Experimental investigation of the Near-Field Noise generated by a Compressible Round Jet

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Abstract. An experimental study of the pressure field generated by a subsonic, single stream, round jet is presented. The investigation is conducted in the near-field region at subsonic Mach numbers (up to 0.95). The main task of the present work is the analysis of the near-field acoustic pressure and the characterization of its spectral properties. To this aim, a novel post-processing technique based on the application of wavelet transforms is presented. The method accomplishes the separation of nearly Gaussian background fluctuations, interpreted as acoustic pressure, from intermittent pressure peaks induced by the hydrodynamic components. With respect to more standard approaches based on Fourier filtering, the new technique permits one to recover the whole frequency content of both the acoustic and the hydrodynamic contributions and to reconstruct them as independent signals in the time domain. The validity of the method is verified through several tests on measured signals and comparisons against literature data. The near field acoustic pressure is analyzed in terms of spectral content, Sound Pressure Level and directivity and the results are compared to published far-field observations. Simultaneous velocity/pressure measurements have been also performed using a hot wire probe located in the region close to the nozzle exit. The analysis of the velocity/pressure correlations clearly shows that the main noise sources are located close to the end of the potential core while the largest hydrodynamic pressure peaks are generated further downstream.

1. Introduction

The problem of noise generation by turbulent compressible jets has been of great interest since the early 1950s when the first jet engines were installed on commercial aircraft and even later when quieter high bypass ratio turbofan engines were adopted. Since that time, considerable research activity has been undertaken to understand the generation and propagation of jet noise, as well as to devise techniques for its reduction. The jet mixing noise is one of the stronger sources of the aircraft engine total noise and it has historically received the most attention since the Lighthills works. In the Lighthills analogy (Lighthill 1952-1954) the noise is a result of the fluctuating Reynolds shear stress. The community noise, also defined as far-field noise, is well described by the acoustics models. In the jet noise the convection of the sources downstream the flow has the effect to give a significant directivity to the jet noise. In fact, the far-field noise
presents a maximum angular direction, with a maximum direction around 140 - 150 (defining 180 downstream the jet axis). The near-field noise, that influences passengers comfort, on the contrary, seems to be different and not so well described by acoustics models. The near pressure field investigation of an unbounded jet has been the subject of a considerable number of experimental and theoretical investigations over the past 60 years to understand flow-dynamics and its sound production and propagation. Howes (1960), Ffowcs-Williams (1992) and Ribner (1964) describe the presence of pressure fluctuations, called pseudo-sound, in the near-field that are not sound but are undistinguishable, using a microphone, from the sound. In fact, when sound is generated by an unsteady flow, only a small part of the energy associated with pressure fluctuations radiates as sound and the main pressure fluctuations masks sound field near the jet. A filtering method to separate sound from pseudo-sound is necessary to compare the far-field with the near-field noise and it is also useful for noise-control applications. Ffowcs-Williams (1992) writes: It is only when the pressure satisfies this equation (He refers to the wave equation: rev.) that it is properly regarded as sound. Other pressure fluctuations, indistinguishable by a single microphone from proper sound, have been termed Pseudo Sound, only pseudo because they lack some essential characteristics of sound. They do not propagate through the fluid but are convected with the eddy structures in the flow, often in chaotic path and usually with a speed very much smaller than the sonic velocity. The pseudo-sound is convected with eddies and does not propagate, it is the rotational part of the flow; instead the sound propagates with the sound speed. When a measure is performed in the near-field the acoustical contribution is affected by the hydrodynamic one, a microphone is subjected to fluctuations both of the sound both of the pseudo-sound (Howes 1960). Considering the different nature of the two parts of the pressure fluctuations the main aim of this work is to filter the two contributions from a near field signal. The pseudo-sound is associated to the convection of structures through the flow and for this reason carries information on the coherent structures, it has to convect with a speed smaller than the sound; the remaining part is the sound and it is associated to the incoherent part of the pressure fluctuations. Usually a Fouriers based filter is used to distinguish the two parts but this is not efficient because, for its nature, this filtering is equivalent to a high-pass and low-pass filtering, in fact the Fourier transform is located only in the frequency domain. Sound and pseudo sound may have energy to the same frequencies and filtering only in the frequency domain is not sufficient for a complete signal splitting. For this reasons a Wavelet filtering tool is performed, the Wavelet transform is located both in the frequencies both in the time domain and the signal splitting is possible considering the intermittency of events; in fact, using the wavelet, is possible to separate the inter-mittent events from the rest of the signal; the coherent structures pass through the microphone at intermittent intervals and the remaining signal is related only to the acoustic field.

2. Wavelet Decomposition: A novel approach

Comprehensive reviews of the theory and application of wavelets can be found in many reference papers or books (e.g. Mallat, 1989, Daubechies, 1992, Farge, 1992) to which the reader can refer to clarify general mathematical aspects. Of interest for this work is the application of wavelet transform to analyze pressure signals such as the wavelet–based studies of wall pressure fluctuations induced by attached or separated turbulent boundary layers (e.g. Poggie & Smiths, 1997, Lee & Sung, 2002 and Camussi, Robert & Jacob, 2008) and the wavelet-based investigation of the wall and far field pressure induced by an airfoil in a tip-leakage configuration, recently presented by Camussi et al (2010). To the best of our knowledge, the only wavelet analysis of near field pressure in a turbulent jet is the study by Ukeiley & Ponton (2004). In this work, the pressure signals are represented in the wavelet domain to highlight the intermittent nature of the hydrodynamic component. In the present approach the wavelet transform is used to set
up a procedure able to extract the acoustic contribution from a pressure signal dominated by hydrodynamic effects, as is the case of the near field pressure of a transonic jet. The wavelet transform of a pressure time series \( p(t) \) consists of a projection over a basis of compact support functions obtained by dilations and translations of a given function, the so called Mother Wavelet \( \Psi(t) \), localized both in the time domain and in the transformed space. The resulting wavelet coefficients \( w \) are functions of the translation time \( t \) and the resolution time scale \( r \), whose inverse is proportional to the frequency \( f \). The formal representation of the wavelet transform is the following:

\[
w(r,t) = C_{\Psi}^{-1/2} \int_{-\infty}^{+\infty} \Psi^* \left( \frac{t - \tau}{r} \right) p(\tau) d\tau
\]  

where \( C_{\Psi}^{-1/2} \) denotes a coefficient that accounts for the mean value of \( \Psi(t) \), and the integral represents a convolution between \( p(t) \) and the dilated and translated complex conjugate counterpart of \( \Psi(t) \). In the present approach, the wavelet transform is performed using the Matlab Wavelet Tool and the selection of orthogonal discrete wavelets in order to ensure the invertibility condition that, as clarified below, is a fundamental requirement for the present application. The orthogonal wavelet transform is based upon a multiresolution analysis that gives successive approximations of the field at different resolutions, from the smallest scale (twice the sampling time) to the largest. This corresponds, in principle, to the whole signal length. In this approach the wavelet coefficients are arranged in a dyadic distribution to guarantee orthogonality (see e.g. Mallat, 1989, for the details). The filtering procedure adopted therein is similar to that which Farge (1992) and Ruppert-Felsot et al (2009) proposed for separating coherent structures from fully turbulent fluctuations. As pointed out above, a near-field pressure signal has to be considered as a combination of acoustic fluctuations and hydrodynamic or pseudo-sound contribution induced by the eddy structures. We assume that the hydrodynamic contribution, being related to localized vortices, compresses well into a wavelet base and can be represented by only a few strong wavelet coefficients. In contrast, the acoustic counterpart is given by the remaining weaker coefficients corresponding to the incoherent background which is homogeneous and does not compress well. According to this idea, the part of the signal associated with pseudo-sound can be extracted by selecting the wavelet coefficients exceeding, in absolute value, a proper threshold. The thresholding procedure enables the wavelet coefficients to be separated into two sets: coefficients above the threshold, denoted as \( w_h \), correspond to the pseudo-sound or hydrodynamic part of the signal; those having magnitude lower than the threshold, denoted as \( w_a \), correspond to sound, i.e. to the acoustic part of the signal. Thanks to the orthogonality of the wavelet base adopted the two wavelet sets can be anti-transformed and the sound and pseudo-sound contributions reconstructed in the physical space as two distinct signals, denoted as \( S_a \) and \( S_h \) respectively. Once available, these two signals can be analyzed through standard processing tools including Fourier analysis. From the above discussion it is apparent that the selection of the threshold level plays a fundamental role in our approach. This selection is accomplished through an iterative process that highlights the acoustic or hydrodynamic nature of the reconstructed signals in terms of their typical propagation velocity. The procedure requires the simultaneous acquisition of two pressure signals by a microphone pair. The microphones should be located in the near field and sufficiently close to each other to permit an hydrodynamic perturbation to be sensed by both transducers within a measurable time delay. The propagation velocity can then be measured by the location in time of the peak of the cross-correlation between the two signals and this information is used to select the threshold applying the the following procedure:

1) An initial value of the threshold amplitude is guessed
2) The – first guess – signals \( S_a \) and \( S_h \) are extracted from each microphone signal
3) The cross-correlations between the two acoustic parts of the signals and the two hydrodynamic parts are computed.

4) Three conditions have to be satisfied to complete the iterations:

(i) the temporal location of the peak of the cross-correlation between the hydrodynamic components of the two signals has to correspond to a convection velocity equal to or lower than the flow velocity.

(ii) the temporal location of the peak of the cross-correlation between the acoustic components of the two signals has to correspond to a propagation velocity equal or larger than the speed of sound.

(iii) the first and second peak ratio of the cross-correlation between the hydrodynamic components of the two signals must be higher than a convenient value, typically representative of the signal-to-noise ratio.

5) If the criteria of point 4 are not satisfied, the threshold is incremented by a discrete quantity and the process re-starts from point 2.

The first guess of the threshold value is set according to classical wavelet based denoising procedures used to remove Gaussian white noise (for details see Donoho & Johnstone, 1994, Ruppert-Felsot et al., 2009) and it is found that the iterative process converges after a few (order of 5) steps.

Examples of cross-correlations, spectra and cross-spectra demonstrating the validity of the adopted approach are given in Sec. 4 together with a physical interpretations of the results.

We finally point out that several tests have been performed to verify that the results are not dependent upon the choice of the wavelet type. This is due to the fact that the events are discriminated on the basis of their localization and not on their shape. After those tests, following the procedure of Ruppert-Felsot et al. (2009), the wavelet kernel selected was the Coifman 12 type.

3. Experimental Setup and Jet Qualification

A semi-anechoic chamber was prepared for this measurement; the walls and the top of the room are covered with sound-absorbent panels, a draining space is provided in the wall in front of the nozzle (see Figure 1). The chamber measures 2 m x 4m and the walls (including the roof and the floor) are covered with sound-absorbent panels 10cm in length and backed with wooden insulation. This provides anechoic conditions at frequencies above 500 Hz. During the measurement also the jet, the strut and the main part of the floor were covered with sound-absorbent panels. The jet is connected to the compressed air duct through a pressure regulation valve and a muffler. The jet has two main parts:

1) A duct with honeycomb and nets to avoid undesired turbulence and maintain a uniform flow.

2) A nozzle with an aspect ratio of 44.4 that allow reaching high jet velocities maintaining very low flow speed inside the duct.

Just upstream the nozzle are mounted small static-pressure ducts and thermo-couples for measuring the jet characteristics and calculating the jet velocity, the small diameter of the holes for the sensors (less than 1 mm) doesn't interfere with the flow, in the sensor section the duct diameter is 80 mm and the flow velocity is less than 7 m/s; the nozzle exit diameter is 12 mm. The jet has axial-symmetric flow with a regular top hat profile at the exit (Figure 2 Left), the self-similarity of the velocity profiles in the fully developed region is verified at several distances measuring along some diameters (Figure 2 Right). The potential core end is located where the Kurtosis is maximum along the jet axis, the length is 4 diameters and the axial velocity decreases...
down-stream the potential core just as the turbulence increases (see Figure 3). Also a far-field acoustic qualification is performed; a Brüel & Kjær 4135 microphone is mounted on a wood strut partially covered by acoustic absorbent material to reduce any sound reflection. Using this microphone the far-field is mapped to a distance of 90 diameters and of 120 diameters from the jet, angles from 80 to 160 are covered with steps of 5 - 10, the measurements are performed at Mach numbers of 0.5 and 1. The OASPL directivity (see Figure 4) and the sound spectra (see Figure 5) match with literature data and with two sources theory (Tam et al 2008).

4. Near-field pressure fluctuations: Sound and Pseudo-Sound

The near-field tests were performed at Mach=0.5 using simultaneously a couple of B&K 4135 microphones mapping a planar zone from 1 to 7 diameters in the radial direction and from 0 to 22 diameters in the axial direction with an angle of 10 respect the jet axis; the microphones are mounted on a wood strut that moves to the measurement points maintaining microphones to a distance of 14 mm. As previous mentioned a microphone in the near-field measures both
Figure 3. (Left) Axial velocity decrease profile (blue) and axial turbulence increase (red). (Right) Skewness and Kurtosis along the jet axis: the potential core end (4D) is located at the maximum Kurtosis.

Figure 4. Far-field OASPL for 90D and 120D from the jet: Mach=1 OASPL shows a maximum directivity near 145; this maximum directivity in the mach=0.5 OASPL is near 140.

Figure 5. Mach=1 Far-field spectra comparison: as described in two sources theory (Tam et Al. 2008) at low angles (Left) there is a typical fine scale spectrum (as defined by Tam) and at high angles (Right) there is a typical large scale spectrum.
Figure 6. Near-field pressure fluctuations: OASPL of the unfiltered signal

Figure 7. Original spectrum divided in Sound and Pseudo-sound spectra

sound and pseudo-sound (Ffowcs-Williams 1992), so the acoustic field is hidden by the pressure fluctuations that are convected with eddies, in fact there isn’t the typical directivity in the measured near-field and the levels seem parallel to the jet streamlines (see Figure 6). Applying the previous described wavelet filtering algorithm is possible to split the pressure signals in two contributions: the sound signal and the pseudo-sound signal, this filtering is different to the Fourier transform filtering because the filtered signals can exist at the same frequencies. In the Figure 7 the spectra of the complete, Sound and Pseudo-sound signals are shown: in this point for example the sound has more energy at high frequencies but is evident that the two signals coexist at same frequencies even if with different energies. In the Figure 8 the OASPL of the pseudo-sound signal is shown, its propagation direction is parallel to the jet shear layer and presents a conical shape, the top-left angle is less influenced by the jet and the flow is almost undisturbed and the OASPL is very low. Considering only the Sound component of the signal the directivity is evident: in the Figure 9 the OASPL of the acoustic fluctuations is shown, the Sound has maximum intensity propagation between 130 to 150 as usually shown in the far field directivity. In the Figure 9 is also evident a relative silent zone where the OASPL is 15 - 20 dB lower than the rest of the field, this is a peripheral part of the cone of silence (Tanna 1977).
Figure 8. OASPL of the pseudo-sound component: in the top-left angle the correlation of the pseudo-sound signals is weak because that zone is low influenced by the main flow

Figure 9. Sound OASPL: the sound propagates principally from 130 to 150; above 160 the cone of silence is evident

5. Sound sources localization

Another advantage of the proposed wavelet filtering is the possibility to obtain both sound and pseudo-sound signals without the loss of the phase; for this reason hot-wire and acoustic synchronized measurements are performed. The target is to obtain velocity, sound and pseudo-sound contemporary time history and correlate velocity with pressure signals to find the zones of the jet that more contribute to the noise generation. Two B&K microphones are positioned around 7D position on the jet axis with a radial distance about of 4D, the microphones are positioned in a transition zone where the energies of the sound and of the pseudo sound are similar; the jet plane is mapped with a hot-wire probe on a grid along a plane of symmetry simultaneously with the sound measurements. The data from the microphones, filtered to obtain sound and pseudo-sound signals, are correlated with the anemometric data from the h-w, from the correlation peak distribution is possible to locate the zones of sound emission and the zones that generate the pseudo-sound pressure fluctuations. As shown in Figure 10 Top, the maximum
correlation values are in the potential core with higher peak values at the end of the core that is a zone of strong fluctuations; this confirms the observations of Hileman et al (2005) and of Grassucci et al (2010) that locate the maximum noise emission at the potential core end where the core contractions are a noise source mechanism. The H-W with Pseudo-Sound correlation (see Figure 10 Bottom) confirms that all the field contributes at similar levels with this pressure fluctuations; there are two zones of higher correlation values that are at the start of the potential core and in a downstream axial zone. The first zone, near the nozzle borders, depends to the vortices release; the second zone (X=6D 9D) needs further in-vestigations but is also present in Kerherv et al (2008) and in Grassucci et al (2010).

6. Conclusions
In this work, near-field acoustic measurements were performed around a compressible round jet at Mach numbers spanning from 0.5 to around 1. The main scope of the work is the analysis of the acoustic pressure in the near field that originates the acoustic waves propagating in the far field. To this aim, a novel signal analysis procedure based on the application of the wavelet transform to pressure time series, has been developed. The main idea of the method relies on the evidence that, despite the acoustic counterpart, hydrodynamic pressure fluctuations exhibit a local nature and thus compress well over a wavelet basis. The hydrodynamic and acoustic components can then be extracted from a pressure signal by selectively filtering the wavelet coefficients and by anti-transforming the resulting filtered coefficients set. The separation between sound and pseudosound is accomplished by selecting a threshold whose amplitude is determined on the basis of the pressure perturbation propagation velocity. This quantity is computed from the maximum of the crosscorrelation between the filtered components of two pressure signals measured simultaneously. The application of the technique therefore requires the simultaneous acquisition of pressure time series from two microphones positioned close to each other in the near field. Several measurements have been performed to asses the method and extract relevant properties of the near acoustic field. The statistical properties of the acoustic and hydrodynamic components of the acquired signals, indeed show the expected behavior in terms of cross-correlations, spectra shape and pressure levels. Concerning the spatial variation of the acoustic/hydrodynamic pressure field, it has been shown that the prefential radiation direction of the acoustic pressure is located at angles that, with respect to the flow axis, are larger that those of the hydrodynamic counterpart. The signature of the cone of silence has been indeed evidenced as the main directivity feature of the acoustic near field. Simultaneous velocity-pressure measurements permitted us to determine the flow regions exhibiting maximum correlation levels with the acoustic or hydrodynamic components of the pressure signals. In the acoustic case, the largest correlations are determined at the end of the potential core. Conversely, the largest hydrodynamic pressure-velocity correlations are located close to the nozzle exit and in the far region, between x/D = 6 and x/D = 9, where the shear layer surrounding the potential core rejoins on the jet axis. The present analysis contributes to shed light on the properties of the nearfield pressure. However, the intimate nature of the sources of acoustic and hydrodynamic pressure in the nearfield is still unclear and the elucidation of this aspect remains a challenge for future studies.

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Figure 10. Hot-Wire velocity Microphones correlation: cross-correlation with the Sound signal (Top); cross-correlation with the pseudo sound signal (Bottom)
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