Doctoral School on Engineering Sciences
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Extended summary

Noise Development of methods and experimental procedures

to characterize the jet aeroacoustics

Curriculum: IngegneriaMeccanica e Gestionale

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Abstract.

The acoustic emission of air jets is a very important issue for the optimization of systems in the industrial sector. In this study, the jet behavior has been analyzed using different measurement techniques, evaluating the benefits and limitations of each of them. Non-invasive techniques have been chosen in order not to alter the measured field. Additionally, the techniques were selected among those that are sensitive to different physical quantities (acoustic and fluid dynamics), so that the correlations between the different phenomena can be assessed. The following techniques have been considered: the dynamic tomographic interferometry, the sherografia , the acoustic beamforming and the acoustic holography. The mentioned techniques allow the mapping of the pressure fluctuations in and around the jet. In particular, the fluid-dynamics measure, which is based on interferometry, does not require flow seeding. In this paper a hybrid approach is presented in which acoustic measurements are processed together with fluid–dynamic data taken from the Interferometric Laser Tomography. Data from different techniques are not simply compared in order to verify correspondences, but are also coherently elaborated in order to separate different contributions to the problem of aero-acoustic noise emission.

Keywords.

Beamforming, Jet-Noise, Dynamic Tomographic Interferometry, Shearography, S.T.S.F.

1 Problem statement and objectives

Jet noise control and characterization is, nowadays, an important issue and therefore is the subject of numerous studies. Although a lot of work has been done from a numerical point of view, starting from the pioneering research of Lighthill, who put the mathematical basis for the calculation of the noise generated by a jet whose fluidynamic is known, there is still a lack of experimental techniques able to characterize the jet aerodynamics and subsequently its acoustic behavior. In fact, a part the invasive technique based on Constant Temperature Anemometer (CTA), all the well-established non contact techniques as Particle Image Velocimetry (PIV) and Laser Doppler Anemometry (LDA) require the presence of seeds inside the flow, this being very difficult even for medium speed jets.
For a Reynolds number greater than a few thousands the flow fields of turbulent jets obey a similarity solution. The shear layer evolves mainly due to the velocity difference between the jet and the ambient fluid right behind the nozzle exit. The naturally occurring turbulent structures in the mixing layer show a high degree of three dimensional behaviour and therefore these anisotropic flow structures in high speed free streams are difficult to observe. However, there is a common understanding about the Fine & Large Scale Turbulent Structures12 Directivity Index22 overall structure of turbulent free streams.
As the jet leaves the nozzle the mixing region begins and it is Fine Scale and Turbulent Fine Scale Noise Structures supposed to extend over a length of about 5 times the nozzle diameter D. The constant mean flow along the jet axis in the so called potential core is enclosed by the annular shear layer, which expands with increasing Large Scale Turbulent Structures distance from the nozzle exit by broadening concurrently Large Scale Noise in- and outwards. Outside the potential core the main axial velocity decays, whereas the turbulent velocity grows and reaches its maximum in the symmetry axis of the shear. Subsequent to the potential core extends the jet’s transition region from approximately 5 D to 10 D, where the turbulent actions in the shear layer range over the total cross section. The detailed analysis of the mixing process in the shear layer remains a subject of investigation till today. Ideas of a rather stochastic turbulence pattern took an abrupt turn, when E. Mollo-Christensen5 stated “turbulence may be more regular than we think it is” and it was discovered that turbulence in jets and shear layers was not made up of randomly distributed turbulent eddies acting as single concentrated sound radiators, but possessed fine and in particular large scale structures with associated directional noise characteristics. The large turbulence structures are regarded as dominant for the dynamics and mixing processes of jets and free shear layers at high subsonic speeds and are identified of being responsible for the highly directional noise pattern of turbulent jets.13-15 Furthermore, the large scale structures determine the jet’s sound pressure level and therefore a promising approach of influencing the significant jet noise emissions is to affect the formation of these turbulent structures. In this study the measure to follow that approach is the application the nozzle exit.

2 Research planning and activities

In this thesis the behavior of the jet flow has been analyzed using different measurement techniques, in order to assess the benefits and limitations of each. Non-invasive techniques have been chosen in order not to alter the measured field. Moreover, the techniques were selected from those sensitive to different physical quantities (fluid dynamics and acoustic) in order to assess the correlations between different phenomena.

These are considered:
1. dynamic tomographic interferometry
2. shearography
3. the acoustic beamforming
4. acoustic holography

All the techniques allow the mapping of pressure fluctuations within and around the jet. In particular, the fluid-dynamics measure, based on interferometry, does not require the presence of seeding particles within the fluid.

In this paper, a relatively new technique has been applied to measure the density variation inside the jet flow that is the Tomographic Laser Interferometry (TLI). The basic principle **Errore. L'origine riferimento non è stata trovata.** of this method is that the laser beam which passes through the flow and is back-reflected by a steady object will experience a Doppler shift proportional to the derivative of the displacement (*s*) to which the laser itself undergoes. In particular the output of the TLI is a pseudo-velocity (*v*) related to the optical path of the laser beam (*Z*) and to the refraction index of the medium (*n*) crossed by the beam:

$$v(x,y,t)=\frac{ds(x,y,t)}{dt}=\frac{d\left[n(x,y,t)Z\right]}{dt}=Z\frac{dn(x,y,t)}{dt}+n(x,y,t)\frac{dZ}{dt} \qquad (1)$$

Since the optical path is constant being the object to which the laser beam impinges is steady, the second term of Equation (1(1) is null. Therefore the TLI output is a measure of the refraction index variation inside the flow and consequently of the density fluctuation (ρ) which is related to the refraction index by means of the Gladstone-Dale constant (*G*):

$$n(x,y,t)-1=\sum_j G_j\rho_j \qquad (2)$$

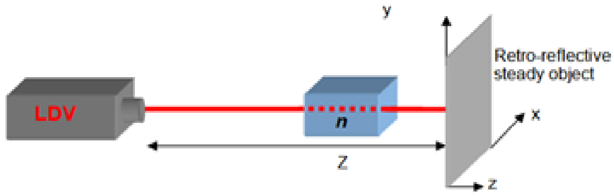


Figure 1. TLI basic principle scheme.

The sound produced by the air density fluctuation in the surroundings of the free jet can be thus calculated following the next relationship:

$$p(x,y,t) = c_0^2 \rho(x,y,t) \tag{3}$$

It should be pointed out that the laser beam crosses the measurement volume in the z-direction and therefore the measured density fluctuation is not relative to a point on the volume but is the integral along the optical path and in particular along the dashed line in

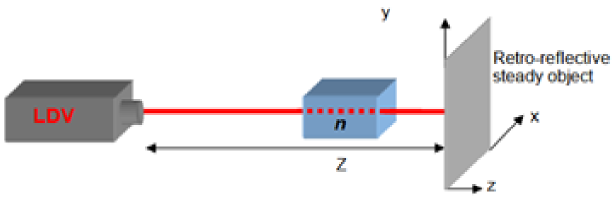


Figure 1, where a density fluctuation exists. In order to calculate the density oscillation at each point of the measurement volume a tomographic reconstruction is needed. For arbitrary flows, the measurement must be repeated from several projections. In the condition of axial symmetry, as it mostly happens for jets, a single projection is sufficient for being used to regenerate an arbitrary number of equivalent projections.

In this work the density measurements have been performed together with acoustic pressure measurement (via a near-field microphone) in order to assess the coherence between the two quantities. Specifically, the coherent component would be the one that will contribute to the noise propagation, whereas the residual part represents the aerodynamic component that won't be irradiated acoustically.

The previous technique, the sherografy system, is used here in an original way. Also in this case, the system observes a surface infinitely stiff (and therefore does not deform) through the project under consideration. The optical path of the system is therefore affected by the jet itself. The image so obtained is compared with the reference obtained in the absence of the jet, providing an interferometric image linked to the density distribution in the casting.

The acoustic holography is a technique for reconstruction of two-dimensional acoustic fields on planes parallel to the plane of measurement. It operates in the near field, the acoustic holography is a technique for measuring sound pressure using an array of microphones. This technique can provide high resolution maps of a flat surface source from measurements taken on a rectangular grid of points near the same. The array of measures must capture most of the radiation noise and should completely cover the noise source of a solid angle of 45 degrees. The spacing of the grid must be less than half a wavelength at the highest frequency of interest. This technique therefore requires a large number of microphones or in the case of stationary sources, scan them again in different portions of the measurement using a method known as scanning. The near-field acoustic holography has never been applied to characterize the noise emission of fluid dynamic phenomena. This work has highlighted the difficulties of application and the criticality of the method.

The flow downstream a nozzle has been analyzed and, firstly, it has been characterized in terms of its aerodynamics, by measuring the pressure ratios and the velocity field with a CTA.

3 Analysis and discussion of main results

TLI analysis of results

The application of TLI combined with acoustic measurement, using a reference microphone placed in the field near the jet, allows a consistent analysis to forecast the behavior of pure aeroacoustic jet. The microphone was used as a reference for identifying the part of the density fluctuations consistent with the acoustic pressure measured by the microphone, this component is linked to the rest of the flow acoustic radiation is the aero component that will not be radiated in the far field.

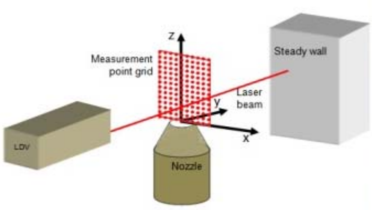


Figure 2. TLI setup

Following the tests, there are two phenomena: that the of detachment of vortices and in particular how they interact with the wave fronts that originate from the detachment of vortices with spherical waves that propagate to the far field (turbulent jets at low Mach) and the phenomena of cavities due to the geometry of the nozzle.

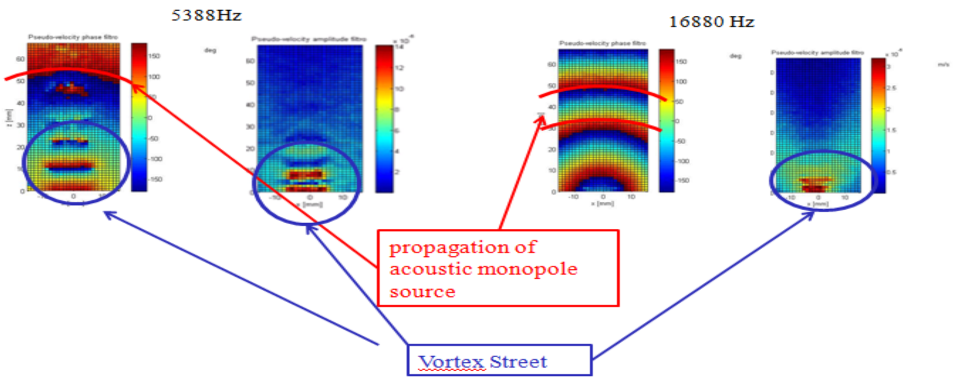
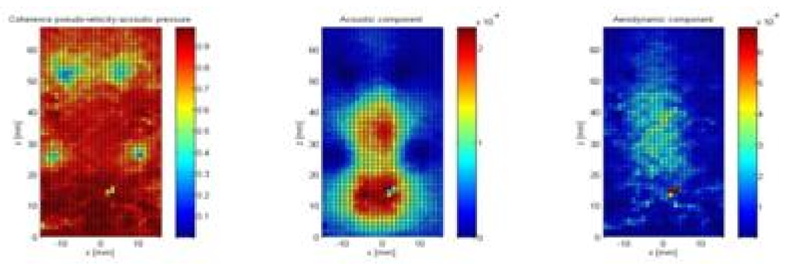


Figure 3. Pseudo-velocity amplitude and phase distributions at the vortex street frequency of 5388 Hz± 50 Hz RMS and 16880Hz ± 50 Hz RMS



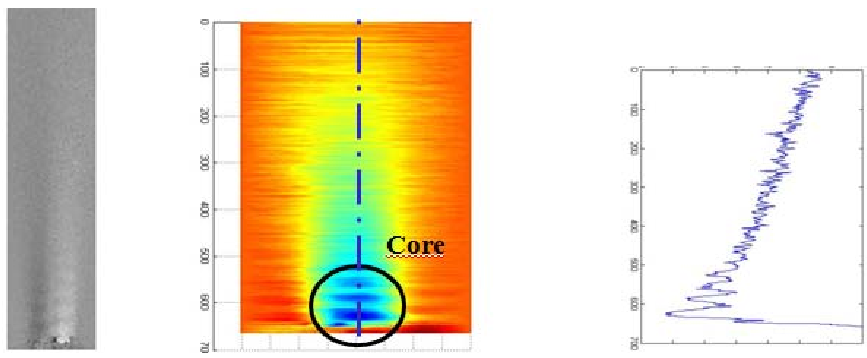
(a) (b) (c)

Figure 4. Maps of the coherence between pseudo-velocity and reference microphone distribution (a), of the acoustic component (b) and of the aerodynamic component (c) of the pseudo velocity amplitude at the vortex street frequency of 2929 Hz ± 50 Hz RMS

The component of the pseudo-velocity coherent with the reference microphone, i.e. the acoustic component, and the residual part, i.e. the aerodynamic component are reported together with the coherence map between the pseudo-velocity and the acoustic pressure are shown in Fig4. It can be noticed that the acoustic component is located in the core region, while the aerodynamic one in the mixing region, that starts at about 5 diameters from the nozzle exit.

Shearography analysis of results

In the next figures the results relative to the shearography approach are reported. In the map of the shear signal you can see the core of the jet and the vortex street. Now no control over the timing of integration of image development needs of specific HW.



(a) (b) (c)

Fig.4 filtered image(a)an interferometric image linked to the density distribution of jet (b)and profile of the signal along the axis of the jet shear(c)

Beamforming analysis of results

The acoustic power distributions calculated at the vortex street frequency and its harmonics averaged on a frequency bandwidth of ± 50 Hz..The system is capable to recognize the noise emitted at the nozzle exit region, with the typical resolution of the up to 12 kHz. For the higher frequency range spatial aliasing effects are visible.

Acoustic holography of results

The system provides a good location of the jet (monopole)but has limit high-frequency and in near-field assumption is not respected.

4 Conclusions

It can be concluded that among the above listed techniques, the TLI measurement is a very good one as it provides extremely detailed information in terms of high resolution frequency analysis. The application of TLI combined with acoustic measurement using a reference microphone placed in the field near the jet exit, allows the development of a consistent analysis extrapolating the jet aeroacustic behavior only. The analysis time for this type of survey is extremely long. The shearography technique provides information about the jet behavior in low-frequency state. The measure is quite fast but it has limitations in terms of frequency bandwidth. No control over the timing of integration of image development needs of specific HW.

The technique of measurement in far field beamforming provides a good source of localization through a quick view, but it does presents important limitations on the spatial resolution. In the acoustic holography technique trough planar STSF (Spatial Transformation of Sound Field) in the near field, the assumptions about the STSF, i.e., having unrelated sources, are not met and this do not allow accurate measurements. That inaccuracy can be attributed to the fact that assumptions STSF is based on are not completely fulfilled.

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