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Wall pressure fluctuations measurement during boundary layer transition

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Abstract. *With the constant raise in fuel prices and regulation of new pollutant emission standards, reducing consumption and greenhouse gas emissions are problems that are becoming increasingly relevant in commercial and military aviation. The benefits of using laminar flow control over larger regions of the surface can reach* 10% *of the total drag of the aircraft, which would result in great savings in operating costs. However, for this technology to develop, being able to properly predict the transition point between the laminar and turbulent flow is of great importance. This work objective was to experimentally study the transition of the boundary layer between the laminar and turbulent flow by measure of wall pressure fluctuations with microphones. Experiments were conducted at the Low Acoustic Noise and Turbulence (LANT) wind tunnel at University of São Paulo.The model consist of a flat plate with* $2320mm \times 1000mm \times 10mm$ *and the surface finish was specially selected to reduce the influence on the transition. Measurements of wall pressure fluctuations were carried out using an array of* 90 *microphones attached to the rear surface of the plate and connected to the test surface through pinholes (*$0.3mm$*). The model has more than* 400 *pinholes where the microphones can be placed according of interest. The diameter of the pinholes were carefully studied not to affect the development of the boundary layer in the model and to set the Helmholtz resonance frequency distant from the frequencies of interest. Results shown that the microphones were able to locate the region where the boundary layer transition occurs and to identify disturbances inside the boundary layer.*

Keywords: *Wind tunnel, Wall pressure fluctuations, Boundary Layer transition*

1. INTRODUCTION

The reduction in fuel consumption and in the emission of polluting gases are topics of great importance in the aeronautical industry. Reneaux (2004) shows that about 22% of the costs of an airline are due to fuel consumption. Pearce (2015) estimates that this number may reach 24% in the coming years. Aviation fuel was responsible for 81% of the air force energy budget in the year 2014 (Felder *et al.*, 2017). The flow over a surface is subject to irregularities and disturbances that can change the transition location between the laminar and turbulent regimes. Being able to correctly predict this transition is of paramount importance, since turbulent flow causes greater frictional drag and consequent increases the total drag of an aircraft. A study done on an Airbus $A320$ showed that friction drag is responsible for 50% of the aircraft's total drag, with 25% coming of the wings (Marec, 2001). Studies supported by NASA (Malik *et al.*, 2015) estimate that the application of the control of the Laminar flow may have a potential to reduce 10% of total aerodynamic drag in a commercial aircraft.

The transition from a laminar to turbulent flow is a problem that has been studied for a long time, however, until today, it remains open. This transition is associated with flow instability. Tollmien (1932) and Schlichting (1933) theoretically studied the effect of small perturbations in a boundary layer with a Blasius laminar profile, such as perturbations came to be known as Tollmien-Schlichting (T-S) waves. In some cases, depending on the Reynolds number and the frequency of the disturbance, these waves grow propagate through the flow, (Schlichting and Gersten, 2000). When these perturbations have low amplitude, up to 0.1% of the free flow velocity, its behavior is linear and well predicted by the theory of linear instability (LST). However, as these perturbations grow, the effects do not Linear lines present begin to take on greater importance. (Klebanoff *et al.*, 1962) discovered the non-linear growth of oblique waves with a frequency equal to the linear T-S wave that generated three-dimensional effects. Subsequently, it was found that oblique waves with a subharmonic frequency with respect to to T-S waves can also occur (Kachanov and Levchenko, 1984; Corke and Mangano, 1989). Both nonlinear regimes were explained and predicted by a general model (Herbert, 1984) called secondary boundary layer instability (Herbert, 1988). These two phenomena became known as Type K or fundamental and Type H or subharmonic, respectively.

Wall pressure fluctuations is a topic that has been and is still much studied in recent years. years, theoretically, numerically and experimentally. Many studies have been conducted of pressure fluctuations in the turbulent boundary layer wall (Willmarth, 1956; Bull, 1967; Blake, 1986; Alexander *et al.*, 2011; Hu and Herr, 2016; Park and Lauchle, 2009). Pressure fluctuations pressure on the wall have also been extensively studied in the flow behavior in boundary layer separation and reattachment cases, either with just one microphone (Heenan and Morrison, 1998; Lauchle and Kargus,

2000) or with an array of microphones (Liu *et al.*, 2005; Hudy and Naguib, 2007). Despite the use of microphones for measuring of pressure fluctuations in the wall, its application to the boundary layer transition is not so widespread.

2. METHODOLOGY

This work was carried out in the Low Acoustic Noise and Turbulence (LANT) wind tunnel present at the Aeronautical Engineering Department at USP-EESC. The LANT (Low Acoustic Noise and Turbulence) is a closed circuit and closed test section wind tunnel that has low background noise and low level of turbulence, in the order of 0.05%, in addition to good flow uniformity, being suitable for experiments in aeroacoustics and hydrodynamic instability. The test chamber has a cross section of $1000\text{mm}\times1000\text{mm}$, with a length of 3000mm. A *Dallas Temperature* DS18b20 is responsible for tem Amaral *et al.* (2021) presents the LANT wind tunnel project in detail. Two digital temperature sensors, model *Maxim Integrated* DS18b20 , are installed inside the test chamber, the $DS18b20$ has a resolution of 9 to 12 bits, with a reading accuracy of $\pm0.5°$C. To measure the dynamic pressure inside the test chamber, which needs the most precision of all, the laboratory has 3 pressure sensors from the *Honeywell* brand. Models: RSCDRR2.5MD(0 to 250Pa), RSCDRR002ND(0 to 497.68Pa) and RSCDRR005ND(0 to 1244.2Pa) models.

The test model used consists of a 2320mm x 1000mm x 10mm flat plate made of aluminum with leading edge and a set with flap and tab, Fig.1. The surface finish of the flat plate has an rms roughness value of $3.2\ \mu$m. The leading edge, also made of aluminum, was properly designed to ensure the stagnation point on the model's experimental side. 30 static pressure taps, 0.7 mm diameter holes, distributed throughout the model are used to verify stagnation point location and pressure distribution. The set consisting of flap and tap perform the pressure gradient adjustment. The model also has a fairing attached to its back that has the function of protecting all the instrumentation present on the back of the flat plate. A loudspeaker model *Visatron* BF32S, is present at the rear of the model at 200mm from the leading edge, this is responsible for generating disturbances that will be inserted into the flow through 7 holes forming a hexagon with a hole central.

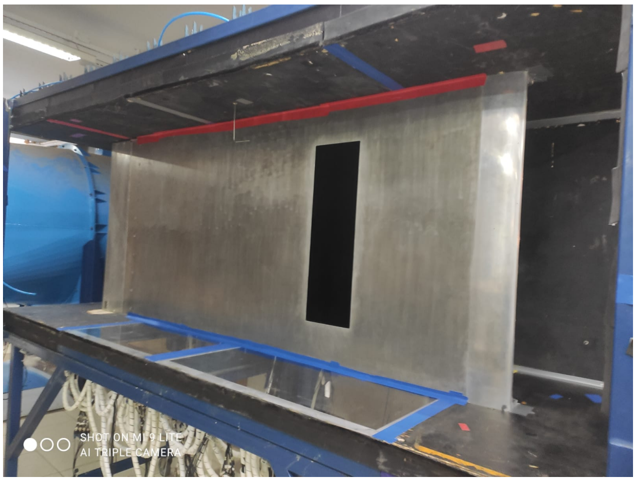
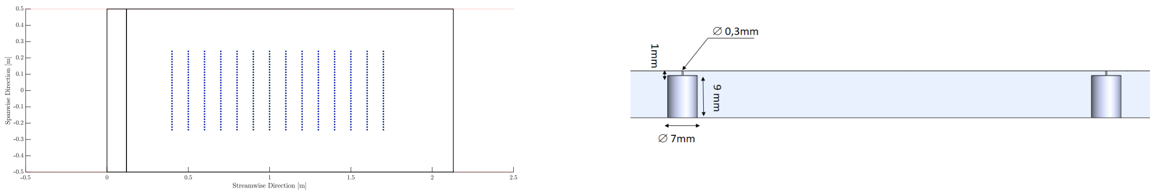


Figure 1: Experimental model inside test section.

The flat plate features 14 rows with 31 holes of 0.3mm in diameter, totaling 434 holes. Each row is spaced 100mm from the previous one and goes from 400mm from the leading edge to 1700mm, Fig.2. The holes are 1mm deep and then widened to 7mm in diameter, Fig.2(b). These holes are used for the placement of microphones that will carry out measurements of pressure fluctuations on the wall of the plate. The holes are 16mm apart within the row, covering a region between -240mm and 240mm in the span of the model. The dimensions of the holes was chosen based on the literature (Bull, 1996; Shaw, 1960; Farabee and Casarella, 1991; Abraham and Keith, 1998; Lueptow, 1995; Tsuji *et al.*, 2007) and through previous experiments carried out in the laboratory. The microphones used are from the 40PH model from the company *G.R.A.S Sound and Vibration*, have a Frequency Range of up to 20 kHz, a Dynamic Range between 32dB and 135 dB and a factory sensitivity of 50mV/Pa . 112 microphones are available and can be positioned according to experimental need.

Hot Wire Anemometer(HWA) was also used to measure the boundary layer profile. The circuit used was the *A.A.Lab system* AN-1002 with a *DANTEC dynamics* 55P15 probe. A Traverse system is used to set the probe position inside the test section, and allows movements of 25μm in all directions. Data acquisition, for microphones and HWA, is performed with seven PXI-4496 boards of 24-bit and 16 analogical inputs each, arranged into a PXI-1042Q chassis.



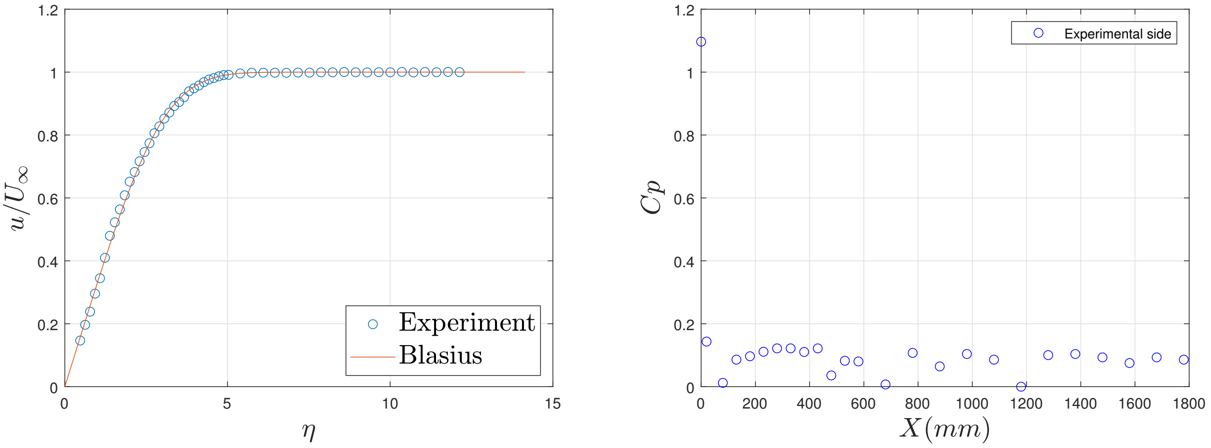
(a) Position of the Microphones at the model.

(b) Pinhole dimensions.

Figure 2: Sketch of the Microphone array.

3. Preliminary Results

For this experiment, 90 microphones were positioned in 10 rows from 500mm to 1400mm from the leading edge. 9 microphones were placed at each row covering a region of ±64mm. The flat plate boundary layer was characterized at the position of the first row of microphones(500mm from leading edge). The result, presented at figure 3 shows good agreement between the experiment and the Blasius Boundary layer profile. The measure was made with the HWA circuit for the free stream velocity of 15m/s. The probe was set near the flat plate and than moved 30 steps of 0.1mm followed by 21 steps of 0.5mm. Data were acquired for 10 seconds at a sample rate of 2048Hz. The model pressure gradient is plot at figure 3(b).



(a) Boundary layer.

(b) Pressure gradient.

Figure 3: Characterization of the flat plate boundary layer and pressure gradient.

After assure that the flat plate boundary layer was laminar, a measure of the wall pressure fluctuations with the microphone array was made. Data were acquired for 60s at a sample rate of 10kHz. The experiment were performed at the free stream speed of 15m/s. Figure 4 shows the Power Spectral Density (PSD) for the microphones at the center-line of the array. For all microphone positions the PSD shows the same behavior as the first measure at 500mm from the leading edge. As at this position the boundary layer is laminar, Fig.3, it can be assumed that the transitions does not occurs until the last row of microphones. It was expected due to the wind tunnel low turbulence levels. A peak can be noted around 175Hz at the PSD for all the measurements. This peak is also present at HWA measurements of free-stream turbulence and is not due to the microphones setup.

To verify if the microphone array could measure a T-S wave, a speaker introduced a perturbation on the boundary layer through seven 0.3mm pinholes at a position 200mm from the leading edge. The perturbation used was a continuous 140Hz wave. The stability diagram for two-dimensional perturbations is shown in Fig. 5, the plotted line represents a perturbation of 140Hz.

Figure 5 (b) shows the PSD of the wall pressure fluctuations for the boundary layer with a perturbation of 500mV peak to peak intensity. This intensity was set at the Signal Generator. The results shows a peak at 140Hz for all positions. This confirms that the microphones have resolution to measure a T-S wave at the boundary layer. The peak at 140Hz present a

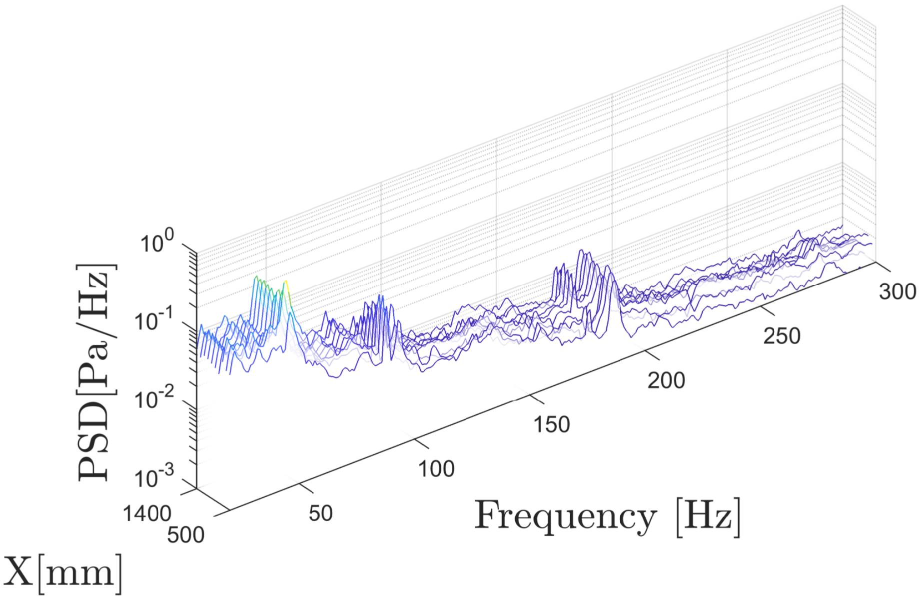
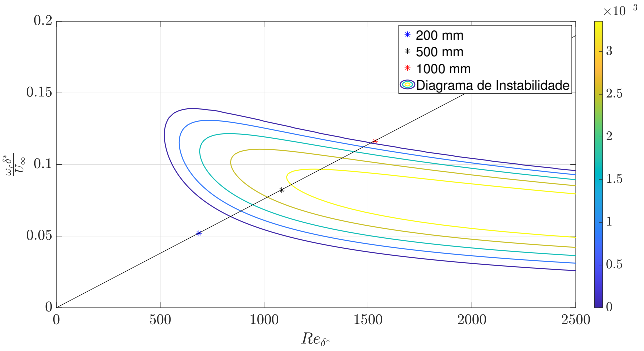


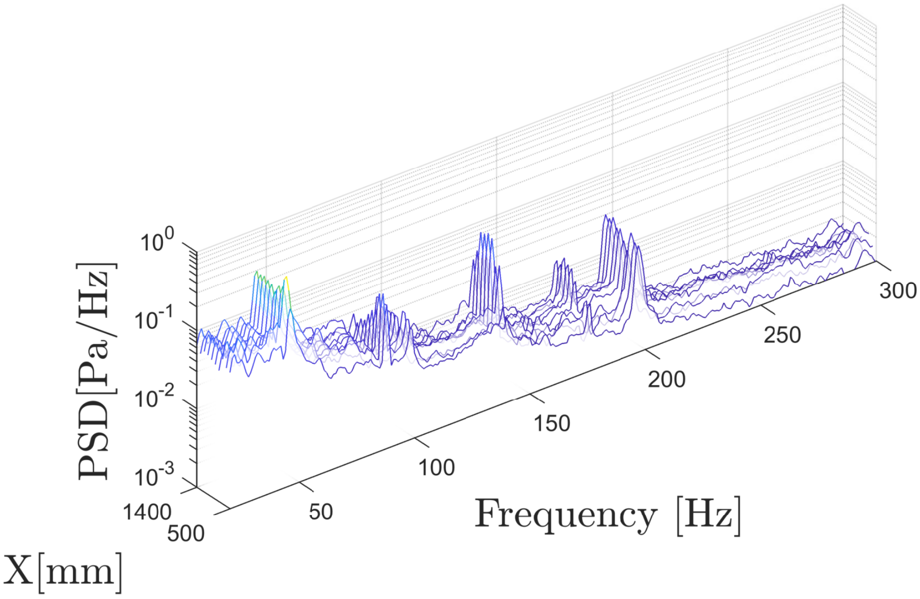
Figure 4: PSD of the wall pressure fluctuations over flat plate.

growth in intensity from 500mm to 1000mm, after 1000mm the peak intensity decays until the last row of microphones. This behavior present a good agreement with the Linear Stability diagram. Between 500mm and 1000mm the frequency of 140Hz is at the unstable region of the diagram. At 1000mm, the microphone is right after the second branch of the diagram, where the perturbation has stable behavior and starts to decay in intensity.

Figure 6 shows the PSD of the boundary layer when a perturbation with intensity of 2V peak to peak is introduced to the boundary layer. The 140Hz peak grows in intensity from the 500mm until 1100mm when the transition begins. After that the peak decays in intensity and a broadband region appears. At 1300mm the boundary layer is already full turbulent and the 140Hz peak can no longer be noticed. Figure 7 shows with details the difference between the PSD for a Laminar and a turbulent boundary layer.The data plotted was taken of the case with a perturbation of 2V peak to peak for the microphones at 500mm and 1400mm.



(a) T-S wave instability diagram. The solid black line shows the two dimensional evolution of the wave over the plate.



(b) PSD of the wall pressure fluctuations over the plate with a point source perturbation of 500mV peak to peak.

Figure 5: T-S wave instability diagram and PSD of the wall pressure fluctuations over the plate.

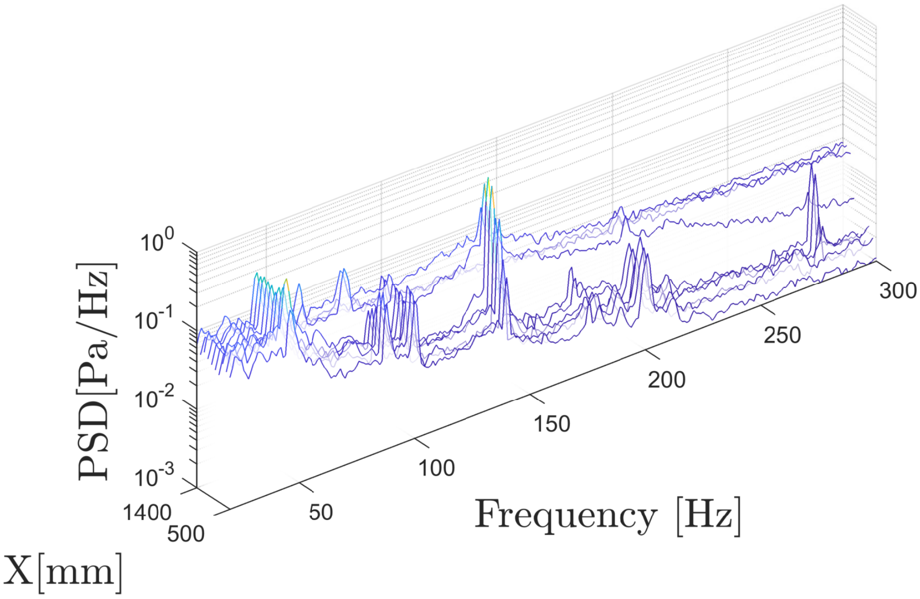


Figure 6: PSD of the wall pressure fluctuations over flat plate with a point source perturbation of 2V peak to peak.

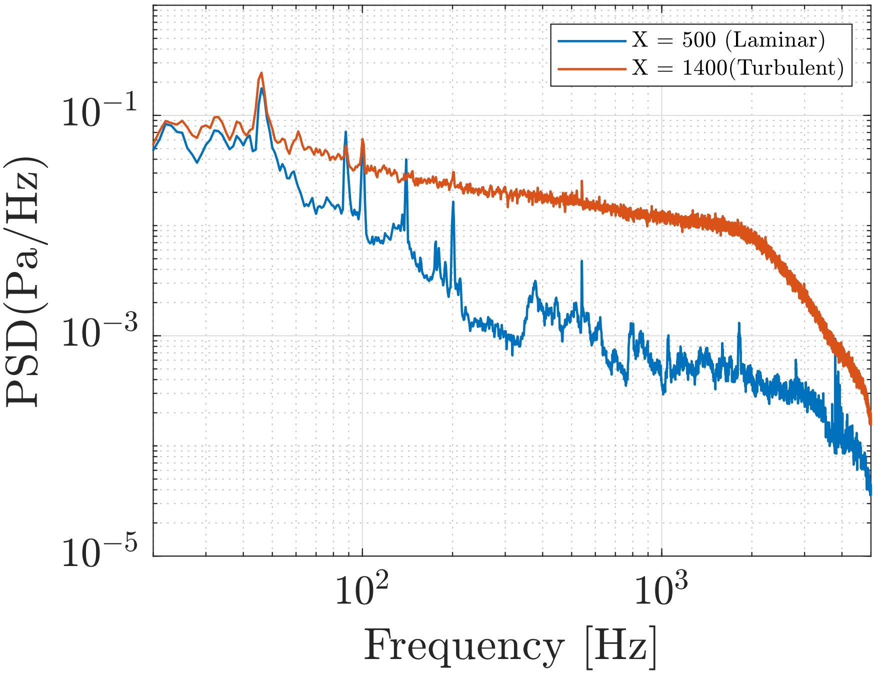


Figure 7: PSD of the wall pressure fluctuations for a Laminar and turbulent boundary layer over flat plate. Point source perturbation of 2V peak to peak.

4. CONCLUSION

It was shown that the boundary layer at the test model was laminar with a good agreement with the Blasius Boundary layer profile. The model also presented a pressure gradient of less than 0.2 along its length. This characteristics are desirable for Hydrodynamic instability experiments.

The microphones were capable of measure the wall pressure fluctuations over the model. The PSD shown the growth of a perturbation inside the boundary layer in agreement with the TS wave instability diagram. When a higher intensity perturbation was introduced, the boundary layer transition occurs. The measures presented the difference between the PSD of a laminar and turbulent boundary layer. The turbulent PSD presents a high intensity at all frequencies, but the peak at the perturbation frequency can no longer be noticed. This agrees with the literature and HWA measurements.

This results shows that this technique can be used to measure transition and the evolution of a TS wave over the Boundary Layer. This were the first measure done with an array of microphones and further experiments and data analysis will be done to develop the technique.

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