Flow-Induced Sound Radiated by a Forward Facing Step
Flow investigation with 3C-LDA system

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Kurz Zusammenfassung

Inhalt der Arbeit sind untersuchungen des Strömungsinduzierten Schallfeldes bei der Überströmung einer Vorwärtsspringenden Stufe. Basirend auf den Schallmessungen im Fernfeld erfolgen umfangreiche Messungen des Strömungsfeldes. Begonnen wird mit einer Analyse des instationären Wanddruck verteilungen. Es folgen detaillirte Untersuchungen der Geschwindigkeits und Turbulenz-verteilung mit einem 2C-LDA (und 3C-LDA) System. Anhand der Bildung der Korrelationsfunktion mit dem akustischen Druck des Fernfoldes wird eine Beschreibung der akustichen Quellterme vorgenommen.

Summary

The present study focuses on the aeroacoustic characteristics of the flow over a forward facing step. Having previously identified relevant regions which is taken as responsible for noise generation, the purpose is thus to characterize the related flow-field. Previous measurements, including coherence measurements between the pressure fluctuations on the wall and the noise in the acoustic far-field, stressed the particular role of the region upstream the step; by use of a LDA system allowing the measurement of two components, and ultimately three components, of the velocity field, one can link the nature of turbulence in the vincinity of the step with the radiated noise.

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1 Introduction

For high-speed transportation industries, each possible noise source, often having an aeracoustic origin, has to be carefully analysed because of restrictive noise regulations. For example, possibly-high contributions to airframe noise can occur from the flow over the airplane surface, in particular if small obstacles, coming from manufacturing imperfections for example, exist. One simplified set-up related to this configuration consists in a flat plate that presents a forward-facing step to the flow; but even in this case, the physics behind the noise generation process is not fully understood. The present study propose to combine a detailled flow exploration, by means of 2C-LDA measurements (preparing later 3C-LDA characterization of the flow) and wall-mounted pressure sensors, to precise the mechanisms governing the noise generation; this flow study is linked with results of acoustic measurements in the acoustical far-field.

2 Acoustic and Wall-pressure measurements

These acoustic measurements are carried-out in a wind tunnel associated with an anechoic room were performed at Lehrstuhl für Sensorik (LSE), University of Erlangen-Nürnberg. The basic set-up, as indicated in Figure 1 and detailed in [5], consists in a sharp step located 38 cm downstream the nozzle of the wind tunnel, the velocity of the free flow over the step being 30 $m.s^{-1}$. Far-field microphones are located at 90° and 45° with respect to flow direction and step location. As indicated in Figure 1, one can compare cross spectra calculated with microphones #1 and #2 (see Fig.1) for the flat plate only, used as a reference, and the configuration with the step. In this way, the frequency range [1 kHz:10 kHz] appears to contain the proper contribution of the step in terms of noise emission. This result is consistent with other noise measurements [2], that indicates a major noise contribution of the step in the non-dimensional frequency range $f \times h/U_0 \in [0.5{:}3]$, where h is the step height and U_0 the free velocity.

Moreover, the wall-pressure at different locations upstream and downstream the step is monitored, and synchroneous acquisitions of wall-pressure and far-field acoustic pressure are used to compute coherence between these two quantities, represented in Figure 2. One can note a remarkable coherence, in the frequency range characteristic of the noise induced by the step, emerges if the reference signal is obtained from a pressure transducer in front of the step ; in the other hand, the far-field acoustic signal seems not to be coherent with the signal obtained with a pressure transducer behind the step.

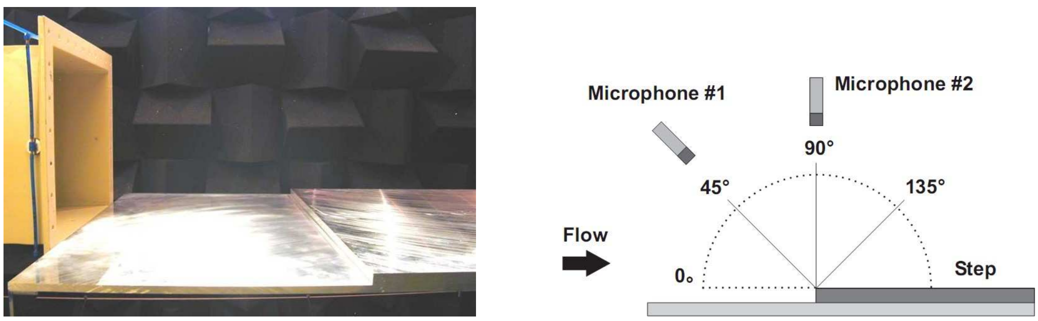


Figure 1: Illustration (left) and sketch (right) of the experimental set-up at LSE

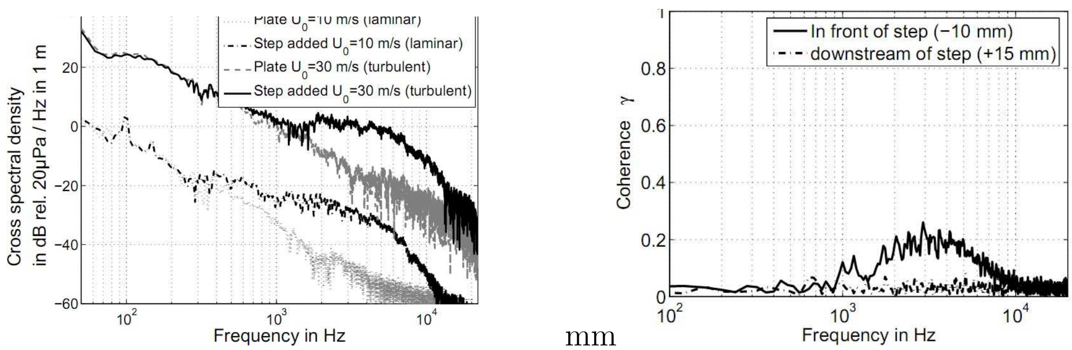


Figure 2: Cross spectra between microphones #1 and #2 (see Fig.1), for the flat plate only and the configuration with the step, for two different flow velocity (left) and coherence of wall-pressure and acoustic pressure in the 90° direction (right)

3 Experimental set-up for LDA measurements

These results appeal to further investigations of the flow over the step, to link the acoustics properties previously measured with the turbulence induced by the step. In this purpose, experiments were made in the opened wind tunnel of Lehrstuhl für Strömungsmechanik (LSTM), University of Erlangen-Nürnberg. One used a model of forward facing step, made of glass plates of width $l = .9$ m, and thickness $h = 12$ mm, setting the height h of the step to 12 mm; the aspect ratio of the model l/h is thus considerably higher than in other experiments [1, 2], providing *a priori* a large area of two-dimensional flow in front of the step. This model was set in the middle of the operating area of the wind tunnel and thus completely emerged in the flow, whose free velocity U_0 is 30 m.s^{-1}. With this velocity, the boundary layer was fully turbulent, and the displacement thickness $20h$ upstream the step is about $h/10$.

To characterize the flow field, one used a 2-components LDA set-up; the two $\lambda_1 = 488$ nm and $\lambda_2 = 514.5$ nm LASER-beams were obtained by help of a Spectra-Physics Argon-Ion Type 2060-7S LASER, coupled with in-house designed probe providing LASER beams couples with an inner-angle $2\phi = 5.54°$. The caracteristic length and width of the measurement volume are $L \approx 1.5$ mm and $l \approx 80$ μm. The system was operated in backward-scattering mode, and the signals analyzed by two DANTEC Burst Spectrum Analysers 57N20.

Preliminary flow measurements were used to match the inflow conditions of this experimental set-up tested in the Lehrstuhl für Strömungsmechanik (LSTM) Wind Tunnel (Figure 3), with the one of Figure 1. Moreover, measurements not reported here were carried out to state the homogeneity of the flow with respect to the axis normal to the flow, denoted as the y axis in the set-up of Figure 3. As previously noted [1], a deviation of flow is expected on the sides of the model, in front of the step. This deviation was shown to have a limited spatial extent from the sides, so that measurements at mid-span, presented in the following, characterize a two-dimensional flow in front of the step.

The probe was located on the side of the step. To avoid low signal-to-noise ratio due to light reflexion, the probe axis was set so that the angle β, represented on Figure 3, was equal to 85°.

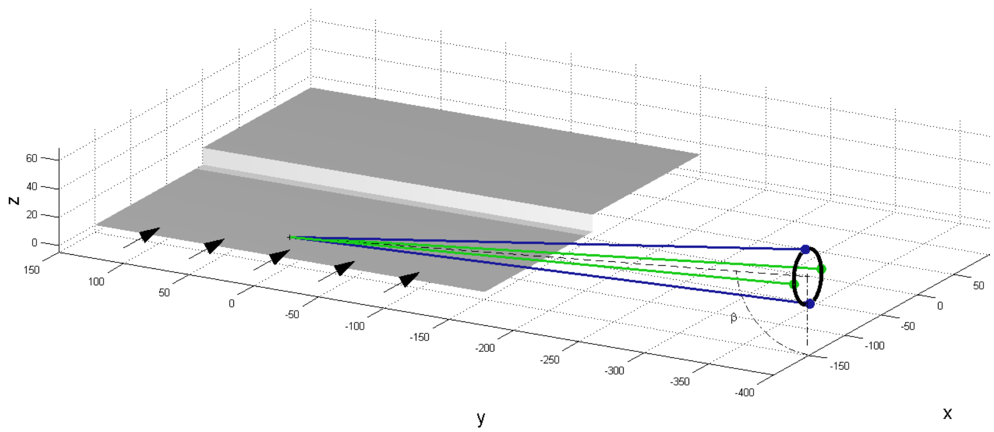


Figure 3: Preliminary flow measurements with a 2C-LDA probe, in the LSTM Wind Tunnel

4 Results and discussion

The flow field characterization relies on a detail study of the mean flow-field properties, such as the flow separation over the step, and turbulence-intensities determination, possibly linked with noise generation. The Figure 4 presents the maps of (a) mean streamwise-component velocity U_x, RMS values of (b) streamwise and (c) normal-component velocity $U_{x \text{ RMS}}$ and $U_{y \text{ RMS}}$.

The mean flow field (Figure 4(a)) is characterized by a flow separation over the step, together with a flow detachment in front of the step. The detachment occurs about $1.1h$ before the step, and the flow separation induces an acceleration of the fluid from U_0 to about 1.17 U_0. This value is in good agreement with those related by [1, 2]. After separation at the edge of the step, the flow exhibits a recirculation bubble whose length is about 4 h and height about 0.3 h. These values are again in fair agreement with previous measurements in other facilities [3, 4]

The turbulence intensities (Figure 4(b) and (c)) are measured to be high in the region over the step, where the detachment occurs; high levels of turbulence intensity are obtained in the region between 0 and 1.5 h downstream the sharp edge, and the maximum of turbulence intensity related to the streamwise component of the velocity corresponds to 36% of the free velocity U_0 for the streamwise component of the turbulent velocity. This value is close to the value of 40% obtained in [2]. Downstream this area, diffusion process, driven by the shear flow consecutive to the separation, tend to decrease the turbulence intensity.

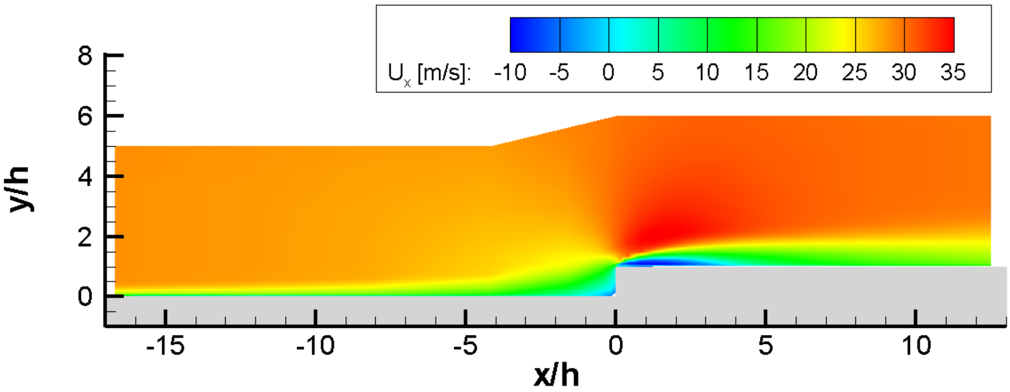
The interpretation of the results obtained in the acoustic and wall pressure measurements study by help of the present aerodynamic measurements is far from simple. One can link, as shown by previous noise sources localisation carried out in LSTM [5] or by others [2], the area of maximum noise production to that of maximum turbulence intensity; this designates the domain located between 0 and 2 h downstream the sharp edge to be the main contributor to noise emission. Numerical simulations [6] confirm such a result, by indicating that the largest values of the source terms, provided by a LES computation coupled with LEE approach, are also obtained next to the step and downstream of it. In the other hand, significant coherence between a wall-pressure signal, collected in the recirculation area in front of the step, and the acoustic signal recorded in the far-field is obtained in the frequency range where the noise induced by the step is predominant, as recalled in Figure 2. If the reference pressure sensor is located 1.25 h downstream the edge, then the coherence between the corresponding signal and the far-field noise is practically zero (see the same Figure for illustration).

The origin of the correlation between wall-pressure in front of the step and acoustic pressure in the far-field still needs to be precised. Two differents possibilities can explain this correlation:

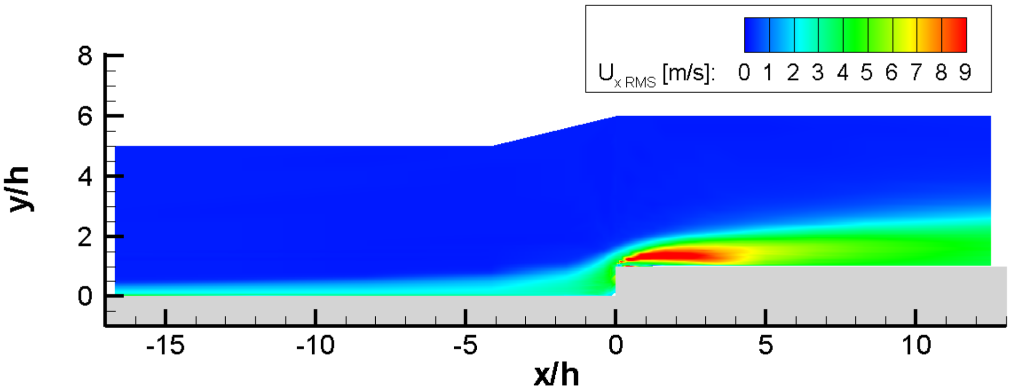
1 the wall-pressure in front of the step is the trace of aerodynamic event occuring in the vincinity of the surface, and as a consequence one could argue that this region is responsible for noise production,

2 the contribution of acoustic waves (maybe produced after the edge of the step) to wall-pressure in front of the step is non negligeable with respect to contribution of hydrostatic pressure.

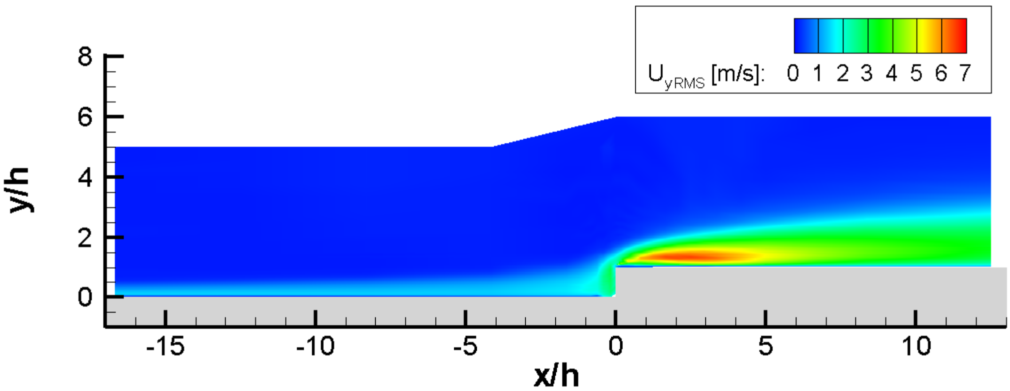
To confirm one of these hypotheses, one should study the complete Reynolds stress tensor that is known to be linked with the acoustical efficiency of turbulent flow in noise radiation. In this purpose, experiments currently made at LSTM imply a 3C-LDA system to determine simultaneously the 6 significant terms of Reynolds stress tensor.



(a) Mean streamwise velocity U_x



(b) RMS value of U_x



(c) RMS value of U_y

Figure 4: Flow characterization with a 2C-LDA probe, in the LSTM Wind Tunnel

5 Further investigations with a 3C-LDA system

The experimental set-up of experiments currently made at LSTM uses a 3-components LDA probe, consisting of two probes arranged in the way indicated in Figure 5. In this system is used one 2-components LDA probe, with $\lambda_1 = 532$ nm and $\lambda_2 = 523.5$ nm, and one 1-component LDA probe, with $\lambda_3 = 428$ nm. The focal distance of each probe is about 400 mm, and the distance between two associated beams is initially about 38 mm. The sketch of Figure 5 indicates the exit points of the optical beams, at the exit of each probe, and the beam paths up to the location of the measurement volume. One indicates also, with dashed lines, the axis of each probe. To ensure the simultaneous measurement of the three components of the velocity with a minimum noise level, the two probes were inclined with respect to the vertical axis and also with respect to the step. The orientations of the measurement volumes are well defined by geometrical considerations; with help of angles α and β as defined in Figure 5, representing the angle of the probe axis with respect the z-axis and y-axis respectively, one can define the orientation of the measurement volumes in the space, and consequently compute the three components (u_1, u_2, u_3) of the velocity in the (x,y,z) orthonormal axis-system linked with the basis $(\vec{e_1}, \vec{e_2}, \vec{e_3})$, from the data (U,V,W) collected in the 2-probes system of axis. Because the orientation of the probes is symmetrical with respect to the $y = 0$ plane, the absolute values of angles α and β are the same for the two probes. Moreover, considering the 2-components probe, the line passing through the two emitting points of the beams couples (represented in light green in Figure 5 is set to remain horizontal.

Simple geometrical considerations lead to express the direction vectors $\vec{e'_1}$, $\vec{e'_2}$ and $\vec{e'_3}$ of the three measurement volumes with the help of α and β. These normalized vectors are expressed in the basis $(\vec{e_1}, \vec{e_2}, \vec{e_3})$ as follow (more details are given in appendix A):

$$\vec{e'_1} = \frac{1}{\sqrt{\tan^2(\beta) + \tan^2(\alpha)}} \begin{pmatrix} \tan(\beta) \\ \tan(\alpha) \\ 0 \end{pmatrix} \quad (1)$$

$$\vec{e'_2} = \frac{1}{\sqrt{\tan^2(\beta) + \tan^2(\alpha) + (\tan^2(\beta) + \tan^2(\alpha))^2}} \begin{pmatrix} \tan(\alpha) \\ \tan(\beta) \\ \tan^2(\beta) + \tan^2(\alpha) \end{pmatrix} \quad (2)$$

$$\vec{e'_3} = \frac{1}{\sqrt{\tan^2(\beta) + \tan^2(\alpha) + (\tan^2(\beta) + \tan^2(\alpha))^2}} \begin{pmatrix} \tan(\alpha) \\ -\tan(\beta) \\ \tan^2(\beta) + \tan^2(\alpha) \end{pmatrix} \quad (3)$$

This leads to define the matrix $\mathcal{M}$, ${}^t\mathcal{M}$ being the passing matrix from $(\vec{e_1}, \vec{e_2}, \vec{e_3})$ to $(\vec{e'_1}, \vec{e'_2}, \vec{e'_3})$:

$$\begin{pmatrix} \vec{e'_1} \\ \vec{e'_2} \\ \vec{e'_3} \end{pmatrix} = \begin{pmatrix} \delta\tan(\beta) & \delta\tan(\alpha) & 0 \\ \omega\tan(\alpha) & \omega\tan(\beta) & \omega\big(\tan^2(\alpha) + \tan^2(\beta)\big) \\ \omega\tan(\alpha) & -\omega\tan(\beta) & \omega\big(\tan^2(\alpha) + \tan^2(\beta)\big) \end{pmatrix} \begin{pmatrix} \vec{e_1} \\ \vec{e_2} \\ \vec{e_3} \end{pmatrix} = \mathcal{M} \begin{pmatrix} \vec{e_1} \\ \vec{e_2} \\ \vec{e_3} \end{pmatrix}$$

with $\delta(\alpha, \beta) = \frac{1}{\sqrt{\tan^2(\beta)+\tan^2(\alpha)}}$ and $\omega(\alpha, \beta) = \frac{1}{\sqrt{\tan^2(\beta)+\tan^2(\alpha)+(\tan^2(\beta)+\tan^2(\alpha))^2}}$

As a consequence, any measurement (U,V,W) in the basis $(\vec{e'_1}, \vec{e'_2}, \vec{e'_3})$ can be reported in the basis $(\vec{e_1}, \vec{e_2}, \vec{e_3})$, where the corresponding components of the velocity are (u_1, u_2, u_3), by use of the passing matrix:

$$\begin{pmatrix} u_1 \\ u_2 \\ u_3 \end{pmatrix} = {}^t\mathcal{M} \begin{pmatrix} U \\ V \\ W \end{pmatrix}$$

The definition of $\mathcal{M}(\alpha, \beta)$ corresponds to an optimistic case where the two probes are set in a perfectly symmetrical way with respect to the step. A more realistic case consists in describing the location of each probe with a set of parameters (α_i, β_i, f_i) representing respectively the two angles previously used and the focal length for each probe. Using this formalism, one can express the matrix $\mathcal{M}$ as follow :

$$\mathcal{M}(\alpha_1, \beta_1, \alpha_2, \beta_2) = \begin{pmatrix} \delta_1\tan(\beta_1) & \delta_1\tan(\alpha_1) & 0 \\ \omega_1\tan(\alpha_1) & \omega_1\tan(\beta_1) & \omega_1\big(\tan^2(\alpha_1) + \tan^2(\beta_1)\big) \\ \omega_2\tan(\alpha_2) & -\omega_2\tan(\beta_2) & \omega_2\big(\tan^2(\alpha_2) + \tan^2(\beta_2)\big) \end{pmatrix}$$

with $\delta_i(\alpha_i, \beta_i) = \frac{1}{\sqrt{\tan^2(\beta_i)+\tan^2(\alpha_i)}}$ and $\omega_i(\alpha_i, \beta_i) = \frac{1}{\sqrt{\tan^2(\beta_i)+\tan^2(\alpha_i)+(\tan^2(\beta_i)+\tan^2(\alpha_i))^2}}$

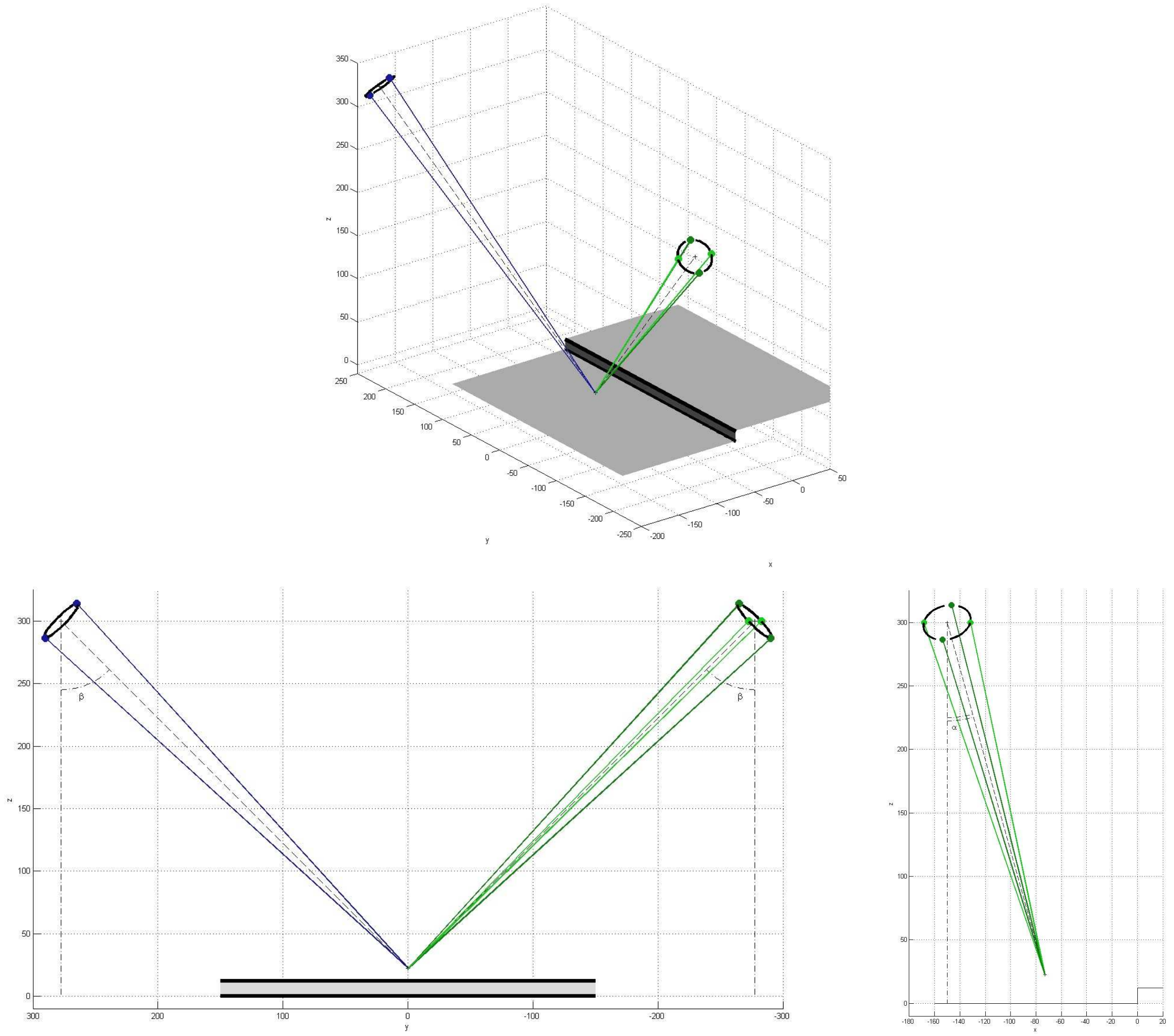


Figure 5: Experimental set-up of the two LDA probes, with respect to the forward-facing-step, located at $x = 0$

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A Detailed calculation of vector orientations

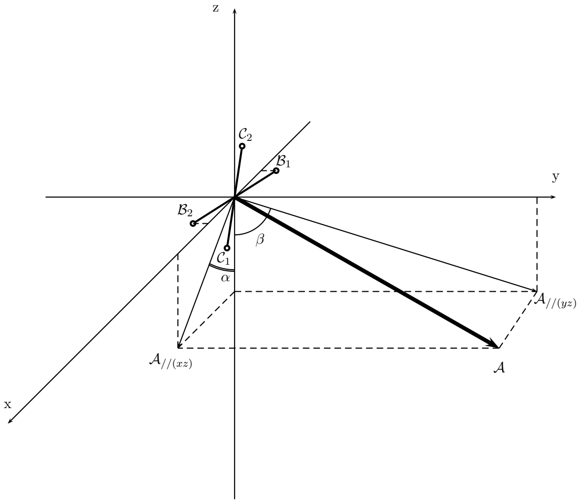

Figure 6: Experimental set-up of the two LDA probes, with respect to the forward-facing-step, located at $x = 0$

One consider here one vector $\vec{\mathcal{A}}$, being the probe axis, in the (O,x,y,z) system. Attached to $\vec{\mathcal{A}}$ are two vectors $\overrightarrow{\mathcal{B}_1\mathcal{B}_2}$ and $\overrightarrow{\mathcal{C}_1\mathcal{C}_2}$ that satisfy a set of constraints with respect to $\mathcal{A}$:

1 - $(\mathcal{B}_1\mathcal{B}_2)$ lies in the (x,y) plane ; as a consequence, $(\mathcal{C}_1\mathcal{C}_2)$ has no particular properties of this kind,

2 - $\overrightarrow{\mathcal{B}_1\mathcal{B}_2}$ and $\overrightarrow{\mathcal{C}_1\mathcal{C}_2}$ are normal to $\vec{\mathcal{A}}$,

3 - $\mathcal{B}_1, \mathcal{B}_2, \mathcal{C}_1, \mathcal{C}_2$ are located at the distance d/2 of the origin of axis.

Expressing these constraints in terms of mathematical properties, it comes straitforward the expression of normalized $\vec{\mathcal{A}}$ in the (x,y,z) coordinates:

$$\vec{\mathcal{A}} = \sqrt{\frac{1}{1+\tan^2(\beta)+\tan^2(\alpha)}} \begin{pmatrix} \tan(\alpha) \\ \tan(\beta) \\ -1 \end{pmatrix}$$

As a result, one obtains for the locations of points $\mathcal{B}_i$ and $\mathcal{C}_i$

$$\begin{aligned} \vec{\mathcal{B}_i} &= \pm \frac{d}{2 * \sqrt{\tan^2(\alpha)+\tan^2(\beta)}} \begin{pmatrix} \tan(\beta) \\ -\tan(\alpha) \\ 0 \end{pmatrix} \propto \begin{pmatrix} \tan(\beta) \\ -\tan(\alpha) \\ 0 \end{pmatrix} \\ \vec{\mathcal{C}_i} &= \pm \frac{d}{2 * \sqrt{\tan^2(\alpha)+\tan^2(\beta)+(\tan^2(\alpha)+\tan^2(\beta))^2}} \begin{pmatrix} \tan(\alpha) \\ \tan(\beta) \\ \tan^2(\beta)+\tan^2(\alpha) \end{pmatrix} \propto \begin{pmatrix} \tan(\alpha) \\ \tan(\beta) \\ \tan^2(\beta)+\tan^2(\alpha) \end{pmatrix} \end{aligned}$$