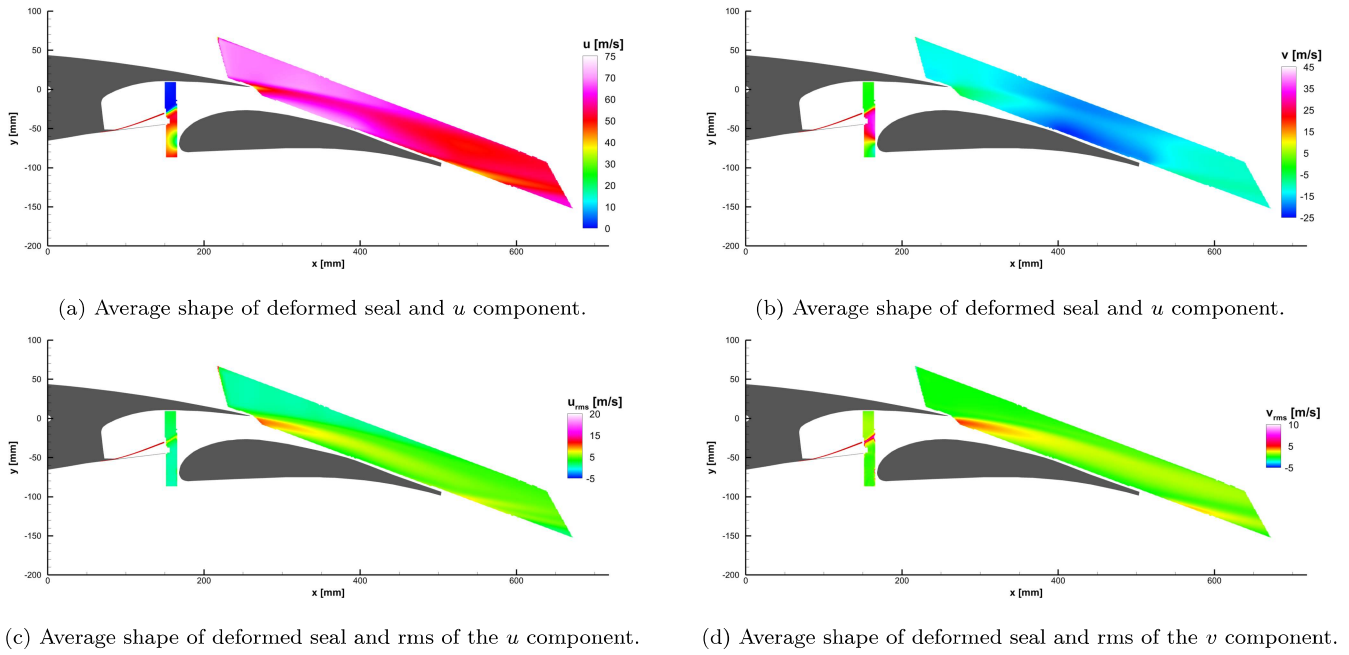
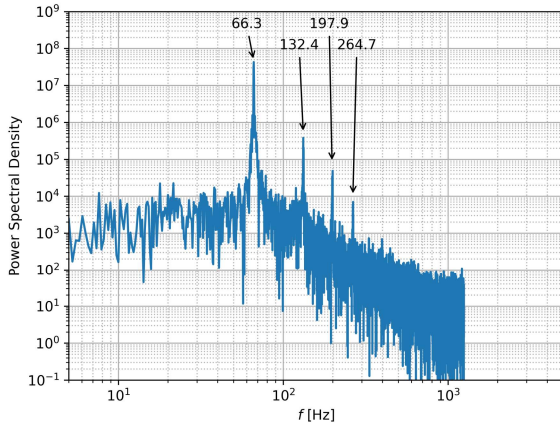


Figure 6. IPCT and PIV result for TC2-2 (curved seal, $L = 80$ mm, $t = 0.2$ mm, $U_\infty = 60.0$ m/s). Average shape of the seal under aerodynamic load (red line) and the seal shape when not loaded by aerodynamic forces (gray line). Average and rms of the flow field into the flap cove (2D2C) and on the upper side of the flap (2D3C).

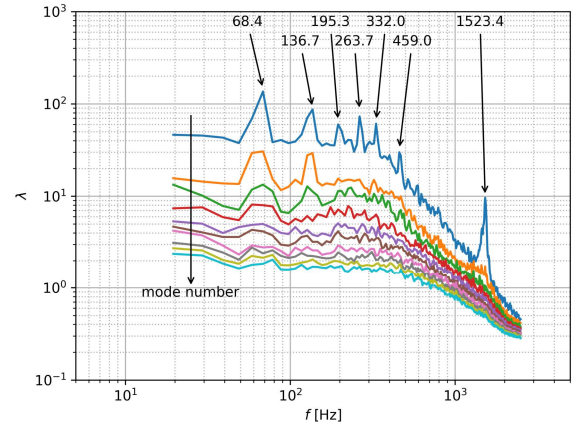
To gain further insight into the FSI a FFT analysis of the time series of the tip of the seal in the middle section of the flow was conducted and plotted as power density spectrum in Fig. 7a and Fig. 8a for the excited seal and bent seal, respectively. Furthermore, a spectral proper orthogonal decomposition (SPOD) analysis (Picard & Delville, 2000) was conducted on the flow field over the flap with a block size of 512 with a 50 % overlap and filter with a Hanning window.

The power density spectrum of the seal bending measured at the seal tip is presented in Fig. 7a for TC2-3 (excited seal). Several distinct peaks are indicated, some of which are also visible in the SPOD results presented in Fig. 7b. The spectral analysis results for TC2-2 (bent seal with negligible oscillation amplitude) shows fewer and weaker peaks (Fig. 8a). From these characteristics only the 133 Hz appears in the SPOD results in the 2nd mode with very small peak (Fig. 8b). Both SPOD results have a high frequency peak at 1523 Hz and 2436.5 Hz, see Fig. 7b and Fig. 8b, respectively. These modes are generated at the flap trailing edge.

The majority of the peaks in the power density spectrum of the seal deformation and in the SPOD

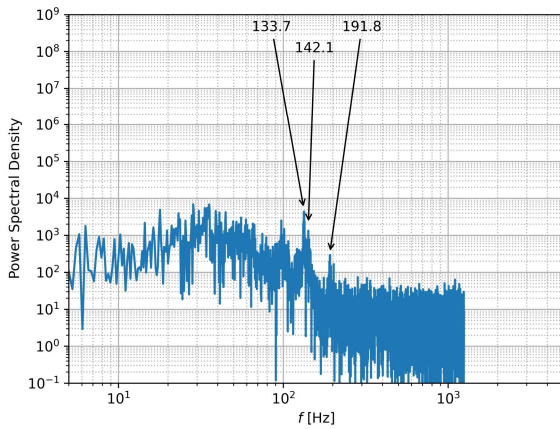


(a) Power density spectrum of the seal tip deformation.

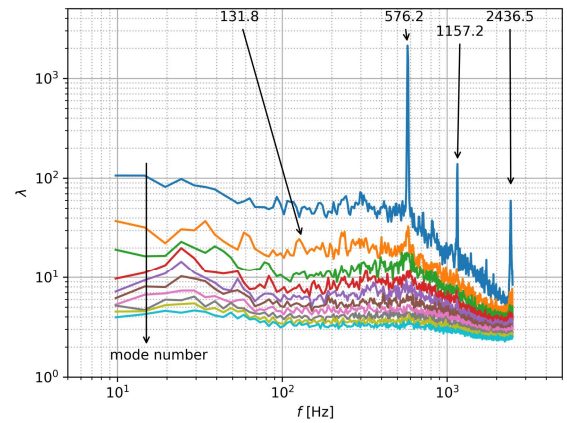


(b) SPOD spectra of the flow field for the first 10 modes.

Figure 7. Spectral analysis of the seal deformation and flow downstream of the wing trailing edge over the flap for $t = 0.1$ mm and $U_{\infty} = 34.3$ m/s, i.e. the seal is excited.



(a) Power density spectrum of the seal tip deformation.



(b) SPOD spectra of the flow field for the first 10 modes.

Figure 8. Spectral analysis of the seal deformation and flow downstream of the wing trailing edge over the flap for $t = 0.2$ mm and $U_{\infty} = 60$ m/s, i.e. the seal is not excited.

spectra of the flow over the flap were also detected in the analysis of a surface pressure sensor in the flap cove (Jente et al., 2026). Since, this data was acquired at several flow velocities for each model configuration, the acoustical effects can be distinguished from the velocity-frequency power-law correlation, i.e., depending on the development of the frequency peak with the flow velocity. The microphone used for this analysis was located in the flap cove on the wing and above the flap.

For TC2-3 (excited seal) the acoustical analysis found tones due to FSI / bending at 67 Hz, 133 Hz, 200 Hz, 267 Hz, 333 Hz and 400 Hz. In the seal tip deformation spectrum the first four of these frequencies are also found, see Fig. 7a. Even better agreement is visible for the 1st mode of the SPOD analysis of the flow field, where also the tone at 333 Hz is detected. However, the tone at 400 Hz is not detected in the velocity field but this tone is also barely above the signal-to-noise ratio of the acoustical analysis (Jente et al., 2026).

For TC2-2 (not excited seal) the acoustical analysis found tones due to FSI / bending and the Rossiter effect. Only one FSI tone was detected at 133 Hz with a small amplitude compared to the test case of the excited seal. In the power density spectrum of the seal tip deformation a broader peak at 133.7 Hz to 142.1 Hz is also detected, see Fig. 8a. The SPOD analysis of the flow field in Fig. 8b shows only a small peak at 131.8 Hz in the 2nd mode. Thus, indicating only a low amplitude for this spectral content which agrees with the acoustic results. Other peaks in the power density spectrum of the seal tip deformation were not detected in the acoustical analysis and in the SPOD analysis of the flow field. Also, the agreement for the Rossiter tones detected at 579 Hz and 1158 Hz (Jente et al., 2026) are well captured by the SPOD analysis of the flow field. The Rossiter effect describes the generation of discrete tones due to flow over an open cavity via a feedback mechanism. It consists of the convective transport in the shear layer downstream the seal trailing edge and - upon reaching the wing trailing edge - an upstream acoustic return to the seal trailing edge (Jente, 2026). For TC2-2 the feedback mechanism is stable and Rossiter tones are generated despite a low amplitude oscillation of the seal. For increasing amplitude a FSI coupling with the Rossiter effect is to be expected.

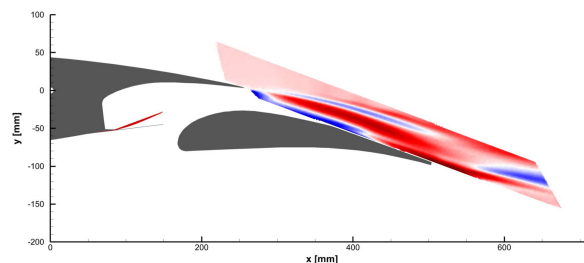


Figure 9. Instantaneous flow field of the u velocity component as derived from the first SPOD mode and the detected FSI / bending tone at 68 Hz for the excited seal condition.

Examples of the flow field as derived from the first SPOD mode for the FSI / bending tone at 68 Hz for the excited seal condition is presented in Fig. 9. Also, the flow field as derived from the first

SPOD mode for the Rossiter tone at 576 Hz for the bent seal with negligible oscillation amplitude is presented in Fig. 10. Furthermore, the flow field for the high frequency peak of the flap trailing edge noise is presented in Fig. 11

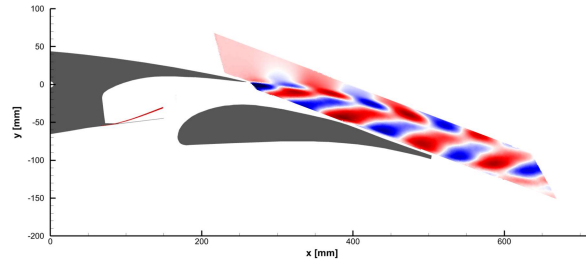


Figure 10. Instantaneous flow field of the u velocity component as derived from the first SPOD mode and the detected Rossiter tone at 576 Hz for TC2-2 (not excited seal).

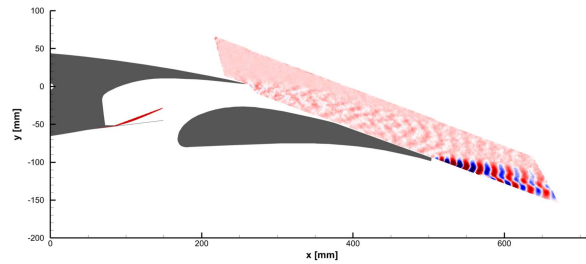


Figure 11. Instantaneous flow field of the u velocity component as derived from the first SPOD mode and the detected peak at 1523 Hz for TC2-3 (excited seal).

4. Conclusions

In the FALCON project's Aeroacoustic FSI Test Case 2 (TC2) Benchmark, the fluid-structure acoustic interaction of a flap cover seal on a two-element 2D wing was investigated. The DLR-F15LSmod model featured a scaled seal, which enabled investigating the key physical FSI mechanisms of the seal. Results are presented for two seal thicknesses, which allowed testing at two different dynamic conditions of the seal: bent seal with negligible oscillation amplitude and excited seal. The periodic motion of the seal was self-excited by the FSI.

The investigation was conducted by time-resolved PIV measurements at the inflow into the flap cove just downstream of the flap cover seal and on the suction side of the flap starting just upstream of the trailing edge of the main wing and including the outlet of the flap cove. The dynamic of the seal was acquired by time-resolved IPCT deformation measurements conducted simultaneously with the PIV measurements. Key findings of the acoustic measurement, which was also conducted in parallel, is presented by Jente et al. (2026).

The spectral analysis of the seal deformation successfully identified several characteristic frequencies in the range of 60 Hz to 400 Hz for the TC2-3 case (excited seal), which result in tones due to the fluid-structure interaction of the seal. These frequencies are also found in the spectral analysis of the flow field. For TTC2-2 (not excited seal) only a single weak FSI mode is detected in the deformation and velocity results. These deformation and velocity data for the FSI tones enhance the findings of the acoustic measurements conducted during the same test campaign. For the bent with negligible oscillation amplitude seal characteristic frequencies are found in the spectral analysis with large amplitudes at 576 Hz and its first harmonic. These modes are caused by the Rossiter effect and show significantly different dispersion compared to the FSI tones.

The presented experimental results are part of the FALCON project's Aeroacoustic FSI Test Case 2 (TC2) Benchmark. A reduced data set will be available upon request via DLR for the validation of FSI modules in numerical codes, especially Lattice-Boltzmann solvers.

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Nomenclature

A_{inlet}	inlet area [m ²]
A_{outlet}	outlet area [m ²]
AR_0	flap cove duct inlet-to-outlet area ratio [-]
AWB	Aeroacoustic Wind Tunnel Braunschweig
C_B^*	dimensionless bending compliance [-]
δ_F	flap angle [°]

E	Young's modulus of elasticity [GPa]
FSI	Fluid-Structure interaction
$FlapLE$	flap leading edge [mm]
Gap	gap between wing and flap at wing trailing edge [mm]
IPCT	Image Pattern Correlation Technique
L	free length of the seal [mm]
ν	Poisson ratio [-]
PIV	Particle Image Velocimetry
ρ_{∞}	fluid density [kg/m ³]
$SealTE$	seal trailing edge [mm]
t	seal thickness [mm]
U_{∞}	flow speed [m/s]

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