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Intermittency and stochastic modelling of low and high Reynolds number compressible jets

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I. Nomenclature

| | | |
|---------------------|---|--|
| M | = | jet Mach number |
| Re | = | jet Reynolds number |
| x | = | stream-wise spatial coordinate |
| r | = | radial spatial coordinate |
| D | = | nozzle exhaust diameter |
| $w(s, t)$ | = | Wavelet transform |
| N_{int} | = | number of intermittent events |
| $N_{samples}$ | = | number of samples |
| f_{KH} | = | Kelvin-Helmholtz frequency |
| St_{KH} | = | Kelvin-Helmholtz Strouhal number |
| A_{KH} | = | Kelvin-Helmholtz spectral amplitude |
| $\langle A \rangle$ | = | mean amplitude of the selected intermittent events |
| St_{int} | = | Strouhal number related to the intermittent events |
| PSD | = | power spectral density |
| Δt | = | time between two consecutive intermittent events |
| PDF | = | Probability Density Function |
| $\sigma_{\Delta t}$ | = | standard deviation of the time between two consecutive intermittent events |
| σ_A | = | standard deviation of the events amplitude |

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II. Introduction

Subsonic jet noise has been a hot topic in the last 50 years because of its relevance in the design of modern civil aircraft tackling the problem of minimizing the noise impact. Since the publication of the Lighthill's famous paper [1], many researchers investigated jet induced pressure fluctuations both in the near-field and in the far-field in the attempt of developing models able to predict as accurately as possible the emitted noise. There is a large body of literature that seeks to clarify the nature of pressure events that dominate both fields. The pressure fluctuations in the near field are influenced by vortical structures generated in the jet shear layer (see [2, 3] and the recent paper by Andres, Pamoschou and Bogey [4]) and, according to the typical statistics of vorticity in turbulence, they exhibit a non Gaussian intermittent behaviour. In a statistical sense, intermittency is intended as a sequence of quiescent phases interrupted by active events inducing a non-stationary distribution of energy in time. As shown by the seminal experiment undertaken by Juvé et al. [5] and by numerous successive studies (e.g. [6–11]), intermittency is a key mechanism in the generation of jet noise and, as shown by several recent papers (see among many, [12–14]) the related turbulence non-linearities are recognized to play a relevant role in the acoustic radiation (see also [15] and [16]).

The results reported by Kearney-Fischer et al. [17, 18] further support the idea that intermittent events are the dominant feature of jet noise. They applied a method to extract the events and developed stochastic models to reproduce their statistics in both the physical and the Fourier domains. A similar approach was adopted by Camussi et al. [19, 20] who used wavelet transform to select intermittent events from experimental data and proposed stochastic models to reproduce their relevant statistics. These analyses provided a direct measure of the degree of intermittency contained in the pressure field induced by compressible jets.

The main objective of the present work is to assess and validate the model proposed in [19, 20] by processing a pressure database obtained numerically. The experimental data analyzed in [19, 20] consisted of pressure fluctuations measured through a single linear array in the near field of a compressible jet for Mach number spanning from 0.5 to 0.9 at a single high Reynolds numbers (of the order of 10^5). The numerical database analyzed therein provides pressure in a very large number of axial and radial positions in the near field, allows for the analysis of different Reynolds numbers at the same high subsonic Mach number and includes the 0-order axi-symmetric mode, extracted through a Fourier azimuthal decomposition of the pressure signals. The paper in [21] analyzes the same numerical database as the present one through the computation of a time-frequency version of the Flatness Factor, a procedure that, as will be clarified below, is different with respect to the one used in the present paper that replicates the approach adopted in [19, 20]. The present paper therefore represents a definite validation of the stochastic models proposed in [19, 20], extending them to a broader range of flow conditions and to the statistics of the 0-order axis-symmetric mode, which is of specific relevance because of its relationship with the jet noise.

The paper is organized as follows: section II reports the numerical setup and the post-processing procedure, results are discussed in section III, whilst final remarks are presented in section IV.

III. Numerical setup and post-processing procedure

A. Numerical setup

The database analyzed has been obtained numerically through DNS and LES of two single-stream circular jets, having respectively diameter-based Reynolds numbers of 3,125 and 100,000 and Mach number 0.9. Both jets originate from a pipe nozzle of diameter D into a medium at ambient temperature and pressure of 293 K and 10^5 Pa respectively and the potential core length is equal to $7.3D$ for both jets (see [22] for the details). The simulation times after the transient periods are equal to $500D/U$ for the high Re jet and to $1,000D/U$ for the low Re jet where U is the jet exit velocity. Pressure time series are obtained for the azimuthal angles that varies from 0 up to 315° by step of 45° for the high Re jet and from from 0 up to 270° by step of 90° for the low Re jet. Signals are recorded at a sampling frequency allowing spectra to be computed up to $St_D = 6.4$. More details about the numerical simulations are reported in [22–24]. Pressure and velocity fluctuations are extracted from virtual probes positioned in the near field of the jets (of diameter D) displaced along the longitudinal (x) and radial (r) directions.

The following table reports the location of the virtual probes considered for the present analysis:

| M | Re | x/D | r/D |
|-----|--------|---------------------------------|-----------------------------------|
| 0.9 | 10^5 | from 1.5 up to 9 by step of 0.5 | from 0.5 up to 1.5 by step of 0.5 |
| 0.9 | 3,125 | from 1.5 up to 9 by step of 0.5 | from 0.5 up to 1.5 by step of 0.5 |

It can be observed that the study is limited to a domain close to the jet exit, usually recognized as the noise-producing region of the jet flow and thus of interest for jet–noise modelling. To this purpose, the original pressure signals are also represented in terms of their azimuthal components through the azimuthal decomposition of the Fourier modes. This approach has been extensively used in the past to extract relevant features connected with the jet noise generation [25]. The wavelet-based statistical analysis is thus applied also to the axi-symmetric mode of order 0, that is known to dominate the sound field for low polar angles [26].

B. Post-processing procedure and the reference stochastic model

As performed in [19], the signals are analyzed using a wavelet-based approach. The wavelet decomposition allows for the simultaneous representation of a temporal signal in terms of a time shift (τ) and a resolution time scale (s) whose inverse corresponds to the frequency (f). Formally, the wavelet transform of the signal $p(t)$ is given by the following expression [27]:

$$w(s, t) = C_\psi^{-\frac{1}{2}} s^{-\frac{1}{2}} \int_{-\infty}^{\infty} p(\tau) \psi^* \left(\frac{t - \tau}{s} \right) d\tau \quad (1)$$

where s is the wavelet scale, τ is the time shift, $C_\psi^{-\frac{1}{2}}$ is a constant that takes into account the mean value of $\psi(t)$ and $\psi^*\left(\frac{t-\tau}{s}\right)$ is the complex conjugate of the dilated and translated mother wavelet $\psi(t)$. In this analysis, we applied the continuous wavelet transform (CWT) using the Morlet mother wavelet.

A relevant outcome of the wavelet transform is the wavelet scalogram, given by the square of the wavelet coefficients. An example is reported in figure 1(a) obtained by analyzing the pressure data taken at $x/D = 2$, $r/D = 1$ and $Re = 10^5$. It provides a decomposition of the energy onto the (f,t) plane, thus allowing us to determine the time evolution of energetic features contained in the signals (see e.g. [28]). Indeed, it should be pointed out that the Fourier power spectral density of the signal can be retrieved by integrating the scalogram into the time domain and an example of a comparison between the Fourier and the wavelet-reconstructed spectra is provided in figure 1(b) showing a striking agreement.

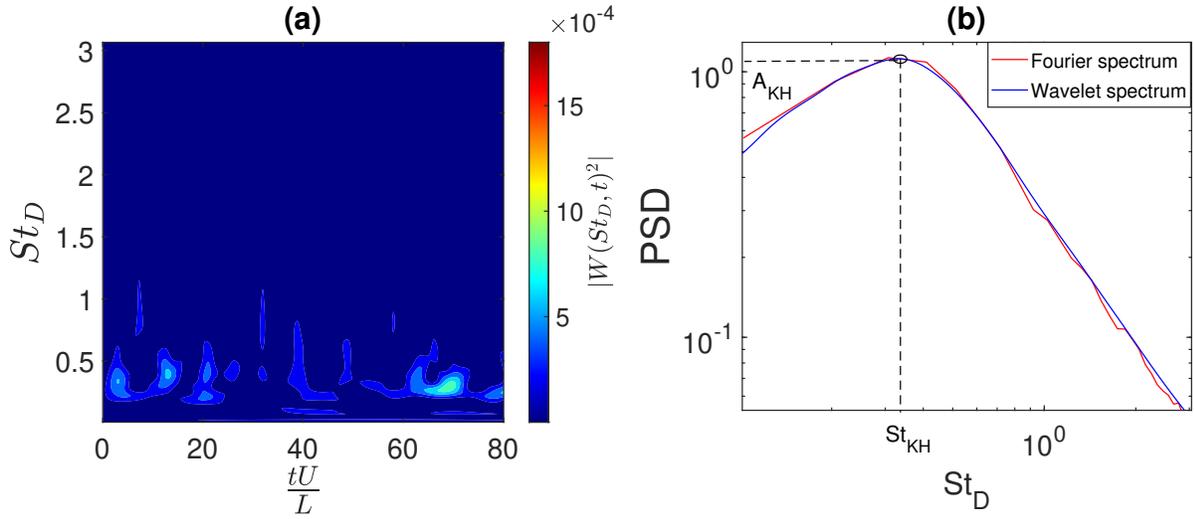


Fig. 1 (a) Wavelet scalogram at $x/D = 2$ and $r/D = 1$; (b) comparison between the Fourier spectrum and the wavelet-reconstructed spectrum obtained by integrating the wavelet scalogram .

In jets, in the region close to the nozzle exit, a spectral bump can be clearly identified especially for laminar exit conditions. It is the trace of the Kelvin–Helmholtz instability mode and the corresponding frequency and spectral amplitude are hereinafter defined as f_{KH} and A_{KH} respectively.

The quantity used to identify intermittent events is the so-called Local Intermittency Measure (LIM) that represents a normalized version of the wavelet scalogram. Its formal definition is the following:

$$LIM(s, t) = \frac{w^2(s, t)}{\langle w^2(s, t) \rangle_t}, \quad (2)$$

where $w^2(s, t)$ are the wavelet coefficients evaluated with eq.(1) whilst the symbol $\langle \dots \rangle_t$ indicates time average. According to [19, 20], the LIM is computed at the wavelet scale corresponding to f_{KH} and the condition $LIM > 1$ is used to identify intermittent events having a local energy greater than the average.

The approach adopted therein is the one presented in [20] that provides a characterization of the statistics of the quantities Δt , the time between two consecutive intermittent events, defined as intermittent time, and A , the event energy amplitude retrieved from the square of the corresponding wavelet coefficient. The model provides analytical approximations of the PDFs of the normalized reduced variables Δt^* and A^* that are defined as follows:

$$\Delta t^* = \frac{\Delta t - \langle \Delta t \rangle}{\sigma_{\Delta t}} \quad (3)$$

$$A^* = \frac{A - \langle A \rangle}{\sigma_A} \quad (4)$$

where $\sigma_{\Delta t}$ and σ_A are the standard deviations of the time interval of intermittent events and the standard deviations of the events' amplitude, respectively.

The functions proposed in [20] consist of an hyperbolic secant to approximate the PDF of Δt^* and a decaying exponential function for the PDFs of A^* :

$$PDF(\Delta t^*) = a_1 \operatorname{sech}(b_1 \Delta t^*), \quad (5)$$

$$PDF(A^*) = a_2 e^{-b_2 A^*}, \quad (6)$$

The validity of these functional forms will be assessed in the following.

IV. Results

An interesting statistical parameter extracted from the wavelet-based tracking procedure is the number of events that satisfy the condition $LIM > 1$ and thus are classified as intermittent. The number of intermittent events, denoted as N_{int} , depends on the flow conditions considered and on the position of the selected virtual probe. As shown in figure 2, N_{int} decreases for increasing axial distances, indicating that intermittency is a relevant feature of the region close to the jet exit where, mainly at low Re , the flow is quasi-periodic and is dominated by the Kelvin-Helmholtz instability mode. Intermittency also decreases for increasing radial distances (Figures 2b and 2d) because of the rapid exponential decay of the hydrodynamic pressure.

By comparing cases (a) and (b) (low Re) against (c) and (d) (high Re) it is clear that the number of educed events is comparable for the two Reynolds number. The numbers of events identified at low Re confirms that, in agreement with results by Camussi and Bogey [21], a large degree of intermittency is present even at low Re where the flow is quasi laminar. A similar trend is observed for the statistics of the 0^{th} mode (previously found out using an azimuthal decomposition) reported in Figure 3. Even though the relative numbers of selected events is lower with respect to the full pressure, the 0 mode also shows a decreasing trend of N_{int} with both x/D and r/D whereas it is larger at the lowest Re .

Averaged values of both the intermittent time and the amplitude are computed and are used as reference for the

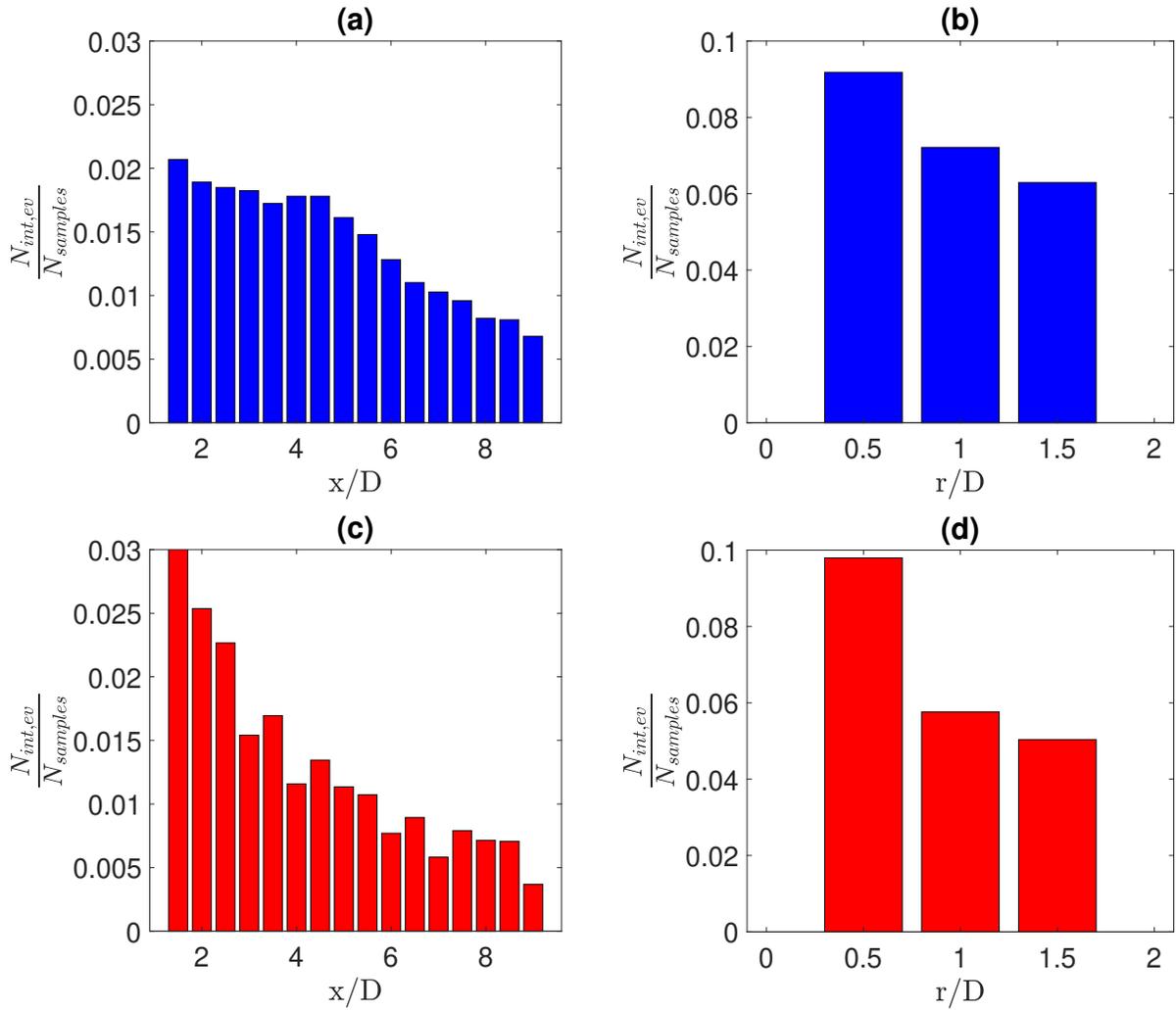


Fig. 2 Number of intermittent events normalized with respect to the total number of samples: (a) as a function of x/D for all r/D and Reynolds number 3,125 ; (b) as a function of r/D for all x/D and Reynolds number 3,125; (c) as a function of x/D for all r/D and 10^5 Reynolds ; (d) as a function of r/D for all x/D and 10^5 Reynolds.

stochastic model. We denote with $\langle A \rangle$ the mean amplitude of the events and, following [20], we define the quantity $\langle St_{int} \rangle$ as the mean intermittent non-dimensional time computed at the K-H frequency and normalized using f_{KH} previously evaluated through the Fourier spectrum.

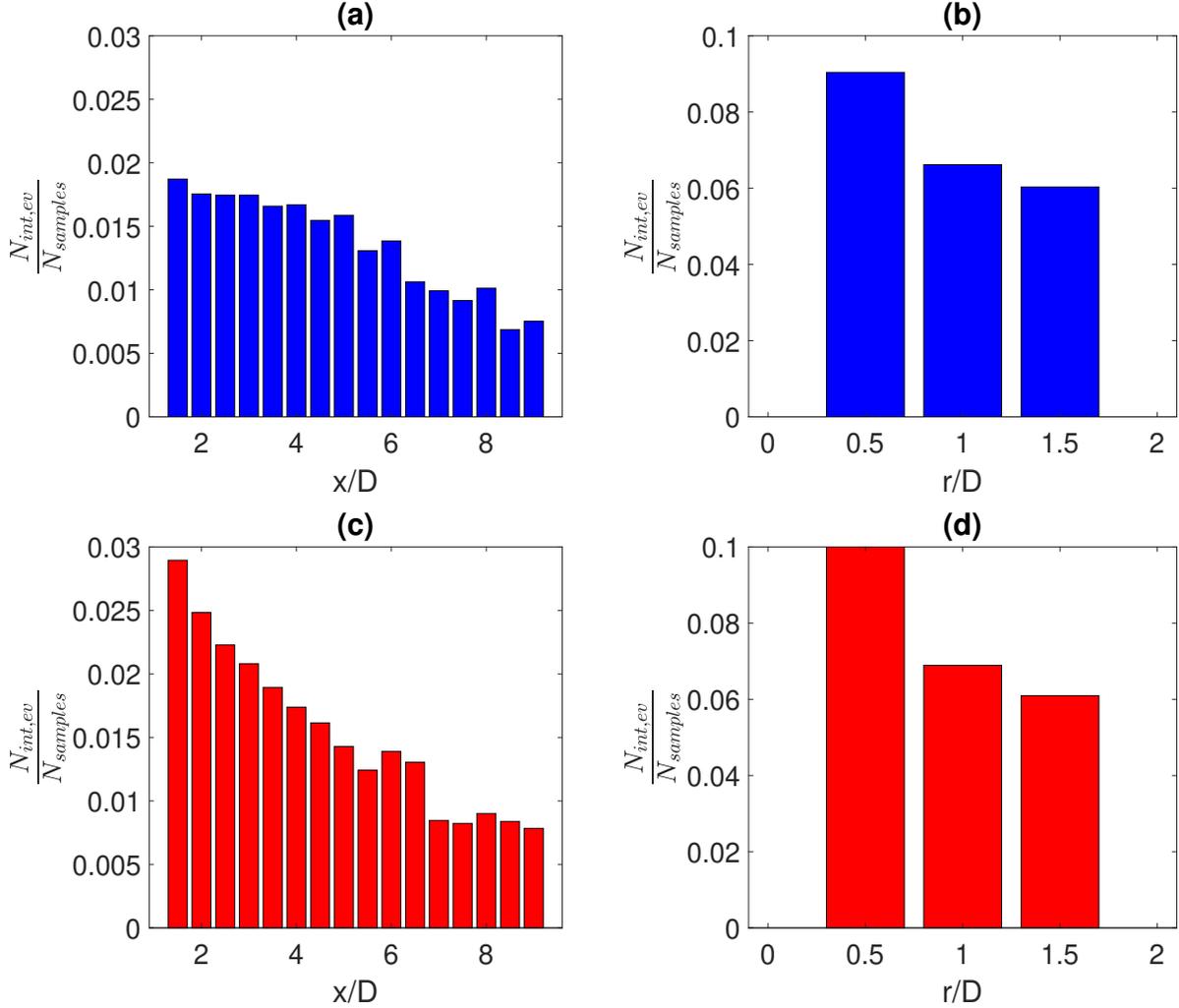


Fig. 3 Same as Figure 2 but for the 0^{th} mode.

We report in figure 4(a) the mean amplitude $\langle A \rangle$ against x/D for the case at low Re . As a first approximation, the averaged amplitude could be considered constant at a reference value that can be computed by averaging the entire set of available data (the solid line in figure 4(a)). As reported in figure 4(b) the mean non-dimensional intermittent time seems not to be constant but it appears as slightly modulated with x/D . This behavior could be ascribed to a slow mean flow distortion generated by the large-scale flow structures [15]. Further studies which include also the jet velocity field are needed to clarify this point and this task is currently underway by the authors.

The results presented in Figures 6 and 7 confirm that also for the 0-mode both the amplitude and the normalized intermittent time are about constant. Also the mean values (the horizontal lines) do not change significantly with respect

to those obtained from the full original signals. This is confirmed by Table 1 and 2 where a summary of the mean values is reported for the original signals and the 0-mode respectively.

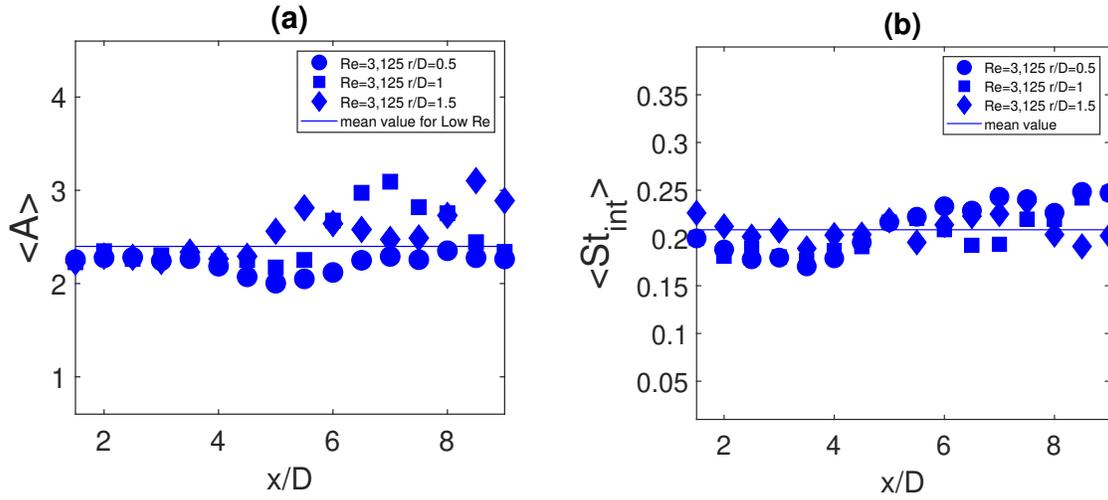


Fig. 4 Axial evolution of (a) $\langle A \rangle$ and (b) $\langle St_{int} \rangle$ at the lowest Re and different r/D .

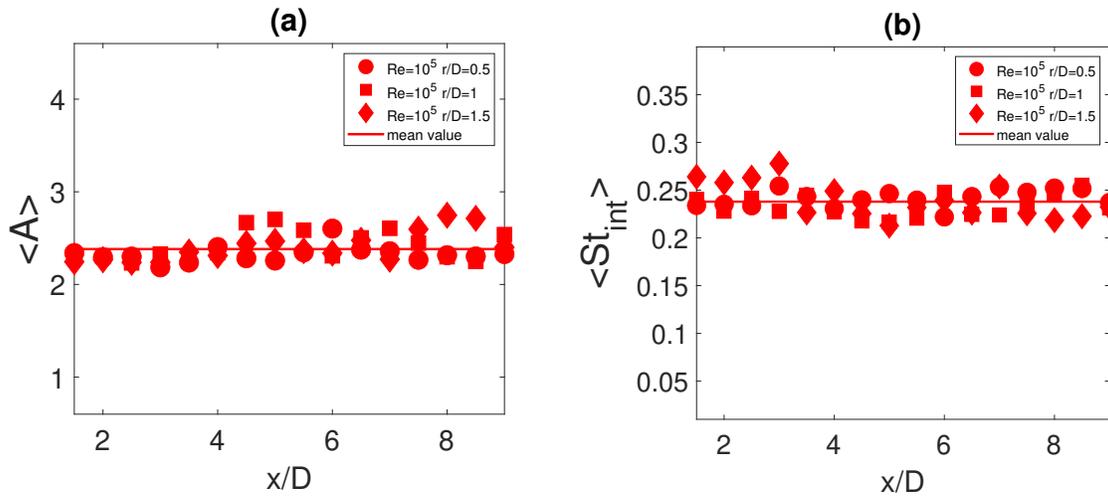


Fig. 5 Same as previous figure but for the highest Re .

| Full pressure signals | Mean |
|--|-------|
| High Reynolds $\langle St_{int} \rangle$ | 0.238 |
| Low Reynolds $\langle St_{int} \rangle$ | 0.208 |
| High Reynolds $\langle A \rangle$ | 2.38 |
| Low Reynolds $\langle A \rangle$ | 2.40 |

Table 1 Statistics of the intermittent events identified in the full pressure signals.

The detailed statistics of the intermittent events are determined by calculating the Probability Density Functions

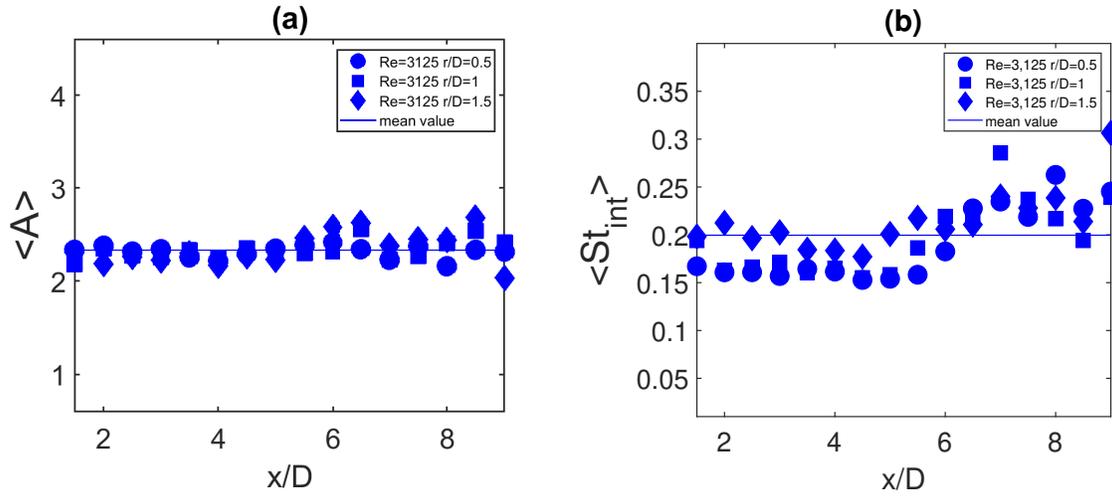


Fig. 6 Axial evolution of (a) $\langle A \rangle$ and (b) $\langle S_{int} \rangle$ at the lower Re and different r/D for mode 0.

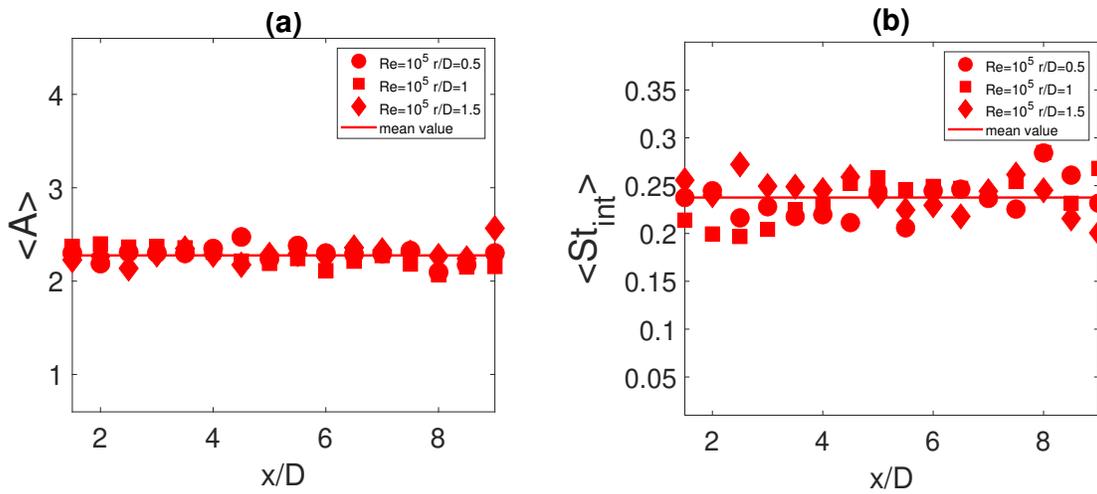


Fig. 7 Same as previous figure but for the higher Re .

| 0^{th} azimuthal mode | Mean |
|--|-------|
| High Reynolds $\langle St_{int} \rangle$ | 0.237 |
| Low Reynolds $\langle St_{int} \rangle$ | 0.199 |
| High Reynolds $\langle A \rangle$ | 2.275 |
| Low Reynolds $\langle A \rangle$ | 2.329 |

Table 2 Statistics of the intermittent events identified in the 0^{th} mode pressure signals.

(PDF) of Δt and A . The main purpose of this analysis is to evaluate the dependence of these PDFs, both for the whole pressure signals and for the 0^{th} mode, upon the considered flow parameters (Reynolds number, axial position, radial distance).

Figures 8 (a) and 8 (b) show the PDFs of the variables Δt and A respectively, obtained from the whole set of virtual probes analyzed therein and for both the two Re . The shape of the PDFs does not change significantly with respect to the parameters considered.

The analytical approximations (5) and (6) are displayed in Figure 8 (c) and (d) along with the uncertainty interval estimated from the numerical data dispersion. The amplitude of the uncertainty is low thus confirming the reliability of the model. According to equations 5 and 6, the coefficients of the approximating functions are: $a_1 = 0.56$, $b_1 = 1.337$, $a_2 = 0.44$, $b_2 = 0.92$ that are very close to those reported in [20].

The analysis is completed with the computation of the statistics of the 0^{th} mode counterpart. The PDFs are reported in figures 9(a) and 9(b) whereas the approximating functions and the corresponding uncertainties are given in figures 9(c) and 9(d). The analytical approximations are again those reported in equations (6) and (5), using the coefficients obtained from the fit: $a_1 = 0.58$, $b_1 = 1.3$, $a_2 = 0.41$, $b_2 = 0.82$. These coefficients are very similar to those obtained from the analysis of the full pressure time series.

V. Conclusions

The pressure fluctuations in the near-field of two compressible jets at $M=0.9$ have been characterized in terms of their intermittent degree with the scope of highlighting the dependence on the Reynolds number and the position in the flow. The data used are obtained numerically in a region spanning 9 diameters in the axial and 3 diameters in the radial directions. The pressure data are decomposed azimuthally, and the statistical properties of the 0-mode component are analyzed as well.

A tracking algorithm based on the computation of a wavelet quantity, the LIM, has been applied to extract the most energetic events at the frequency where the Fourier spectra exhibit the hydrodynamic pressure bump correlated to the Kelvin-Helmholtz mode.

By considering the whole set of available data and following the procedure adopted in [20], a Stochastic model

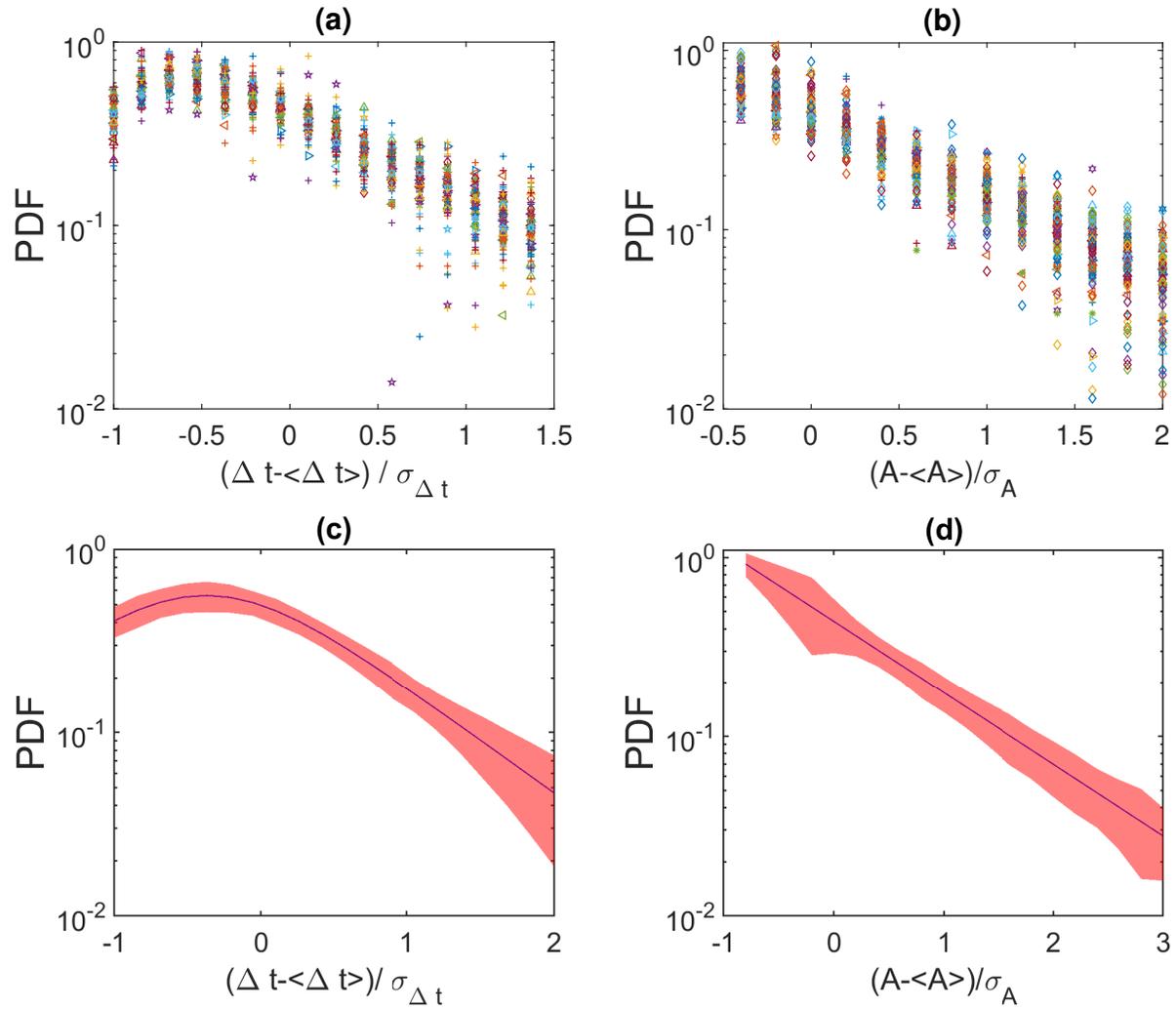


Fig. 8 Probability density functions of the entire database (including both low and high Re): (a) Δt (b) A ; (c) and (d) models (5) and (6) with the corresponding uncertainty.

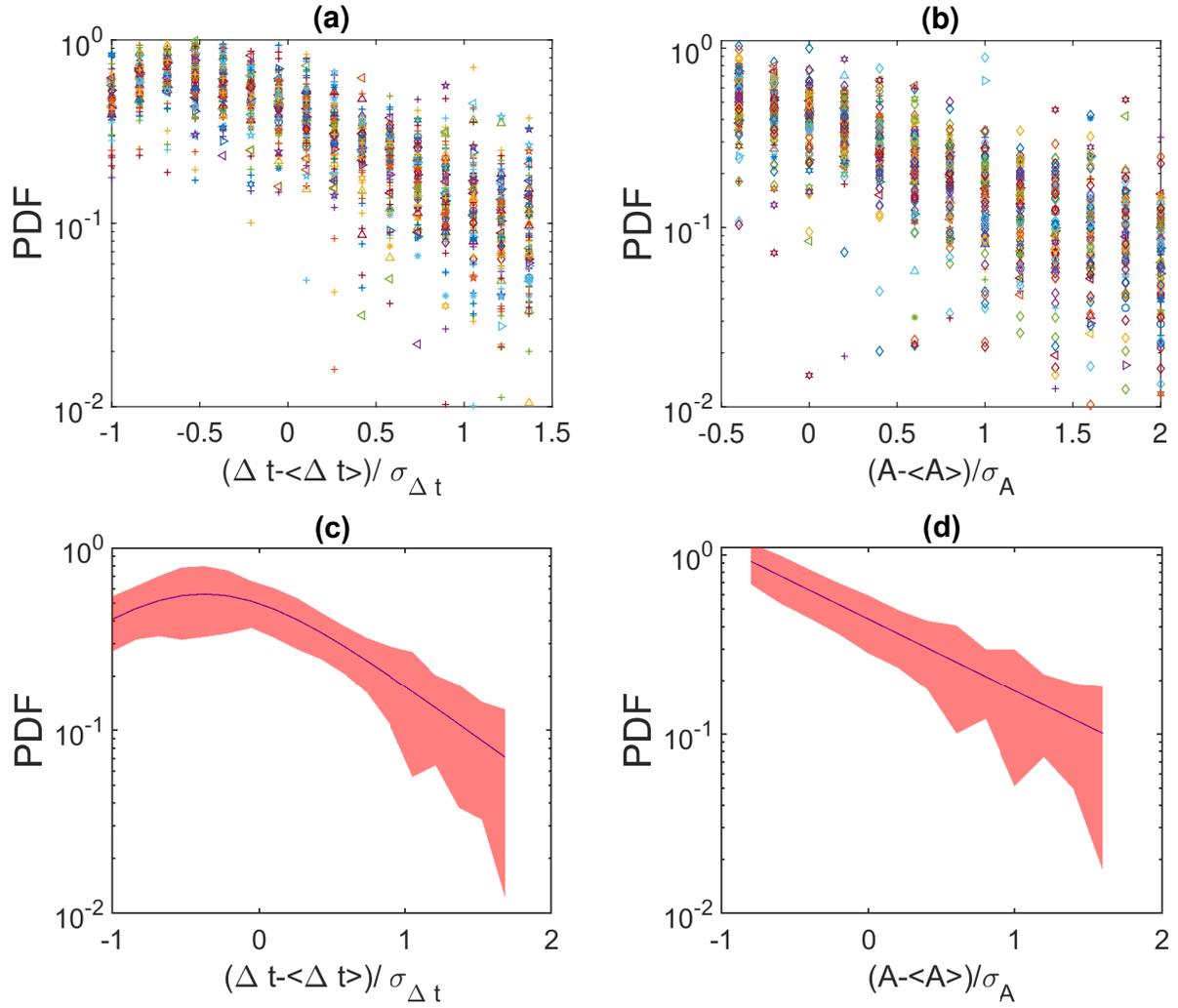


Fig. 9 Probability density functions of the 0^{th} mode for the entire database (including both low and high Re): (a) Δt (b) A (c) and (d) models (5) and (6) with the respectively uncertainty.

is determined by considering the two variables Δt and A denoting the intermittent time and the intermittent event amplitude, respectively. The model and the procedure adopted in the present analysis are exactly the same presented in [20] where the intermittent time statistics were approximated by an hyperbolic secant function and the amplitude statistics by a decaying pure exponential function.

The results presented here, obtained from the numerical database, definitively validate the model originated from the experimental data and, according to [21], demonstrate that even the 0^{th} mode has a significant degree of intermittence. The possible use of the achieved PDFs to predict or correlate jet noise qualitatively, remains an open question. The extracted events are indeed correlated to jet noise production mechanisms because they are associated to the K-H instability and are extracted from the 0th axi-symmetric azimuthal mode. However, the direct estimation of the noise they produce is a non-trivial task. It could be provided, for instance, by using a “stochastic” equation (e.g. a Langevin equation) to model their dynamics or to adjust appropriately the source term of a Lighthill equation. The implementation of this approach is a challenging task that is left for future studies.

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