Tomographic Particle-Image Velocimetry Analysis of the Influence of Artificially Introduced Sound Waves on Transonic Buffet Flow

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ABSTRACT

The scope of this study is to investigate how the feedback loop that leads to the buffet flow and of which the trailing-edge noise represents the upstream propagating part can be influenced by artificial noise that is introduced to the flow in the trailing-edge region of a supercritical airfoil under buffet flow conditions. The airfoil flow is investigated at a freestream Mach number of $M_\infty = 0.73$, an angle of attack of $\alpha = 3.5^\circ$, and a chord based Reynolds number of $Re_x = 1.89 \times 10^6$. Sound waves with a well defined frequency $f_{\text{sound}}$ and variation of the sound pressure level (SPL) with a frequency of $f_{\text{SPL}}$ are generated by a loudspeaker downstream of the airfoil. Time-resolved tomographic particle-image velocimetry as well as unsteady pressure measurements are used to investigate the unsteady transonic buffet flow field with and without artificial sound waves to quantify their influence on the buffet phenomenon. Emphasis is put on the analysis of the three-dimensional Lamb vector that appears as the major source term for vorticity driven sound in acoustic analogies. The results show how the shock oscillation and the natural sound source in the trailing-edge region are influenced by introducing artificial sound waves. The results show that the frequency of the sound pressure level variation has the strongest influence on the buffet flow field and may even force the shock movement to "lock into" the excitation frequency prescribed by this frequency of the sound pressure level variation, whereas a variation of the frequency of the sound waves itself doesn't affect the flow field.

1. Introduction

In transonic flow around airfoils, the shock wave/turbulent boundary-layer interaction with separation may induce large-amplitude, low-frequency, self-sustaining shock wave oscillations without any external forcing. In this case, the initially steady flow around the airfoil becomes unsteady and induces changes in the aerodynamic forces, i.e., oscillations in lift and drag. This aerodynamic phenomenon is known as transonic buffet. As a consequence, the interaction between these periodic aerodynamic forces and the wing structure may finally excite periodic inflection and torsion vibrations, i.e., buffeting, of the wing.
The transonic buffet flow field itself is characterized by large-scale shock oscillations, and the oscillation frequency $f$ often is given as a reduced frequency $\omega^* = 2nf/c_\infty$ based on the chord length $c$ and the freestream velocity $u_\infty$. Experimental investigations of Stanewsky and Basler [9] with a CAST7/D0A1 supercritical airfoil showed that the reduced frequency varies with the freestream Mach number, the angle of attack, and the Reynolds number. Typical values are in the range of $0.3 \leq \omega^* \leq 0.6$. The reduced frequency decreases, if a laminar-turbulent transition of the boundary layer is triggered upstream of the shock wave. Stanewsky and Basler also showed that the thickness of the boundary layer downstream of the shock wave varies with the shock wave position such that, on the one hand, its extension is maximum when the shock is located most upstream and, on the other hand, its extension is minimum when the shock wave is positioned most downstream. Since the strength of the shock wave depends on the shock Mach number, it is a function of the relative velocity of the moving shock wave and the incoming flow. Thus, the shock is the strongest when it propagates upstream during a buffet cycle. Lee [7] suggested a physical interpretation of the self-sustaining shock oscillation, in which the up- and downstream propagating disturbances within the flow field downstream of the shockwave form a kind of feedback loop. The model assumes that the flow is fully separated from the shock to the trailing edge and that the shock oscillation itself is sinusoidal. According to Lee’s model, the oscillating shock wave generates large-scale turbulent structures that propagate downstream and generate sound waves while passing over the sharp trailing edge of the airfoil. These sound waves propagate upstream outside of the separated recirculation area as described by Voss [10] and Finke [3] and impart energy to the shock wave movement. The oscillation period is thereby given by the time it takes a shock induced disturbance to convect downstream towards the trailing edge plus the time it takes the sound waves that originate at the trailing edge to reach the upstream located shock [8]. Investigations of the transonic flow over a supercritical airfoil encountering self-sustained shock wave oscillations conducted by Hartmann et al. [5] indicated that the sound pressure level of the sound waves that originate at the trailing edge and that reach the shock wave varies. As a consequence, the shock is forced to move upstream when the sound pressure level of the sound waves reaching it is high, while the shock moves downstream when the sound pressure level of the sound waves reaching it is low. The experiments by Hartmann et al. also revealed that the sound waves generated at the trailing edge possess a high frequency, which is about ten times higher than the shock wave oscillation frequency. Their sound pressure level (SPL) variation frequency corresponds to the buffet frequency, i.e., the shock oscillation frequency. This variation of the sound pressure level of the trailing-edge noise is based on the variation of the strength of the noise generating disturbances that travel
downstream and interact with the trailing edge. Finally, the variation of the strength of the shock-induced downstream propagating disturbances is based on the variation of the strength of the shock/boundary layer interaction because of different relative speeds of the moving shock wave and the incoming flow during the oscillation cycle. Figure 1 shows the main features of the transonic buffet flow over a supercritical airfoil.

Overall it can be said that, although buffet flows have been investigated intensively in the past, the details of the mechanisms leading to the shock oscillations are not fully understood. This refers especially to the impact of the frequency and the sound pressure level variation frequency of the sound waves generated at the trailing edge of the airfoil. Therefore, a deeper understanding of the mechanisms leading to buffet is still of great interest, since it might help to predict the conditions for buffet onset and to find strategies to further postpone the buffet boundary. Hence, the scope of this study is to analyze in how strong the feedback loop, that leads to the buffet flow and of which the trailing-edge noise represents the upstream propagating part, can be influenced by artificial noise that is introduced to the flow in the trailing-edge region. It is expected that the analysis deepens the understanding of the mechanisms that lead to the shock wave oscillation, especially regarding the impact of the sound wave characteristics such as frequency and sound pressure level on the unsteady buffet phenomenon.

In former studies, the buffet flow field over a supercritical DRA 2303 airfoil has been overlaid with artificially introduced sound waves to study the impact of distinct trailing-edge noise on the buffet flow characteristics [2,4,5]. The results showed that artificially introduced sound waves can influence the buffet flow with respect to the oscillation frequency, the amplitude, and
the periodicity. However, these investigations were limited to the introduction of artificially produced sound waves of low and high frequencies with a constant sound pressure level and to the introduction of sound waves that resemble a reproduction of the natural trailing-edge noise. In the present study, the frequency of the overlaid sound waves and their sound pressure level will be varied. The flow conditions in the test section of the Trisonic wind tunnel are set such that buffet is initiated naturally in the flow around a two-dimensional DRA 2303 supercritical airfoil. Well defined sound waves are introduced to the flow field downstream of the trailing edge of the airfoil using a midrange driver. The three-dimensional velocity field is captured by time-resolved tomographic Particle-Image velocimetry (PIV) along with steady and unsteady surface pressure measurements both on the airfoil model surfaces and on the upper and lower walls of the test section. The effect of these artificially introduced sound waves on the buffet flow field is investigated for different frequencies and variations of the sound pressure level. Emphasis will be put on the analysis of the three-dimensional Lamb vector.

1. Experimental setup

All measurements of this study are conducted in the trisonic wind tunnel which is an intermittent working vacuum storage tunnel that provides flows at Mach numbers ranging from 0.3 to 4.0. Depending on the Mach number, the flow is stable for up to three seconds. The Reynolds number is determined by the ambient conditions and varies from $6 \times 10^6$ m$^{-1}$ to $16 \times 10^6$ m$^{-1}$ depending on the Mach number. For the investigations of transonic flows, the 0.4 m $\times$ 0.4 m square test section is equipped with flexible upper and lower walls to simulate unconfined flow conditions.

The airfoil model is a two-dimensional wing with a supercritical laminar-type DRA 2303 profile and a chord length of $c = 150$ mm. The wing is made of an orthotropic ultra-high modulus carbon fiber laminate sandwich shell around a steel core. The model is light weight, stiff, and can be regarded as rigid. A thin zigzag stripe triggers boundary-layer transition at 5% chord. The airfoil model surfaces and the upper and lower walls of the test section are instrumented with pressure orifices and subminiature pressure transducers for steady and unsteady pressure measurements. A schematic of the experimental setup is shown in figure 2.
Sound waves of varying frequency and sound pressure level are introduced artificially downstream of the airfoil trailing edge in the freestream chamber of the tunnel using a midrange driver BMS 4591 with a power rating of 150 W AES, a maximum sound pressure level of 136 dB within quiescent air, and an efficiency of 118 dB (1 W/1 m). The sound signals are generated by an HP32120A signal generator and are amplified by a Camco Vortex 6 amplifier. The amplitudes of the sound waves are amplified by a horn that is connected to the loudspeaker. Figure 3 shows a close-up view of the setup for the generation of the sound waves in the trisonic wind tunnel.
Fig. 3 Schematic top view (left) and side view (right) of the test section and the freestream chamber of the wind tunnel with the artificial sound source installed.

Prior to the runs, the air is seeded with DEHS droplets with a mean diameter of about 1 μm. The measurement volume inside the test section is generated by two Nd:YLF high speed lasers (Quantronix Darwin Duo 527-100-M and 527-40-M). The conjunction of the laser beams is shaped into a 6 mm thick light volume in the trailing-edge region. A system of three CMOS cameras (one Photron Fastcam SA5 and two Photron Fastcam SA3) is used to record the forward Mie scattering images of the seeding particles from different directions. The cameras are installed symmetrically to the channel in Scheimpflug arrangement. The corresponding viewing angles of the cameras are $\xi_1 = 124^\circ$, $\xi_2 = 130^\circ$, and $\xi_3 = 111^\circ$, see fig. 2. The sampling frequency is 1000 Hz for about one second of steady flow, such that about 170 buffet oscillation cycles are captured during one test run. The evaluation of the raw images is performed using DaVis 8.2.3 (LaVision GmbH, Göttingen, Germany) applying a volumetric self-calibration, an iterative multiplicative algebraic reconstruction technique, and a multi-pass interrogation method with a final window size of $48\times48\times48$ px$^3$ and an overlap of 75%. The evaluation results in a final vector spacing of 0.74 mm.

3. Results

The buffet flow has been investigated at a freestream Mach number of $M_\infty = 0.73$, an angle of attack of $\alpha = 3.5^\circ$, and a Reynolds number based on the chord length $c$ of $Re_\infty = 1.89\times10^6$. First, a reference case has been measured, where no artificial sound is overlaid to the flow field. Next, several cases have been studied, where sound waves are introduced to the flow field by the loudspeaker to analyze their impact on the buffet phenomenon. The parameter variations are listed in table 1. In this context, the parameter $f_{\text{sound}}$ denotes the frequency of the artificial sound waves and $f_{\text{SPL}}$ represents the frequency of the SPL variation of the sound waves emitted by the loudspeaker. Figure 4 shows exemplarily the sound signal emitted by the midrange driver. From
previous experiments [6] it is known that the sound waves originating naturally at the trailing edge are of high frequency of about 1100 Hz and that their sound pressure level is expected to vary with the frequency of the shock wave oscillation. As the buffet frequency was found to be about $f_{\text{buffet}} = 170 \text{ Hz}$, the case $[f_{\text{SPL}}, f_{\text{sound}}] = [170 \text{ Hz}, 1100 \text{ Hz}]$ therefore represents the reproduction of the natural sound.

![Example of the sound signal emitted by the loudspeaker.](image)

**Fig. 4** Example of the sound signal emitted by the loudspeaker. The sound waves are of high frequency ($f_{\text{sound}}$) and their sound pressure level varies with a low frequency $f_{\text{SPL}}$.

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<thead>
<tr>
<th>$f_{\text{SPL}}$</th>
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<th>175 Hz</th>
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<td>$f_{\text{sound}}$</td>
<td>900 Hz</td>
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**Tab. 1** Characteristics of the artificially introduced sound: combinations of the frequency of the sound waves $f_{\text{sound}}$ and the variation of their sound pressure level $f_{\text{SPL}}$ (p: unsteady pressure measurements, PIV: tomographic PIV measurements).

### 3.1 Pressure distribution

The buffet flow field that develops around the airfoil model in the reference case without artificial sound waves is characterized by self-sustained sinusoidal shock wave oscillations on the suction side of the wing at a frequency of about $f = 170 \text{ Hz}$, which corresponds to a reduced frequency of $\omega^* = 0.68$. A detailed description of the general buffet flow field over the DRA 2303 supercritical airfoil can be found in [6]. Figure 5 depicts the frequency analysis of the signal of a pressure transducer on the suction side of the airfoil located in the shock wave region. Previous studies [2] showed that the shock movement can be well captured by this pressure signal. The spurious peaks in the spectrum that appear due to the tunnel configuration are marked by the
circles. They are also present in the spectrum when the tunnel is run empty without the airfoil installed. Figure 6 shows the frequency spectrum of the same pressure transducer when sound waves are overlaid artificially onto the flow field by the loudspeaker. In figure 6a), the spectra are depicted for the cases in which the sound pressure level of the artificial sound waves varies with a frequency of 170 Hz, i.e., the natural buffet frequency. The frequency of the sound waves produced by the loudspeaker is varied (900 Hz, 1100 Hz and 2000 Hz.). The power spectrum indicates that the frequency of the shock oscillation is not influenced by this variation as the frequency bump in the spectra in figure 6a) remains unchanged at 170 Hz, i.e., $\omega^* = 0.68$. When the sound wave frequency of the overlaid sound waves remains unchanged and the sound pressure varies with frequencies $f_{SPL}$ that differ from the natural buffet frequency, the shock oscillation seems to "lock into" the external excitation frequency as indicated by the results shown in figure 6b). Note that the high frequency of the loudspeaker sound waves is also included in the frequency spectra, as marked by arrows in figures 6a) and 6b).

![Figure 5](image_url)  
*Fig. 5* Frequency spectrum of the signal of a pressure transducer on the airfoil suction side located in the shock wave region.
a) Variation of sound frequency, SPL variation: 170 Hz.

b) Variation of sound pressure level, constant sound frequency of 1100 Hz.

**Fig. 6** Frequency spectrum of the signal of a pressure transducer on the airfoil suction side located in the shock wave region for the buffet flow with artificially introduced sound waves.

The plot in figure 7 compares the time-averaged $c_p$ distribution for all test cases. The peak on the suction side at about $x/c = 0.1$ is caused by the transition stripe on the airfoil model surface. The critical $c_p$ value for this configuration is marked by the dashed line such that the mean shock position is given by the intersection of the $c_p$ curve with this line. For the reference case without artificial sound waves, i.e., natural buffet flow, the mean shock position is at $x/c = 0.45$ and the amplitude of the shock oscillation is about $4\%$ chord. The graphs clearly show that the
introduction of an artificial sound field has no crucial impact on the mean shock wave position and on the mean $c_p$ distribution.

![Graph](image)

**Fig. 7** Mean $c_p$ distribution for the reference case and for four cases with artificially overlaid sound waves with a frequency of $f_{\text{sound}}$ and a variation of the sound pressure level with a frequency of $f_{\text{SPL}}$. The dashed line marks the critical $c_p$-value.

3.2 Velocity field

The velocity field in the trailing-edge region of the DRA 2303 wing model is analyzed by time-resolved tomographic PIV. Although the shock wave is not included in the measurement volume, the vector fields can be phase-averaged depending on the shock position. Since the extension of the separated recirculation region is coupled with the shock oscillation, the maximum up-/downstream position of the shock can be determined using this extension as a criterion. Figure 8 shows the mean streamwise velocity $\bar{u}$ around the trailing edge of the wing model for the most upstream and most downstream position of the shock, respectively, space-averaged in the spanwise y-direction. The separated recirculation region can be clearly identified by the low speed area marked in blue in figure 8.
The acoustic perturbation equations (APE) determine the sound propagation and identify the dominant noise sources. Since a compressible flow problem is considered, the APE-4 system is considered [1]

\[ \frac{\partial p'}{\partial t} + \bar{a}^2 \nabla \cdot \left( \bar{p} \mathbf{u}' + \bar{u} \frac{p'}{\bar{p}} \right) = \bar{a}^2 (q_c + q_e) \tag{1} \]

\[ \frac{\partial \mathbf{u}}{\partial t} + \nabla (\bar{u} \cdot \mathbf{u}') + \nabla \left( \frac{p'}{\bar{p}} \right) = \mathbf{q}_m \tag{2} \]

which were derived from the continuity and Navier-Stokes equations. The right-hand side source terms are

\[ q_c = -\nabla \cdot (\rho' \mathbf{u}')', \tag{3} \]

\[ q_e = -\frac{\partial p_e}{\partial t} - \nabla \cdot (\rho_e \bar{u})', \tag{4} \]

\[ \mathbf{q}_m = -\omega \times \mathbf{u}' - \left( \nabla \left( \frac{|u'|^2}{2} \right) \right)' + \nabla \frac{p'}{\bar{p}} - \left( \frac{\nabla p}{\rho} \right)' \tag{5} \]
For trailing-edge noise which is dominant in the current analysis, the Lamb vector, i.e., the vorticity-velocity cross product $\vec{\omega} \times \vec{u}$ is the major source term. A temporal fluctuation of the Lamb vector that can be described by the perturbed Lamb vector,

$$\vec{L}' = \vec{\omega} \times \vec{u} - \bar{\vec{\omega}} \times \bar{\vec{u}},$$

leads to noticeable sound production. In figure 9, the contour plots of the absolute value of the perturbed Lamb vector, phase averaged depending on the shock wave position, are shown for both the reference case (fig. 9a) and 9b)) and for the cases where sound is emitted from the loudspeaker (fig. 9c) to fig. 9h)). The analysis focuses on the trailing-edge region on the suction side of the wing. The perturbed Lamb vector in the trailing-edge region is of opposite sign for the shock being located most upstream and most downstream. The comparison of the results from the reference case in figures 9a) and 9b) with the results from figures 9c) to 9f), where sound waves are emitted by the loudspeaker, suggests that the sound field developing in the trailing-edge region is influenced by the introduction of sound waves by the artificial sound source. However, no crucial differences can be found in between the cases $[f_{\text{sound}}, f_{\text{SPL}}] = [1100 \text{ Hz}, 170 \text{ Hz}]$ and $[f_{\text{sound}}, f_{\text{SPL}}] = [2000 \text{ Hz}, 170 \text{ Hz}]$, where only the frequency of the sound waves is changed and the frequency of the sound pressure level variation corresponds to the buffet frequency. However, figures 9g) and 9h) show a change of the sound pressure level variation frequency $f_{\text{SPL}}$ to affect more strongly the natural sound field in the trailing-edge region. Regarding the feedback loop of down- and upstream propagating disturbances that according to Lee [6] cause the self-sustained shock wave oscillations and of which the trailing-edge sound forms the upstream propagating part, the results suggest that these mechanisms can be manipulated by introducing artificial sound waves to the flow field. Especially the frequency of the variation of the sound pressure level changes the natural trailing-edge noise and may even force the shock movement to "lock into" the excitation frequency prescribed by the frequency of the sound pressure level variation.
a) Reference case

b) Reference case

c) \([f_{\text{sound}}, f_{\text{SPL}}] = [1100 \text{ Hz}, 170 \text{ Hz}]\)

d) \([f_{\text{sound}}, f_{\text{SPL}}] = [1100 \text{ Hz}, 170 \text{ Hz}]\)

e) \([f_{\text{sound}}, f_{\text{SPL}}] = [2000 \text{ Hz}, 170 \text{ Hz}]\)

f) \([f_{\text{sound}}, f_{\text{SPL}}] = [2000 \text{ Hz}, 170 \text{ Hz}]\)
Fig. 9 Contour plots of the absolute value of the perturbed Lamb vector for the reference case and for three cases with artificially overlaid sound waves. The plots are phase averaged depending on the shock wave position (left column: shock wave located most upstream, right column: shock wave located most downstream) and spaceaveraged in the y-direction.

4. Conclusion

The transonic flow field over a supercritical DRA 2303 airfoil model has been investigated experimentally by applying time-resolved pressure measurements and time-resolved tomographic PIV in the trailing-edge region. The freestream conditions were set to \([M_\infty, \alpha] = [0.73, 3.5^\circ]\) and the chord based Reynolds number was \(Re_\infty = 1.89 \cdot 10^6\). Under these conditions, a self-sustaining shock wave oscillation, i.e., buffet, develops on the suction side of the airfoil. In order to investigate the influence of the trailing-edge noise, sound waves with a defined frequency and variation of the sound pressure level are introduced to the buffet flow field by a loudspeaker downstream of the airfoil. Several parameters of the sound wave frequency \(f_{\text{sound}}\) and the frequency of the sound pressure level variation \(f_{\text{SPL}}\) have been tested. The evaluation of unsteady pressure signals of a transducer located in the shock wave region indicate that the shock oscillation frequency is not influenced by the artificial sound waves when only the sound wave frequency differs from that of the natural trailing-edge noise. However, a variation of \(f_{\text{SPL}}\) of the artificial sound waves leads to "lock-in" of the shock wave oscillation frequency into the excitation frequency \(f_{\text{SPL}}\). The results also show that neither the mean shock position on the suction side of the airfoil nor the mean \(c_p\) distribution around the airfoil are affected when sound waves are emitted by the loudspeaker. From the time-resolved three-dimensional velocity field obtained by the tomographic PIV measurements, the perturbed Lamb vector has been
determined. The evaluation of the Lamb vector suggests that a variation of $f_{\text{sound}}$ only weakly influences the natural sound field, whereas a variation of $f_{\text{SPL}}$ has a stronger impact.

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References


