Detection of structure in non-stationary flow by synchronized P.I.V. and wall pressure measurement.

by

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ABSTRACT

The aim of the study is to improve the fundamental understanding of the interaction between spatio-temporal structure flow and wall pressure field. An original experimental set-up has been developed in order to characterize different structures flows with their wall pressure signatures.

For that purpose, several measurement systems are simultaneously used: Particle Image Velocimetry, hot wire anemometry and wall pressure instantaneous measurement. An experiment is carried out in order to generate a well known controlled vortex. The analysis of spatio-temporal wall pressure signature describes clearly the vortex evolution. Using the wall pressure value corresponding in time to the P.I.V. measurements, typology of vortex will be linked to the wall pressure signature. The results were obtained for structures generated by the rapid oscillation of a NACA0020 wing profile positioned outside the boundary layer in a wind tunnel section (figure 1). This generation of one pair of contra-rotative vortex is piloted at demand and perfectly reproducible. The spatio-temporal evolution of the flow structure along the life cycle of the vortex is given thanks to a statistic P.I.V. timed resolved method. Theses data are correlated simultaneously with the evolution at the wall of the pressure fluctuations.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig1.png}
\caption{fig. 1: experimental configuration}
\end{figure}

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig2.png}
\caption{fig. 2: instantaneous wall pressure measurement and P.I.V. fluctuations velocity field (velocity fluctuation). t=38ms}
\end{figure}
1. INTRODUCTION

Aeroacoustic sound generation is an important phenomenon. That can be the source of noise inside the vehicle passenger compartment. Geometrical singularities of the vehicle body are largely responsible for flow separation, resulting in an increased aerodynamic sound radiation as illustrated in figure 3. Different sources of noise appear: the bipolar and quadripolar aeroacoustic sources which are propagated near and in the wake of flow detachments and aeroelastic sources due to the impinging wake on the side windows or the body car (Leclercq 1999). These have been the subject of a considerable amount of theoretical, experimental, and numerical industrial research.

noise due to stress forces
generated by turbulence

pressure acoustic field

fig. 3: sources of noise on a vehicle body

To the present date, the difficulty to understand and then to modelize these phenomena encourage the development of experimental investigations. The study of an interaction between a spatio-temporal vortex over a fully turbulent boundary layer and the wall pressure field is especially interesting in order to identify the structures which are responsible of the pressure fluctuations. This kind of experiment requires successful means to characterize simultaneously the spatial and temporal evolution of the pressure velocity fields.

The possibility to use low cost pressure transducer fixed at the wall and connected to powerful acquisition means allow to characterize the vortex signature (Schlichting 1987, Jeon 1999, Leclercq 1999). The coupling of this with velocity histories in the turbulent flow is possible, based on hot wire measurement (Schewe 1983). But the spatial information is limited and furthermore a high number of probes introduced in the flow may disturb it. Instantaneous P.I.V. allows to overcome these limitations and gives an mean to identify flow structures (Doligalski 1994, Jeong 1995, Stanislas 1999, Adrian 2000). But time resolved measurements are still limited to small measurements area and are difficult to implement. This is why we have developed a system able to generate vortex structures with a good reproducibility. Thus, the velocity field is time resolved by reproducing the event and by temporally shifting instantaneous P.I.V. measurement (see figure 7). These are simultaneously recorded with the pressure field data.

These different contributions on overall interior acoustic signature are still misunderstood because of the complex unsteady state of the flow (Cantwell 1981, Liu 1989, Marchand 1997). An efficient way to understand this complicated aerodynamic phenomenon is to study the case of an interaction between spatio-temporal vortex over a fully developed turbulent boundary layer and wall pressure field (Schewe 1983, Doligalski 1994). This is particularly well described in this reproducible experiment.

The main goal of the study is to determine if the flow contribution to the wall pressure fluctuation is due to the boundary layer or to the large scale structure in the external zone (Schubauer 1956). The investigations of Schewe (1983) indicate that the maximum of turbulence production lies in the transition region from the linear to the logarithmic part of the velocity profile. Moreover, in our case where a structure is artificially generated, we can infer that the main influent effect on wall pressure fluctuation is the result of large structures appearing in the external zone of the boundary layer. In this context, this paper analyzes the boundary layer deformations with the passage of the two contra-rotative structures. The following paragraphs describe the experimental method, including the vortex generation system and the measurement techniques, and present results obtained in the boundary layer zone.
2. EXPERIMENTAL SETUP

2.1 Structure generation and flow characteristics

An experiment is designed in order to generate a single vortex, which interacts with the turbulent boundary layer in a fully developed turbulent flow. The vortex is obtained with the rapid rotation of a wing NACA profile positioned out of the boundary layer in a wind tunnel section. Initially located at an angle of incidence \( \alpha_0 \), the wing oscillates in a few millisecond with an angle of \( +\theta \) and \(-\theta\). This generates a vortical structure perfectly reproductive. Measurements are made simultaneously and synchronized by an impulse, marking the beginning of the wing beating. The configuration is both relevant from the industrial point of view and simple enough to be compared to well-known turbulent flow.

![fig. 4: experimental study](image)

The wing is a NACA0020 profile with a chord \( c=30.25\text{mm} \) and a thickness \( e=6\text{mm} \). The rotation axe is located at 5mm of the leading edge and at an height \( h=40\text{mm} \) of the wall. So when the wing is stopped and positioned at its incidence \( \alpha_0=15^\circ \) the boundary layer is not perturbed. First the wing stand by at its origin position at the incident angle \( \alpha_0 \). When we want to generate a vortex, the wing oscillates by an angle \( \theta=10^\circ \) and returns immediately to its initial position. The time delay of the complete beat is 43ms.

We increase artificially the thickness \( \delta \) of the boundary layer with a glasspaper positioned at the end of the convergent. At the position \( x=90\text{mm} \), it gives us a value of \( \delta=17.5\text{mm} \) for the free stream velocity \( \text{U}_\infty=10.51\text{m.s}^{-1} \). In the way to determine the wall friction velocity \( \text{U}_\tau \), the diagram Clauser method is used. For several values of the skin-friction coefficient \( C_f \), the ratio \( \text{U}/\text{U}_\infty \) is plotted. The value of \( C_f \) is chosen from the plot representing the better agreement with the experimental data (in our case \( C_f=0.038 \)). Considering the relation \( \text{U}_\tau=\text{U}_\infty(C_f/2)^{1/2} \) it comes in our case \( \text{U}_\tau=0.47\text{m.s}^{-1} \).

So we can consider the non-dimensional values of our experimental data: \( x^+=x\text{U}_\tau/\nu \) and \( u^+=u/\text{U}_\tau \) (with \( x=(x,y,z) \), \( u=(u,v,w) \) and the viscosity coefficient \( \nu=1.52.10^{-5}\text{m}^2\text{s}^{-1} \) in the experimental conditions) and it allows us to compare our data to the literature (see figure10). The choice of the beating and the flow characteristics are justified in paragraph 2.3.

2.2 Experimental Techniques

The originality of the measurement is to combine wall pressure measurement simultaneously with P.I.V. or Hot Wire Anemometry. Moreover a time resolved statistical P.I.V. measurement is possible considering the fact that the structure generated by the wing beating and its evolution in time and in space is reproducible and repetitive. So all the measurement are synchronized by a start signal given by the beginning of the wing beat, and we can reconstruct in time the spatial flow history given instantaneously by the P.I.V. Then we have the evolution in space and in time of the velocity field. Pressure transducers and hot wire probes give temporal data witch are synchronized in time always by the top of the wing beat. As we said earlier, the cue signal synchronization is given by the beginning of the wing beat thanks to a signal given by the control positioning card of the wing motor (see figure 5).

Finally all the data are obtained simultaneously in space and in time and thanks to the time synchronization phase average statistical studies can be done.

**P.I.V.** : velocity field are obtained with a DANTEC Flowmap PIV2000 system and a double pulse mini-Yag BigSky laser operated at a wavelength of 532 nm and a power of 100mJ. The camera is the DANTEC HiSence with a 1280*1024 CCD captor 12bits intensified used with a 60mm focal length lens. To increase the definition at the wall fluorescent paint is used. Due to this paint the reflection wavelength is different from the one of the incident laser light, and thanks to an interferential filter placed on the camera objective only the incident laser light is taken into account. So the image are not polluted by the laser reflexion and we have a gain of 90\% in the definition of the velocity field at the wall (1mm distance to the wall instead of 10mm), depending on our camera position and calibration.

**Pressure transducers** : pressure transducers used here were developed and tested prior to this work. (LECLECRQ 1999, 2001). These transducers are Sennheiser Ke4 Electret microphones mounted in the wall behind a 0.5mm pinhole in order to minimize the effects of spatial averaging over the sensor surface. The calibration consists of a standard frequency response function measurement between the wall pressure transducers and a reference microphone.
Hot Wire Anemometry: the acquisition system is DANTEC Streamline, different probes were used: 55P15 probe for the boundary layer velocity profile (Pt-plated tungsten wire, diameter 5µm, length 1.25mm) and the 55P61 X-probe (Pt-plated tungsten wire, diameter 5µm, length 1.25mm, wire separation 1mm) for all other measurements.

fig. 5: experimental setup & pressure transducers setting and calibration

fig. 6: pressure transducers used & P.I.V. acquisition settings

fig. 7: experimental synchronization setup
2.3 Validation of the experimental setup

Making the good choice for the determination of the characteristics of the experiment was not easy. At the beginning numerical simulations were done (with FLUENT) to guide us in the building and the determination of the experimental setup. Then we try to numerically optimized several parameters of the experiment (NACA wing, axe of rotation, as detailed in paragraph 2.1). When the experiment was made and mounted several validations in the wind tunnel were made in different measurement campaign. The choice of the velocity study and the rotation parameters have been confirmed (angle, velocity, acceleration, delay of rotation…). Figure 8 presents the spatio temporal pressure evolution as function of the mean velocity \( U_\infty \).

The x-axis represent the time evolution for one given pressure transducer, the y-axis represent the spatial pressure evolution considering the pressure value of all the transducers at a given time.

![Figure 8: Spatio temporal pressure evolution as function of the mean velocity](image)

The intensity of the wall pressure signature gradually vanishes towards the blade. These iso-contour map of the wall pressure fluctuations shows that the wall is not directly affected by vortex impinging without any reversal flow or separation in the turbulent boundary layer. The vortex signature is distincted by the negative pressure value, so the mean free stream velocity \( U_\infty=10.52 \text{m.s}^{-1} \) is chosen thanks to its quality of pressure signature at the wall. Moreover study of the velocity field is well representative, of the generated structures at this velocity.

We also have compared our experimental data with the Schubauer & Klebanoff (1956) velocity profiles in a boundary layer on a flat plate in the transition region. This comparison allows us to validate our experimental set up considering that we obtained as our wishes a boundary layer in a fully developed turbulent flow.

![Figure 9: Boundary layer validation](image)

P.I.V. measurement are validated wit x hot wire probe. The velocity hot wire measurement is plotted at different \( z \) for a given instant after the beginning of the wing beat and compared to the plot of a P.I.V. profile recorded at the same time. Here are presented in figure 10 these results at a time \( t=38 \text{ms} \) after the wing beat.
fig. 10: P.I.V. velocity field with hot wire measurement localization & velocity profile data comparison

It is important to note that the presented velocity field is an average of 30 instantaneous field representing 30 wing beat whereas the x hot wire probe value correspond to one single beat. Nevertheless the results are in good accordance and show the good accuracy of the P.I.V measurements.

3. RESULTS AND DISCUSSIONS

Convective velocity

The convective velocity of the 2 contra-rotative structures was calculated by using the wall pressure fluctuations and the vortex core localization:

- For each instant, the position of the pressure minimum gives the localization in space (x-position) of the vortex. Then, it is possible to calculate the convective velocity and it comes $U_c = 1.05U_\infty$.
- Using the Q criterion (Jeong 1995) for each instantaneous velocity field, we can clearly detect the spacing position of the 2 vortex cores (x z directions). The knowledge of each spatio-temporal vortex position allows the determination of the structure velocity which corresponds here to $U_c = 0.98U_\infty$.

These results confirm that structures are convected at the free stream velocity.

3 dimensional plots

Figure 11 shows typical results obtained in X-plane and Y-plane. The transverse measurements (camera placed in flow – figure 6) have been performed in order to verify the quasi 2-dimensional behaviour of structures generated by the blade rotation. In the middle of the wind tunnel, the vortex seems to be quasi 2-dimensional. Indeed this is verified by the plots of the transversal velocity profile at different heights. Figure 12b) shows that the transverse velocity $V$ can be neglected compared to the $U$ and $W$ component (figures 13 & 15) in the study area.
fig. 12: a) cross velocity field \((V,W)\); b) profiles of transversal velocity component \((V)\) vs \(Y\)-direction at different vertical positions

**Longitudinal (x-axis) and transversal (y-axis) velocity fluctuation: spatio temporal evolution \(t=37 \& 38\) ms**

![Longitudinal & transversal velocity fluctuations at \(t=37\)ms and \(38\)ms, boundary layer pumping effect](image)

**Vortex influence on the boundary layer**

In the way to characterise the vortex influence on the boundary layer P.I.V. investigation is performed in the vicinity of the wall. A zoom is made on a zone of \(80*68\)mm (figure 14).

![Boundary layer measurements with b) and without a) the fluorescent paint](image)

fig. 14: boundary layer measurements with b) and without a) the fluorescent paint
Moreover by applying fluorescent paint on the wall, the light noise is avoided (see paragraph 2.2) and this significantly improves the quality of P.I.V. measurements made close to the wall (figure 14). It makes it possible to analyse the boundary layer by P.I.V. and an accurate measurement of the velocity field is obtained till a distance from 1mm the wall.

Thanks to these velocity field, U and W profile are obtained at different instant (figure 15). The temporal deformation of the boundary layer is well describe as a pumping effect (up and down) of the vortex (figure 16). To complete this assessment the time evolution of the boundary layer thickness (figure 16a) and the time evolution in Z-direction of the 2 vortex cores (figure 16b) are plotted.

The vortex evolution modifies the thickness boundary layer, but only the border line position is changed and follows the vortex evolution. The crushing of the boundary layer is compensated by velocity ejection and produces a depression at the wall. This phenomenon is outlined in figure 17.

Velocity field and wall pressure fluctuation
Coherence between the longitudinal velocity U and the wall pressure P

The existence of coherence between hot wire and pressure transducers signals carry notable information on this phenomenon. The coherence is calculated at X=160mm for different x-hot wire probe Z positions. Figure 18 shows the evolution of the coherence in the Z-direction.

As expected, there is an increase of coherence from the wall to an height corresponding of the localization of the structures modeling the boundary layer, then the coherence decreases. This confirms the assumption that the wall pressure fluctuation (and in particular the depression) is due to the crushing of the boundary layer by the vortex.

4. SUMMARY

An original experiment was carried out in order to improve the understanding of the relationship between a simple vortex structure and the wall pressure signal. The analysis of spatio-temporal wall pressure signature describes clearly the vortex evolution. Using the P.I.V. measurements corresponding in time of the wall pressure value, the vortex typology is linked to the wall pressure signature. The validity of the flow turbulent characteristics have been verified by comparing experimental with literature data.

Measurements close to the wall have been successfully made by P.I.V. This allowed to observe the crushing of the boundary layer during the vortex evolution. These results provided a part of the answer on the link between large scale structure of the external zone and the near wall area. It has been showed that the most contributing term to the wall pressure perturbation was the deformation of the flow field velocity inside the turbulent boundary layer. The crushing of the boundary layer is compensated by velocity ejection and produces a depression at the wall.
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