## Surface pressure fluctuations on a DU96 profile with flow separation

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# Abstract

In an effort to characterize noise induced by separated turbulent boundary layer flow, surface pressure fluctuations on a DU96-W-180 airfoil were measured using miniature pressure sensors. Because of limitation in amplifier channels and number of sensors, a rearrangeable configurations of sensors was applied. Spanwise and streamwise distributions of surface pressure were obtained at aerodynamic angles of attack  $-0.4^{\circ} < \alpha <$  $10.2^{\circ}$  and at three different Reynolds numbers Re = (0.8,1.0, and 1.2)  $\times 10^6$ . The measured surface pressure spectra are compared with predictions from published empirical models for zero and nonzero pressure gradient turbulent boundary layers. While the absolute level is under predicted by the models at some chordwise positions and  $\alpha$ , the shape of the spectrum can be approximated using the spectrum model proposed by Catlett et al.

#### Introduction

Wind turbines in Germany are located near residential areas. To limit the environmental effect of wind turbine installations to public health, noise compliances are followed strictly. Additional noise can be induced by atmospheric gusts that increase the effective angle of attack of a blade section and result in flow separation. An effort to improve the noise prediction due to flow separation was reported in Schüle and Rossignol [4] by modifying the equation of wall pressure cross spectrum that was proposed by Parchen [6]. While the noise prediction is promising there is a lack of evidence on the behavior of the model at low frequency, mainly due to the degradation of resolution of the applied directional microphone system at low frequency. To overcome this, the wall pressure fluctuations p were measured using miniature piezoresistive pressure sensors from Kulite semiconductors. Spanwise and streamwise distributions of p were obtained for the aerodynamic angles of attack  $-0.4^{\circ} < \alpha < 10.2^{\circ}$ and at three Reynolds numbers Re = (0.8, 1.0, and1.2)  $\times 10^{6}$ , in the acoustic wind tunnel of DLR Braunschweig (AWB). This paper focuses on the comparison of the pressure spectra to publicly available empirical pressure spectra models. The boundary layer properties were produced numerically using XFOIL [11], the necessary boundary layer information are  $C_P$  the static pressure coefficient,  $\delta$  the boundary layer thickness,  $\delta^*$ the displacement thickness,  $\theta$  the momentum thickness,  $U_e$  the velocity at height  $\delta$  from the surface,  $\tau_w$  the wall shear stress,  $u_{\tau}$  the friction velocity, and  $C_f$  the skinfriction coefficient. The assigned flow properties are  $U_{\infty}$ freestream velocity,  $\rho$  freestream density of air, and  $\nu$ 

kinematic viscosity of air.

An empirical model of the surface pressure spectrum  $\Phi_{pp}$  was developed by Goody [8] and extended Rozenberg et al. [9] and Catlett et al. [10]. The general form of the empirical model is given in Eq. (1) with  $R_T = (u_\tau \delta/\nu) \sqrt{C_f/2}$  as the ratio of the outer and inner boundary layer time scales.

$$\frac{\Phi_{pp}U_e}{\tau_w^2\delta} = \frac{a_1(\omega\delta/U_e)^{a_2}}{\left[(\omega\delta/U_e)^{a_3} + a_4\right]^{a_5} + \left[a_6R_T^{a_7}(\omega\delta/U_e)\right]^{a_8}} \quad (1)$$

The Goody model accounts for zero pressure gradient flow and is expressed as a function of the Strouhal number  $\omega \delta/U_e$ , where  $\omega = 2\pi f$  the angular frequency and f the linear frequency. This spectrum is calculated using the prescribed parameters  $a_1 = 3, a_2 = 2, a_3 = 0.75, a_4 =$  $0.5, a_5 = 3.7, a_6 = 1.1, a_7 = -0.57, a_8 = 7.$  Herr [13] adapted the Goody model to fit the pressure spectrum of a flat plate with  $5^{\circ}$  declination with the same Goody parameters except for  $a_3 = 2, a_4 = 1.8432, a_5 = 1.5, a_6 =$  $1, a_7 = -0.5$ . Equation (2) is the model from Rozenberg et al. (RRM), which uses the maximum shear stress  $\tau_{max}$ and  $\delta^*$  as the normalizing parameters replacing  $\tau_w$  and  $\delta$ , respectively. The RRM model takes into account the streamwise pressure gradient for flows prior to separation and in this study we assume  $\tau_{max} \approx \tau_w$  for cases without flow separation.

$$\frac{\Phi_{pp}U_e}{\tau_{\max}^2\delta^*} = \frac{\left[2.82\Delta^2(6.13\Delta^{-0.75} + F_1)^{A_1}\right] \left[4.2\frac{\Pi}{\Delta} + 1\right] \left(\frac{\omega\delta^*}{U_e}\right)^2}{\left[4.76\left(\frac{\omega\delta^*}{U_e}\right)^{0.75} + F_1\right]^{A_1} + \left[C_3'\left(\frac{\omega\delta^*}{U_e}\right)\right]^{A_2}}\tag{2}$$

The following parameters are required to calculate Eq. (2).

$$\begin{split} \Delta &= \delta/\delta^* & A_1 = 3.7 + 1.5\beta_c \\ \Pi &= 0.8(\beta_C + 0.5)^{0.75} & C_3' = 8.8R_T^{-0.57} \\ A_2 &= \min\left(3, \frac{19}{\sqrt{R_T}}\right) + 7 & \beta_c = \frac{\theta}{\tau_w} \left(\frac{\mathrm{d}P}{\mathrm{dx}}\right) \\ F_1 &= 4.76(1.4/\Delta)^{0.75} \left[0.375A_1 - 1\right] \end{split}$$

The spectrum model by Catlett et al. (CFAS) is also a function of streamwise pressure gradient dP/dx. Catlett et al. determined the model parameters of Eq. (1) based on one or more of the following non-dimensional parameters  $\beta_{\delta} = \delta/q_e \cdot dP/dx$ ,  $\beta_{\ell} = \ell/q_e \cdot dP/dx$ ,  $Re_{\ell} = U_e \ell/\nu$ and  $H = \delta^*/\theta$ , where  $q_e = 0.5\rho U_e^2$  and  $\ell = \delta^* \sqrt{C_f/2}$ . An important parameter to note is the Clauser parameter  $\beta_c$ , which represents a non-dimensional value of dP/dx. Other definitions of the Clauser parameter were used in CFAS,  $\beta_{\delta}$  and  $\beta_{\ell}$ . Here,  $\beta_c$  will be used to indicate the strength of dP/dx.



Figure 1: (a) DU96-W-180 model with (b) 4 sets of removable panels. Surface discoloration near the trailing edge does not influence the surface roughness of the model. Fractional chordwise positions relative to the leading edge are indicated in (a)

#### Experimental setup

Measurements were performed in the anechoic open section of the AWB. The wind tunnel's nozzle dimension is 800 mm wide and 1200 mm high with maximum exit velocity of 65 m/s. The turbulence level is 0.3% at the nozzle exit. The model fixed coordinate system is shown in figure 1 given as x chordwise, z spanwise, and y the chord-normal direction. The green circle depicts the zero position of the coordinate system (midspan and on the trailing edge). The span length of the DU96-W-180 model is 800 mm and its chord length, c, is 300 mm. It is equipped with 62 static pressure taps covering the suction and pressure sides used to measure the static pressure P. The trailing edge thickness is 0.5 mm. A panel on each side of the model is removable to equip the model with sensors. The panel is  $180 \text{ mm} \times 100 \text{ mm}$  and when installed the panel adhered to the surface curvature of the model. Eight piezo-resistive pressure transducers were used. The head of these pressure transducers is 1.6 mm in diameter and 0.4 mm high from its base. The installation of these sensors was designed to be removable, rearrangeable, and to reproduce results easily. To do so, several sensor stations with 3 mm diameter and 0.5 mm depth were drilled on the underside of the removable panel. Pinholes of 0.5 mm diameter were drilled at the center of these stations. Silicone was molded on the stations to fit the sensor's head and create a sealant, while maintaining a clear air passage for the pinhole. To keep the sensors in place mechanical holders in the shape of rods with foam attached on one end were glued on the panels. The sensor and the instrument panel are shown in figure 2.

The model's lift coefficient  $C_l$  and static pressure coefficient  $C_p$  were measured in the laminar wind tunnel (LWT) of the Institute for Aerodynamic and Gas Dynamics at the University of Stuttgart and again in the AWB. A zig-zag boundary layer trip with thickness 0.205 mm was placed at the 5% chord from the leading edge on the suction side and a similar tripping with thickness 0.4 mm



Figure 2: The underside of one of the removable panels instrumented for the installation of miniature pressure transducers. Three sensor locations are represented x = -13, -36, -70.5 mm

high at 10% chord was placed on the pressure side. This configuration was made to be similar with the previous work done in the same facility [4]. The  $C_l$  and  $C_p$  distribution for  $\alpha = 9.6^{\circ}$  are shown in figure 3. This figure shows  $C_l$  measured in AWB and LWT. At  $\alpha = 9.6^{\circ}$  a mushroom shaped separation line appears on the suction side with the largest separated region spanning over 40% cas shown in Fig. 4. Two side fences, placed 100 mm from the side walls, were installed on the model to limit the effect of the side walls to the flow. Without them, side vortices can be observed at scales similar to the maximum separated flow region (40% c). The maximum separated region in figure 4 is located to the left of the midspan and has been confirmed to be a repeatable result attributed to the present experimental facility.

For the three Re, the surface pressure was measured for  $\alpha = -0.4^{\circ}$ ,  $3.4^{\circ}$ ,  $4.8^{\circ}$ ,  $7.2^{\circ}$ ,  $7.9^{\circ}$ ,  $8.7^{\circ}$ ,  $9.6^{\circ}$ , and  $10.2^{\circ}$  with the sensors distributed in the chordwise and spanwise directions. For brevity, only data for a few sensor locations, a few  $\alpha$ , and Re =  $1.2 \times 10^{6}$  are presented here.

#### Results

Figure 5 shows  $\Phi_{pp}$  for the position closest to the trailing edge x = -13 mm from 3 independent measurements. The spectra fit each other very well showing that the installation of the sensors can produce repeatable results. The maxima of  $\Phi_{pp}$  increase with increasing  $\alpha$  with the peak frequency shifting to the lower frequencies. An increase of approximately 15 dB is shown in figure 5 between  $\alpha = -0.4^{\circ}$  and  $\alpha = 10.2^{\circ}$ . The roll-off starts earlier and the spectrum decays more rapidly with increasing  $\alpha$ .



Figure 3: Aerodynamic properties of the DU96-W-180 profile (a)  $C_l - \alpha$  and (b)  $C_p - x/c$  shown relative to the leading edge at  $\alpha = 9.6^{\circ}$ . The region of the airfoil covered by miniature sensors are given in red.



Figure 4: Ink visualization on the DU96-W-180 airfoil at  $\alpha = 9.6^{\circ}$ . The rectangular oil grid is approximately  $60 \times 60$  mm.



Figure 5: Autospectra near the trailing edge x = -13 mm from three independent measurements.

Figures 6–7 show  $\Phi_{pp}$  for  $\alpha = -0.4^{\circ}$  and 4.8°, respectively. Both figures show x = -13, -36, -70.5 mm from top to bottom. In these figures, the absolute levels of the Goody and Herr models are increased by 3.5 dB and by 7.5 dB for the CFAS model. These increments were selected based on arbitrary fitting of the model spectrum to the measured spectrum. In figure 6  $\Phi_{pp}(f; x = -13 \text{ mm})$  behaves according to the CFAS model but deviation starts as  $\beta_c$  decreases and  $\phi_{pp}(f; x = -70.5 \text{ mm})$  follows the spectral shape given by the Goody model. Here, the difference of power level from the zero pressure gradient



Figure 6: Surface pressure spectra on the suction side at  $\alpha = -0.4^{\circ}$  along the chordwise positions from top to bottom x = -13, -36, -70.5 mm.

spectrum of Goody can be attributed to the pressure gradient. Similar increase can also be observed in [14]. The peak spectrum at this location is predicted better with the Herr model, although the transition to high frequency started too early. For all configurations, the RRM model fails to predict the transition location from the overlap to high frequency region. Issues with the RRM model were discussed in [10]. In figure 7, similar trends to the previous figure can also be observed;  $\Phi_{pp}$  is influenced by the increase of  $\beta_c$  and because of it the CFAS spectrum deviates from the measured one. However, this deviation is still within the ±5dB uncertainty that was described in [10]. Closest to the trailing edge, the measured spectra is affected by flow separation, where the empirical models are no longer valid.

The success or failure of the CFAS model to predict the



**Figure 7:** Same as figure 6 for  $\alpha = 4.8^{\circ}$ 

spectra is shown in figure 8. Successful predictions are approximately at: 4000 <  $Re_{\theta} = U_{\infty}\theta/\nu < 5500$  and  $20 < R_t < 35$ . The model validity limits are 4000 <  $\operatorname{Re}_{\theta} < 20000$  and  $10 < R_T < 150$  [10].

#### Summary and concluding remarks

The objective of this communication is to compare the spectra of measured surface pressure of the DU96-W-180 airfoil with those given by published empirical models. To do so, the wind tunnel model was equipped with surface pressure sensors providing local wall pressure fluctuation data. Repeatable results were obtained from independent measurements. Pressure gradient affects the wall pressure spectra by increasing its power level and increasing the rapidity of the spectral decay. The pressure spectra are compared with empirical zero and nonzero pressure gradient spectra. As long as the Clauser parameter  $\beta_c$  remains small the zero pressure gradient model



Figure 8: Surface pressure spectra that are predicted by the model given by [10] shown in red.

of Goody predicts the shape of the autospectra well, i.e. at x = -70.5 mm and  $\alpha = -0.4^{\circ}$ , well in the present experiment. The shape of the measured spectra can be fitted with the model of Catlett et al. until  $\beta_c < 8.3$ . This study is part of a larger framework of an ongoing development of a flow field noise model influenced by flow separation.

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