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On the free jet bench validation inside its similarity region

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Abstract.
In order to study the free jet, first it is necessary to validate a bench with the desired configuration. This article presents some considerations for the free jet fully merged zone, showing how the bench was assembled, which components were used and how the analysis for the validation was made. The bench was assembled in the Dinam - Dimci - Inmetro lab, and was designed to support the passive control using coaxial nozzles. Compressed air was used as a flow source and the Hot-Wire anemometry system was used to data acquisition. It is known that the free jet has a self-preserving zone where the flow is fully developed and, in this zone, the different local velocity profiles collapse when the transverse variable is made dimensionless with respect to the local momentum thickness. To investigate these profiles, along with the initial zone velocity and perturbation profiles, as well as turbulent decay were analyzed in this validation.

Keywords: *jets, nozzle, fluid, flow, similarity*

1. INTRODUCTION

The ultimate goal of the present research project is the study of coaxial elliptic jets. Our final objective is to analyze how the inner jet instability under blowing or suction through the outer nozzle is affected by the coupling between different modes introduced by the elliptic geometry. Its convective instability as well as its onset of absolute instability are going to be investigated. As far as the authors are aware, such a research is yet to be presented in the literature. The present study, an experimental analysis inside the similarity region, represents another step towards this goal (a previous work presented Souza *et al.* (2013)). Hence, the short literature review presented next is focused on free jets.

It's well known that the jet has basically three regions and each one with it's own characteristics. The initial merging zone will show a potential core (where the velocity profile is constant) and a mixing region (where the disturbances grow). The intermediate zone is mostly a mixing zone with high turbulence. And in the fully merged zone one can collapse the velocity profiles. Searching for a complete solution for the vortexes, Batchelor and Gill (1962) assumed that a solution for the vortex formation is known and then applying this in the quantum momentum and continuity equations, obtaining a solution and further showing the need of a inflection point in the velocity profile for the instability existence. Years later, Wygnanski and Fielder (1969) showed that the velocity profile follows a repeatable pattern when in the fully merged zone. This pattern can be observed when the velocity profile is shown with a characteristic length known as similarity variable (η). Some time later, George (1989) shows also that the mass flow variation tends to an increasing straight line from a certain distance from the nozzle, showing the existence of a virtual origin. And later on, Hussein *et al.* (1994) extended Wygnanski and Fielder (1969) work for the similarity zone.

2. EXPERIMENTAL PROCEEDINGS

2.1 Experiment layout

The bench was assembled as shown in Fig. 1. The air inlet (1 and 2), previously filtered, is supplied by a compressor with capacity of 8 bar, that is kept far from the filters, in order to reduce the perturbation caused by the compressor engine (while it is turned on to keep the pressure constant). After, the air will reach screens (Soltani *et al.*, 2010) and a honeycomb, in order to minimize the turbulence of the air flow. After this composition, there is a pipe with at least 10 diameters long and then the nozzles. For the present work only the inner nozzle was used (acting as a free single jet). Vibra-stops were used in all the supporting structure and in the Hot-wire traversing system.

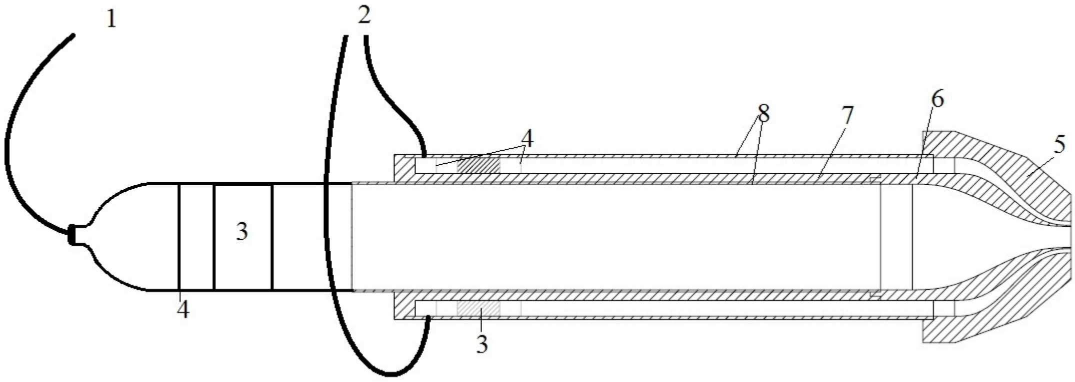

Figure 1. Schematic of jet apparatus. 1 and 2. Air inlet. 3. Honeycomb. 4. Screens. 5. Outer nozzle. 6. Inner nozzle. 7 and 8. Plastic parts.

The inner nozzle is made of plastic. The inner and outer profile for this nozzle was acquired using a 5^{th} grade equation, as a result of smooth entries for first and second velocity variations. And the nozzle was made with a CNC lathe.

The hot-wire velocity calibration was performed using the Dantec calibration unit along with the StreamLine system. The acquisition was made with the StreamWare system also from Dantec System Dynamics. The traverse system used was the Sigma Koki.

2.2 Hot-wire anemometry

The hot-wire system used here was the Constant Current Anemometry (CTA). The functioning principle is quite simple. As the flow runs by the wire, it removes some heat from the wire, causing a reduction of the wire resistance (according to Eq. (1)). This is detected by the CTA bridge that immediately varies the current to restore the initial temperature value (Bruun, 1995). This returns a new voltage value for the Wheatstone Bridge, and this value can be correlated to the velocity value. After collecting some values for different velocities, one can perform a calibration curve (that in the present work was performed using a 4^{th} degree equation). This calibration was made with the Dantec's calibration unit.

$$R_w = R_0[1 + a_0(T_w - T_0)]] \quad (1)$$

2.3 Complementary proceedings

The nozzle was assembled to work with the flow in the vertical direction. The bench has a *x* axis, that is the nozzle axis, with zero at the nozzle exit. The nozzle has axial symmetry. The traverse system was then aligned to correspond to the bench axis and was used a caliper rule to set *x* to zero. The *y* axis is settle by the velocity profile, as the acquisition goes, the profile (as in Fig. 2 left) is symmetric, and then one can infer the zeroes to the axis. This data represent a 1 kHz acquisition frequency and for 45000 samples (different from the further figures).

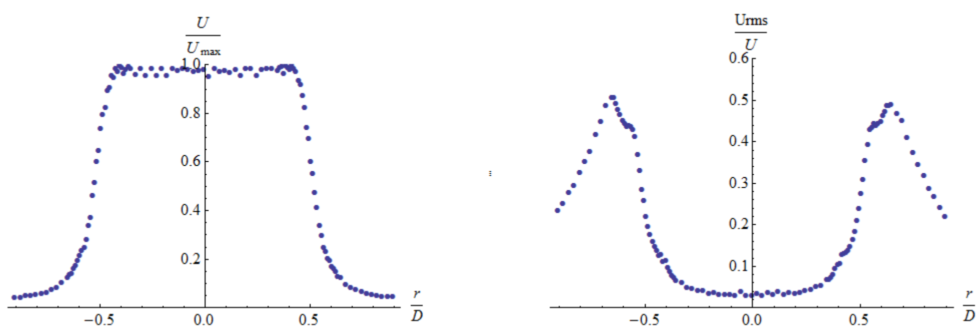

Figure 2. Velocity profile and turbulent intensity - 1 D.

The series of acquisition were made at 1D, 2D, 3D and 4D (D = 20 mm) so the x_0 (non-dimentional radial coordinate: $\eta = r/(x - x_0)$), the velocity profile (as in Fig. 2 left), the instant disturbance (as in Fig. 2 right) and the potential core could be estimated. Further, there were series of acquisition at 25D, 30D and 35D so the self-preserving zone could be analysed. Some attempts were made to evaluate the relation between the number of samples and frequency of acquisition. As the acquisition time for each series is long enough, the temperature was monitored during each series and a correction was applied to each velocity value acquired. There are still undergoing studies at the lab to set the best sampling and acquisition sampling, and the uncertainty analysis (Yavuzkurt, 1984).

3. RESULTS

3.1 Initial merging zone

All the data acquired was processed with the software Mathematica. The velocity profile is shown in Fig. 3, for Reynolds values of Re_D=10000 and 13000, respectively. The profiles have the expected shape like a square wave form for the values near the nozzle, and gradually changing into a sinus wave form as the distance to the nozzle increase.

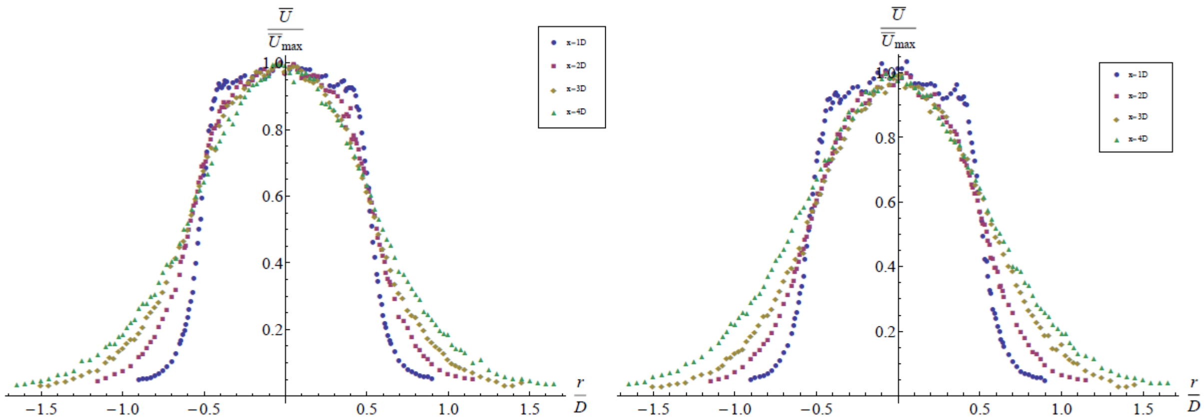

Figure 3. Velocities profiles for Re_D=10000 and 13000 - 1 to 4 D.

The instant disturbance is shown in Fig. 4. The increase in the disturbance can be seen in the shear layer, and grows as x increase. It's peak also hold off from r/D=0.5 due to the increase of the shear layer. It's perceptible that there is some error in the acquisition, for the 13000 Reynolds series, and it probably is caused by some noise in the lab or either by the bad choice for the sampling and frequency ratio.

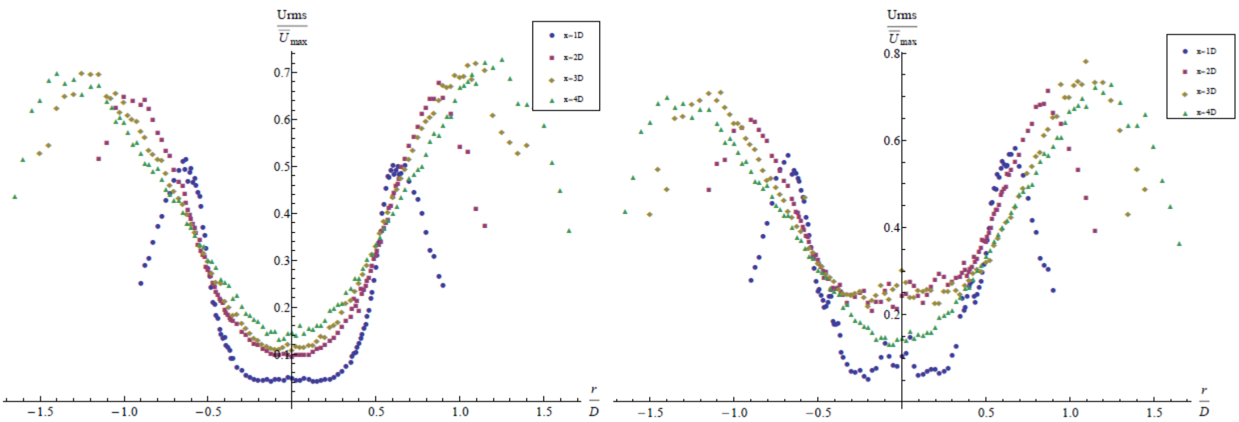

Figure 4. Instant disturbance for Re_D=10000 and 13000 - 1 to 4 D.

Another important factor to observe is the frequency analysis. It's quite simple to make, one just need to use a Fast Fourier Transform, and the result should be transformed into dB. Then, the variable we're after is the Strouhal number ($St = f.d/U$). The results from the FFT must be multiplied for the nozzle diameter and divided by the velocity in that point. The frequency spectrum is expected to be like represented in Fig. 5. Though the results need to be passed through a low-pass filter, so it can be easier to compare with the literature (Strykowski and Niccum, 1991). The higher value of frequency is usually between 0.2 and 0.6 St at the jet shear layer.

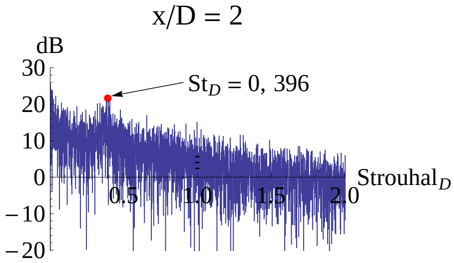

Figure 5. Frequency spectrum, excitation frequency in red - 2 D.

3.2 Fully merging zone

Further, there was a concern with the sampling and frequency ratio, as shown in Fig. 6. As the values chosen were changing, for the same value of inlet velocity, the velocity profile at a distance of 30D changed drastically, showing that the hot-wire will add the environment noise to the data and it will change what is expected to see. A further work will be written to check the best fit for that relations. The comparison between the ratios can be made with the best tendency line (fit with one of the ratios used) for the nozzle in Fig. 7, the red dot is an important value stated by some authors (Hussein *et al.*, 1994).

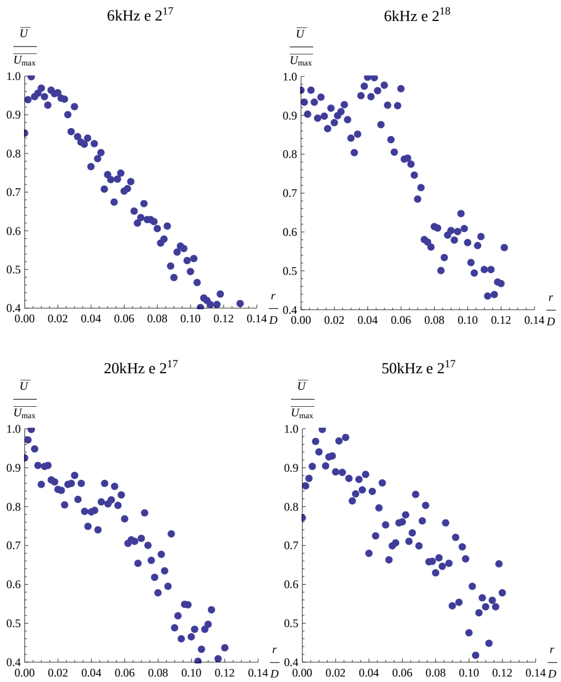

Figure 6. Sampling and frequency ratio changes - 30 D.

If the bench is assembled correctly, another observation that should be made is if the jet is has self-preserving zone. This is indicated by the graphics with the normalized velocity plotted versus the non-dimensional radial coordinate (η), and it's shown in Fig. 8, for values of Re_D=10000 and 13000 and for distances indicated in the figure. Even for values of Reynolds lower than the stated by Hussein *et al.* (1994) and other works the profiles collapse. Fits can be made in the data for better understanding, and one important value of η is the point where the velocity decays to the half ($\eta_{1/2}$=0.1, when $\overline{U}/U_{max}$=0.5).

4. CONCLUSIONS AND FUTURE WORK

The bench seems to present similar data as the ones present in the literature. One can say that some of the analyzed data still need some better presentation. There is still some work to be done until the hole bench is validated. The present bench has a coaxial nozzle, allowing the experiments to be carried with coaxial flows or just an annular flow. Those will be presented in a future work.

There are still several problems with the present experimental data. The reasons diagnosed so far are: 1) sample size is not accurate, which is the wrong choice for the sampling and frequency ratios, 2) some fluctuations in the potential

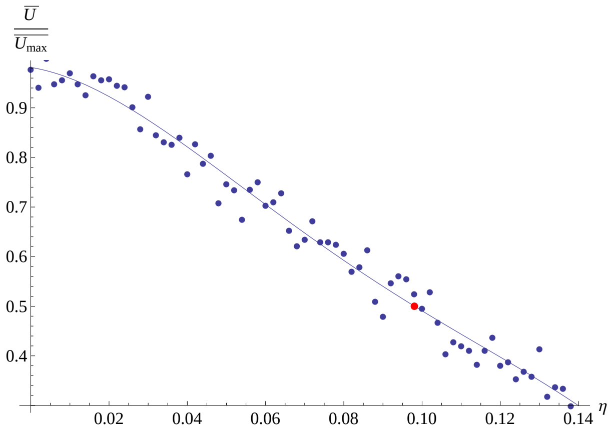

Figure 7. Tendency line for the best relation sampling and frequency ratio - 30 D.

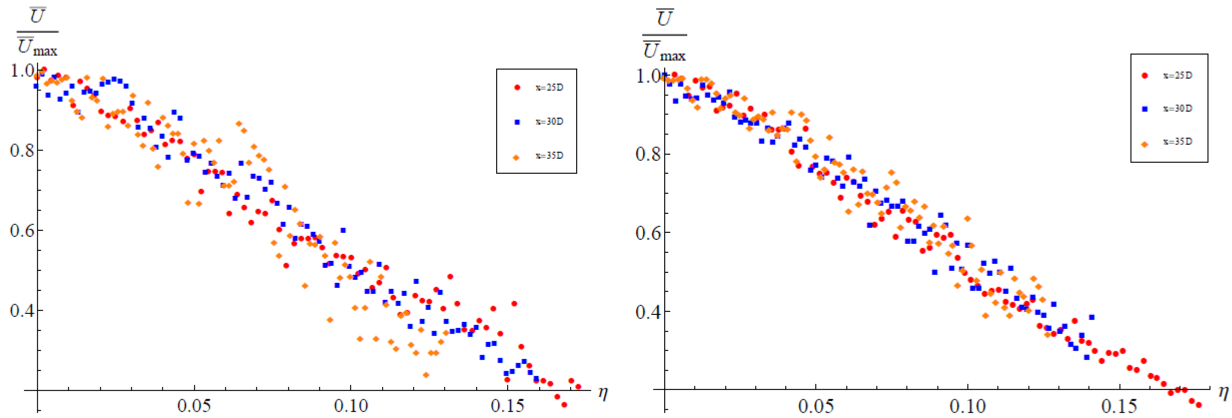

Figure 8. Self-similarity for Re_D=10000 and 13000 - 25D, 30D and 25D.

core, probably due to fluctuations in the air filter (can be solved with a long tank, 3) absence of an isolation system for the experiment, which explains why the measured velocity profile does not go to zero away from the jet centerline (jet with entrainment), 4) limitations in the traversing system.

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