ANALYSIS OF THE EFFECT OF BROADBAND ACOUSTIC EXCITATION ON A LAMINAR SEPARATION BUBBLE

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ABSTRACT

The paper presents the results of an experimental investigation of the effect of broadband acoustic excitation on separated shear layer developing on the flat plate subjected to an adverse pressure gradient (APG). The study includes the effect of sound pressure level (SPL) as well as the Reynolds number. The aim of the work was to investigate how the boundary layer reacts under conditions similar to those found in an aircraft engine. The inherent complexity of the problem is simplified by providing acoustic forcing from a controlled source, acting on the boundary layer developing on the flat plate of a channel with a given streamwise pressure gradient distribution. In addition to the naturally developing flow (no-excitation), the flow was exposed to the pink noise characterized by SPL = 125 dB and 135 dB, respectively. It has been shown that the acoustic excitation in the frequency range from 100 Hz to 650 Hz can lead to a more rapid increase in flow instability around the central frequencies 48 and 64 Hz, followed by an earlier laminar-turbulent (l-t) transition. This is believed to be a coupling effect of the forcing generated by acoustics to the natural frequency of an inviscid Kelvin-Helmholtz instability.

KEYWORDS

boundary layer separation, laminar-turbulent transition, acoustic excitation, flow control

NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>$c_p$</td>
<td>pressure coefficient</td>
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<tr>
<td>$H$</td>
<td>shape factor</td>
</tr>
<tr>
<td>$NE$</td>
<td>no-excitation</td>
</tr>
<tr>
<td>$PN$</td>
<td>excitation with pink noise</td>
</tr>
<tr>
<td>$U$</td>
<td>streamwise mean velocity component</td>
</tr>
<tr>
<td>$u'$</td>
<td>r.m.s. of fluctuating velocity</td>
</tr>
<tr>
<td>$U_e$</td>
<td>velocity at boundary layer edge</td>
</tr>
<tr>
<td>$U_{in}$</td>
<td>mean velocity at test section inlet</td>
</tr>
<tr>
<td>$St_s$</td>
<td>Strouhal number</td>
</tr>
<tr>
<td>$x$</td>
<td>streamwise coordinate</td>
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<tr>
<td>$y$</td>
<td>wall-normal coordinate</td>
</tr>
<tr>
<td>$\delta$</td>
<td>boundary layer thickness</td>
</tr>
<tr>
<td>$\delta^*$</td>
<td>displacement thickness</td>
</tr>
<tr>
<td>$\theta$</td>
<td>momentum thickness</td>
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INTRODUCTION

The problem of increasing of overall efficiency and performance of aero-engines and, on the other hand, significant reductions of aircraft noise is currently a challenge of the modern aviation industry. It is known that the boundary layer transition and separation play important roles in determining the engine efficiency. A laminar-to-turbulent transition is very sensitive to surface roughness as well as to the level of external disturbances like free-stream turbulence or incident wakes (Piotrowski et al., 2010). Additionally, in modern turbofan engines, the boundary layers developing on surfaces of compressors and turbine blades are exposed to strong perturbations caused by high intensity acoustic fields. The high concentration of acoustic energy inside such an engine can have an impact on the stability of the laminar boundary layer and can trigger an earlier laminar-to-turbulent transition (Ezerskii, 1985). For current high bypass ratio engines the sound spectrum consists of both tonal and broadband components, contributions of which come from all rotating elements i.e. the fan, the compressor, the turbine, but also from the combustion chamber and the jet.

On the other hand, when the boundary layer develops along an aerodynamic surface exposed to a strong adverse pressure gradient (APG) it may separate, and then l-t transition occurs in the separated shear layer. This is typically followed by the boundary layer reattachment and formation of a closed region of recirculated flow, referred to as a laminar separation bubble (LSB). In a flow with low freestream turbulence level, the Kelvin-Helmholtz instability (K-H) leads to formation of spanwise-oriented vortex structures, called rolls. They grow downstream and become unstable by spanwise perturbations, which finally leads to breakdown. As shown in Wei and Smith (1986) the appropriate length scale for shear layer instability is the momentum thickness at the separation point. The results presented by Yang and Voke (2001) and Talan and Hourmouziadis (2002) indicate that the instability correlates well within a relatively narrow range of Strouhal number, $St_c=0.005-0.012$, defined by the momentum thickness and edge velocity at the separation point. McAuliffe and Yaras (2008) showed that in APG flow subjected to low freestream turbulence level a growth of the Tollmien-Schlichting (T-S) instability is observed downstream of the point of separation, results in formation of roll-up structures typical of K-H instability. This indicates that K-H instability may be preceded by the development of T-S waves, which, however, is difficult to observe experimentally (Talan and Hourmouziadis, 2002).

Most studies that investigate stability characteristics involve artificial forcing of the boundary layer by means of plasma actuation at a location upstream of the separation point (Yarusevych and Kotsonis, 2017). Jones et al. (2008) investigated by means of DNS the effect of volume forcing introduced in momentum equations on the breakdown process in the separated boundary layer developing on the NACA0012 airfoil. Bons et al. (2002) investigated experimentally the effect of synthetic jets on airfoils operating at low to medium Reynolds numbers. Research in the field of control of laminar separation using flow injection and absorption using Unsteady Reynolds averaged Navier Stokes and Large Eddy Simulations were performed for a wall mounted hump, mimicking the rear suction side of a low pressure turbine profile (Saavedra and Paniagua, 2018).

A number of previous studies have used controlled periodic forcing to investigate the sensitivity of transition in the shear layer of LSBs. Yarusevych and Kotsonis (2017) demonstrate that forcing at the frequency of Kelvin–Helmholtz instability has a significant impact on the reduction of the size of existing LSB. Marxen et al. (2015) observed that increasing the excitation amplitude leads to upstream shift in the mean reattachment locations, which however can lead to the mean flow deformation and a reduction in the frequency of most amplified disturbances. Kurelek et al. (2018) studied the effect of tonal and broadband acoustic excitation on transition in the separated boundary.
layer formed over a NACA0018 airfoil. Bernardini at al. (2012) studied the influence of acoustic excitation at tonal frequencies on boundary layer separation of a highly loaded low-pressure turbine (LPT) blade. They show that the excitation at the unstable frequency intensifies coherence of vortical structures (K-H type) in the shear layer, thus increasing turbulent mixing and effectively reduces the size of the separation bubble.

The present investigation aims to examine the impact of broadband acoustic excitation on the transition in the separated boundary layer on the flat plate surface with APG. The inherent complexity of the problem is simplified by providing acoustic forcing from a precisely controlled external source (loudspeaker). Two sound pressure levels (SPL) were applied, namely 125 and 135 dB. Preliminary research has been reported in paper by Sokolenko at al. (2022), and this paper aims to compare cases with the reference unexcited flow for two different Reynolds numbers and to elucidate underlying physical mechanism of flow instability.

EXPERIMENTAL SETUP

Experiments were carried out in an open-circuit wind tunnel at the Laboratory of Experimental Fluid Dynamics, Częstochowa University of Technology. The test section was equipped with geometrical profile allowing to generate requested streamwise pressure gradient, corresponding to conditions encountered in a typical axial compressor blading (Figure 1a). The channel cross-section was equal to 0.25 m x 0.2 m and its length was equal to 1.45 m. Measurements were performed on the lower flat test plate where separation bubble was generated downstream the channel throat. A settling chamber with several screens and a contraction ratio of 13:1 allowed for a low level of inlet turbulence intensity level $T_i = u'/U_{c,in}$ equals to 0.7%, which was necessary in order to provide a cleaner environment that magnifies the effects of the acoustic excitation. To protect against the boundary layer detachment at the leading edge, the plate was inclined at an angle of 1 degree.

The velocity measurements were performed with the use of hot-wire anemometry (HWA) Dantec Dynamics Streamline Pro apparatus. The HWA probe type 55P05 with 1.25 mm in sensing length and 5 μm in diameter was used. To minimize flow perturbations, the probe was inserted into the test section from behind the separation region. Data acquisition was performed with sampling frequency 25 kHz and with sampling time 60 s. Variations in temperature when measuring a single velocity profile were not larger than ±0.2 °C. When the temperature in the wind tunnel was far from the calibration temperature, temperature-based voltage correction was automatically performed. During the whole experiment, the free-stream velocity and static pressure at the inlet plane ($x = 0$) were monitored with uncertainties of 1% and 10%, respectively.

Sound field measurements were performed with the use of advanced GRAS microphones system. The system consists of flush-mounted and free-field microphones connected with an analogue-digital National Instruments sound and vibration input module. The acquisition and postprocessing was performed using in-house LabVIEW software. One free-field microphone was placed at the outlet of the test section during the measurement in order to measure the SPL generated by the loudspeaker. Based on the instrument’s accuracy for a frequency range of 10–4000 Hz, the uncertainty in the measured SPLs was of ±0.1 dB, which is typical for such measuring devices (Niegodajew et al., 2018).

To perform the effective boundary layer flow control a 15-inches 1-way loudspeaker T115-800 of frequency response 100-500 Hz ± 3dB was used. The impedance of the loudspeaker was 8 Ohm and the peak power was 800 W. The loudspeaker was located at a certain distance from the tunnel outlet and pointed upward the flow, as it is shown in Figure 1a. The position of the loudspeaker has
been fixed so that it does not disturb the flow in the measuring area. The loudspeaker was connected to a Powersoft K 10 DSP amplifier driven by a signal generator controlled by LabVIEW software and connected with a digital-analogue National Instruments converter, generating a noise in a specified frequency range.

**Figure 1. Schematic of the test section and loudspeaker location (a), PSD noise spectra at the test section outlet (b).**

**EXPERIMENTAL CONDITIONS**

The experiment was conducted for two inflow conditions determined in the core flow at the inlet plane to the test section, placed at $x = 40$ mm. The inflow mean velocities $U_{in} \approx 5$ m/s and 10 m/s, which correspond to the Reynolds numbers, $Re_x = 185 000$ and $370 000$, based on the length of the flat plate to the location of separation point, were applied. As stated above inlet turbulence intensity level $Tu$ equals to 0.7%, and an integral length scale to 0.015 m. The inlet values of turbulent quantities were measured at distance $x = -100$ mm in front of the leading edge of the flat plate.

In addition to the naturally developing flow (NE - no-excitation), the flow was exposed to the pink noise characterized by the sound pressure levels: $SPL = 125$ dB and 135 dB at the frequency range 100 – 650 Hz. The pink noise is a random signal for which the spectrum density, i.e. narrow-band signal, varies as the inverse of frequency. It is often used to test various parts of an acoustic systems. Figure 1b presents the noise power spectral density (PSD) measured by the free-field microphone, positioned 300 mm in front of the loudspeaker at the test section exit, for three considered sound pressure levels. It can be seen that the activation of the broadband acoustic forcing in the 100 - 650 Hz range causes a strong increase in sound energy level above 80 Hz, with a characteristic decrease in sound power level above 100 Hz (pink noise).

Flow conditions in the detachment area are described by the edge velocity distribution $U_e(x)$ obtained from hot-wire measurements taken in the freestream. Figure 2 shows $U_e$ distributions for two Reynolds numbers for unexcited (NE) and excited (125 and 135 dB) conditions. The values have been non-dimensionalized with the edge velocity at the channel throat. The dashed line represents the condition for attached boundary layer. One can observe that boundary layer separation promotes in both cases the development of a more or less constant edge velocity region followed by its drop to the level given by the dashed line. These data also indicate that the reattachment point moves upstream with the Reynolds number.
Figure 2. Edge velocity $U_e$ distributions in the LSB region for $Re_x = 185 000$ (a) and $Re_x = 370 000$ (b).

RESULTS

In order to accept the reference flow conditions, the most important parameters near the point of separation for NE case ($x=525$ mm) for all analysed cases are presented in Table 1. This table contains the following data: the mean velocity at the edge of boundary layer – $U_e$, the boundary layer thickness – $\delta$, the shape factor – $H = \delta^*/\theta$, and the Reynolds numbers based on displacement – $Re_\delta^*$, and momentum – $Re_\theta$, thicknesses, respectively. The data show that as SPL increases, only a slight change in flow parameters is observed at the point of separation. A detailed analysis of the effect of acoustic forcing on the various phases of the boundary layer development will be discussed later.

Table 1. Parameters of the boundary layer (BL) near the point of separation for NE cases ($x=525$ mm).

<table>
<thead>
<tr>
<th>$Re_x$ [-]</th>
<th>Case</th>
<th>$U_e$ [m/s]</th>
<th>$\delta$ [mm]</th>
<th>$H$ [-]</th>
<th>$Re_\delta^*$ [-]</th>
<th>$Re_\theta$ [-]</th>
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<tbody>
<tr>
<td>185 000</td>
<td>NE</td>
<td>5.43</td>
<td>6.89</td>
<td>3.77</td>
<td>1105</td>
<td>293</td>
</tr>
<tr>
<td></td>
<td>125dB</td>
<td>5.39</td>
<td>7.00</td>
<td>3.99</td>
<td>1118</td>
<td>281</td>
</tr>
<tr>
<td></td>
<td>135dB</td>
<td>5.38</td>
<td>6.62</td>
<td>3.85</td>
<td>1078</td>
<td>280</td>
</tr>
<tr>
<td>370 000</td>
<td>NE</td>
<td>11.02</td>
<td>4.94</td>
<td>3.41</td>
<td>1522</td>
<td>445</td>
</tr>
<tr>
<td></td>
<td>125dB</td>
<td>10.98</td>
<td>4.57</td>
<td>3.32</td>
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<td>1085</td>
<td>428</td>
</tr>
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</table>

The boundary layer was inspected in several traverses from $x = 70$ to 700 mm from the leading edge downstream. Velocity signals in each traverse were recorded at several points, ranging from the wall vicinity to 20 mm above the plate, in the wall-normal direction. Sample velocity profiles are shown in Figure 3. From a general point of view, it can be seen that initially ($x=525$), regardless of acoustic forcing, the velocity profiles coincide almost perfectly. One can see faster filling up of velocity profiles in the cases with acoustic excitation active. This is visible at distances $x=625$ and 650 mm in Figure 3a (SPL=125dB) and $x=575$ and 600 mm in Figure 3b (SPL=135dB). The increase
of acoustic excitation leads to shortening of the separation bubble in the low Reynolds case (figure 3a) and to bubble suppression in the high Reynolds case (Figure 3b). It is evident that the effect of acoustic forcing is much stronger for SPL=135 dB.

Figure 3. Velocity profiles measured in the LSB region for unexcited (NE) and excited (125 and 135 dB) cases for $Re_x = 185\,000$ (a) and $Re_x = 370\,000$ (b).

Figure 4 shows the distribution of the shape factor, $H$, on plate surface. The experimental data were fitted with a B-spline function, which, with a small number of measurement traverses, allows a study of the tendency of this parameter. For $Re_x = 185\,000$, a clear increase in $H$ is reported at $x = 500$ mm, which is due to influence of APG. At $x = 525$ mm, $H$ reaches a value close to 4, which according to Drela (2014) indicates the laminar boundary layer separation. High values of shape parameter for undisturbed flow in the range $x = 525 – 625$ mm confirm the presence of the LSB. Piotrowski et al. (2010) and Dellacasagrande et al. (2020) observed that the maximum of the shape factor indicates locations of mean l-t transition. In the unexcited case (NE) the transition onset is observed at $x = 600$ mm. It is difficult to judge on relative change in the transition onset location in the cases with the acoustic excitation active, based only on shape factor (Figure 4 a), due to a limited number of experimental data. But comparison of results in Figures 3 (a) and 4 (a) shows a small change in the
boundary layer characteristics at streamwise distances $x=600-650$ mm in the flow with the acoustic excitation at SPL=125dB. Much shorter separated boundary layer is observed in the case with the acoustic excitation at SPL=135dB ($x=600-625$ mm), suggesting an earlier laminar-to-turbulent transition. A valuable finding is, from a statistical point of view, that despite a strong level of acoustic excitation, there is no visible effect on the laminar ($x < 500$ mm) and fully turbulent boundary layers ($x > 675$ mm and $x > 625$ mm for low and high Reynolds numbers, respectively). Confirmation of this finding is provided by the analysis of the time traces presented in Figure 5. Assuming, that the shape factor at separation takes the value $H = 4.0$, and this value is reached for all cases (unexcited and exited) at $x = 525$ mm, it can also be concluded that effect of acoustic excitation on separation point is hardly noticeable.

For $Re_x = 370\ 000$ (Figure 4b) the impact of the Reynolds number is evident by suppression of the LSB. This is confirmed by $H$ values below 4. The shrinking or vanishing of the LSB with the acoustic excitation active might also be understood by analysing the distribution of the mean velocity profiles at the boundary layer edge (Figure 2a and 2b) and the velocity profiles in Figure 3 (b). With the active acoustic forcing the mean velocity profiles approach the velocity distribution for the attached flow, denoted by the dashed line. These results confirm the observations of Kurelek et al. (2018) that acoustic forcing has a significant impact on the reduction of the size of existing LSB.

![Figure 4](image_url)

**Figure 4.** Shape factor distribution $H$ for unexcited (NE) and excited (125 and 135 dB) cases at $Re_x = 185\ 000$ (a) and $Re_x = 370\ 000$ (b).

In order to gain better insight into the effect of acoustic excitation onto the transition process in the separated boundary layer, the time traces for the selected lower Reynolds number are analysed in Figure 5. Four streamwise distances, $x = 575$, 600, 625 and 650 mm have been selected for this purpose. In each case the velocity signal was measured at the same wall-normal distance equal to $y = 2$ mm. In the unexcited case (NE), as depicted in Figure 5a, large-scale instability waves in the free shear layer of the bubble are visible at $x = 575$ mm and 600 mm. This observation is further validated by the Fast Fourier Transform (FFT) analysis presented in Figure 6a, where a clear peak for the 48 Hz is observed. The amplitude of disturbances increases at distance $x = 625$ mm and the first symptoms of turbulent spots can be observed. Breakdown to turbulence is reported for the next traverse i.e. for $x = 650$ mm. In the presence of acoustic forcing at 125 dB (Figure 5b), the high-frequency perturbations superimposed on low-frequency unsteadiness are observed at $x = 575$ and
600 mm, however, the energy of these perturbations is not sufficient to activate the turbulent motion. The clear change in the shape of the time signal between cases can be seen from the distance $x = 625$ mm on, where, with acoustic amplification, more events that resemble the shape of turbulent spots appear. For example, for SPL = 135 dB in Figure 5c the time traces at $x = 625$ mm resemble the time traces for the unexcited flow (Figure 5a) at $x = 650$ mm. This clearly shows earlier turbulence breakdown with the acoustic excitation being activated. At distance 650 mm the time traces for all the cases show similar heavily perturbed flow character, suggesting the transition is almost complete, which is in line with the trend of shape factor observed in Figure 4a.

![Figure 5. Sample hot-wire signals for the flow at $Re_x = 185 000$: without the acoustic excitation (NE) (a), with the acoustic excitation at SPL = 125 dB (b) and SPL = 135 dB (c).](image-url)

To clarify the phenomenon occurring in the separated boundary layer a spectral analysis of the velocity signal has been performed. Figure 6 (left column) presents the premultiplied power spectral density (PSD) of the near-wall velocity at several streamwise locations ($x = 525 - 650$ mm) for the lower Reynolds number. In the unexcited case (see Figure 6a, left column), initially ($x = 525$ and 550 mm) the energy is concentrated in a very narrow frequency range ~48 Hz, where the Strouhal number of the vortex shedding based on the momentum thickness and the velocity at the separation point equals $St_s = f \frac{\delta}{U_s} = 0.007$, which according to Yang and Voke (2001), ($St_s=0.005-0.011$) and Talan and Hourmouziadis (2002), ($St_s=0.008-0.012$) suggests the presence of the Kelvin–Helmholtz instability. At further streamwise locations (from $x = 600$ mm), there is an increase in energy in a wider bandwidth, but with a still visible maximum at around 48 Hz. In subsequent traverses a strong increase in the energy level of fine-scales is observed, characteristic of transitional flow. At the same time, there is a pronounced increase in the energy of the broadband peak concentrated around the characteristic frequency of 48 Hz. Keeping in mind that acoustic forcing is applied in the range of 100-650 Hz it is interesting to note that for both SPLs there is also an effect for the low frequency range (Figure 6 b and c, left panel). In particular, in the early stages of LSB development ($x = 525$ and 550 mm), frequencies around 64 Hz are amplified. This frequency corresponds to a Strouhal number around 0.009 and can also be associated with the Kelvin–Helmholtz instability (Yang and Voke, 2001, Talan and Hourmouziadis, 2002), which is stimulated by broadband noise. Downstream in the flow the peak is distorted, indicating a redistribution of the energy to adjacent scales and forcing
an early loss of stability. Note that a similar effect was reported by Kurelek et al. (2018), however in this case deploying the broadband acoustic excitation with the frequency range including the frequency of most amplified disturbances of the unperturbed flow. The current analysis shows that similar effect is observed with broadband acoustic forcing employed with the higher frequency range \(f = 100 – 650\) Hz than the frequency of the unperturbed flow instability mechanism \(f = 48 – 64\) Hz. The physical mechanism of this phenomenon is not entirely clear, but it can be assumed that there is coupling of the sub-harmonic forcing generated by acoustics to the natural frequency of the K-H instability.

The more obvious response of separated shear layer occurs for a higher Reynolds number (Figure 6, right panel). For the unexcited case (Figure 6a, right panel), initially \((x=500-550)\) the dominant frequency is not apparent. Only from distance \(x = 575\) mm on, a broadband peak appears with a maximum of about \(f = 150\) Hz. The corresponding Strouhal number of the vortex shedding equals here \(St_s =0.008\). This means that despite more than three times higher frequency, the Strouhal number is only slightly higher, which is due to the higher freestream velocity at the point of detachment. So, in this case too, the l-t transition is due to the Kelvin–Helmholtz instability. For a higher Re number, the acoustic frequency band forcing \((f=100 – 650\) Hz) covers the natural frequency of the shear layer instability \((f =150\)Hz). A pronounced resonant enhancement of the natural frequency in the flow and acceleration of the l-t transition is evident, especially for \(SPL = 125\) dB (Figure 6b, right panel). For a higher value of SPL (Figure 6c, right panel), the level of transmitted acoustic energy is so high that for \(x=500-650\) mm a rapid increase of PSD occurs over the entire frequency range.

![Graphs showing PSD for different distances and frequencies.](image-url)
CONCLUSIONS

The study presented in this paper addresses the process of l-t transition in a separated boundary layer without and with acoustic forcing at two different Reynolds numbers (185 000 and 370 000). In both cases without the acoustic excitation the transition was due to the Kelvin–Helmholtz instability. An application of acoustic forcing, in the frequency range $f = 100 – 650$ Hz, enhanced the natural flow instability and advanced the l-t transition. An important observation was that the effect of acoustic excitation on the separation point was hardly noticeable, while earlier reattachment point and decrease in the height of the bubble was observed. This phenomenon was evident through the change of the mean velocity at the boundary layer edge as well as by the decrease in the value of the shape factor in the excited cases.

For the lower Reynolds number the results indicate a phenomenon, not yet observed in the literature, namely an amplification of flow instability ($f = 48 – 64$ Hz) in the initial phase of the transition, forced by broadband pink noise generated by the higher frequency range ($f = 100 – 650$ Hz). It might be a result of coupling of the sub-harmonic forcing generated by acoustics to the natural frequency of the K-H instability. On the other hand, for a higher Reynolds number, the acoustic frequency band forcing ($f = 100 – 650$ Hz) covers the natural frequency of the shear layer instability ($f=150$ Hz) and the resonant enhancement is more obvious.

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