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Technical Notes

Intermittency and Stochastic Modeling of Low- and High-Reynolds-Number Compressible Jets

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Nomenclature

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

I. 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 Adam et al. [4]), and, according to the typical statistics of vorticity in turbulence, they exhibit a non-Gaussian intermittent behavior. In a statistical sense, intermittency is intended as a sequence of quiescent phases interrupted by active events inducing a nonstationary 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 nonlinearities are recognized to play a relevant role in the acoustic radiation (see also [15,16]).

The results reported by Kearney-Fischer et al. [17] and Kearney-Fischer [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 number (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 zero-order axisymmetric 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 zero-order axisymmetric mode, which is of specific relevance because of its relationship with the jet noise.

The paper is organized as follows: Sec. II reports the numerical setup and the postprocessing procedure, results are discussed in Sec. III, and final remarks are presented in Sec. IV.

II. Numerical Setup and Postprocessing Procedure

A. Numerical Setup

The database analyzed has been obtained numerically through direct numerical simulations (DNS) and large eddy simulations (LES) of two single-stream circular jets, having, respectively, diameter-based Reynolds numbers of 3125 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 $1000D/U$ 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 0 up to 270° by step of 90° for the

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Table 1 Location of virtual probes considered for 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

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.

Table 1 reports the location of the virtual probes considered for the present analysis.

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 modeling. 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 axisymmetric mode of order 0, which is known to dominate the sound field for low polar angles [26].

B. Postprocessing 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]:

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

where s is the wavelet scale, τ is the time shift, $C_\psi^{-(1/2)}$ is a constant that takes into account the mean value of $\psi(t)$, and $\psi^*((t-\tau)/s)$ 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 Fig. 1a 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 Fig. 1b, showing a striking agreement.

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 (K-H) 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:

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

where $w^2(s,t)$ are the wavelet coefficients evaluated with Eq. (1), and the symbol $\langle \ldots \rangle_t$ 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 probability density functions (PDFs) of the normalized reduced variables Δt^* and A^* that are defined as follows:

$$\Delta t^* = \frac{\Delta t - \langle \Delta t\rangle}{\sigma_{\Delta t}} \tag{3}$$

$$A^* = \frac{A - \langle A\rangle}{\sigma_A} \tag{4}$$

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^*:

$$\mathrm{PDF}(\Delta t^*) = a_1 \mathrm{sech}(b_1 \Delta t^*) \tag{5}$$

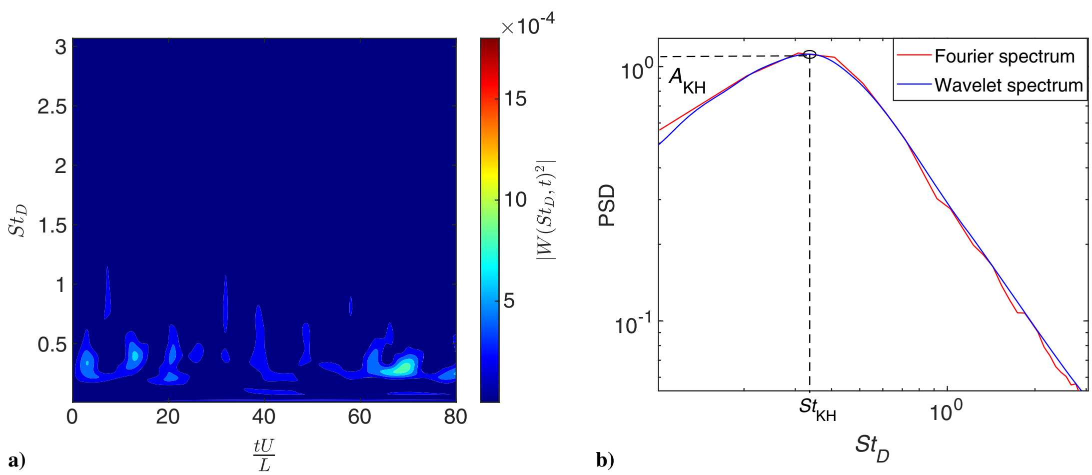

Fig. 1 a) Wavelet scalogram at $x/D = 2$ and $r/D = 1$; b) comparison between the Fourier spectrum and the wavelet-reconstructed spectrum obtained by integrating the wavelet scalogram.

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

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

III. 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 Fig. 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 K-H instability mode. Intermittency also decreases for increasing radial distances (Figs. 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 numbers. The number 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 0th mode (previously found out using an azimuthal decomposition) reported in Fig. 3. Even though the relative number 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 stochastic model. We denote with $\langle A \rangle$ the mean amplitude of the events and, following [20], we define the quantity $\langle St_{\mathrm{int}} \rangle$ as the mean intermittent nondimensional time computed at the K-H frequency and normalized using f_{KH} previously evaluated through the Fourier spectrum.

We report in Fig. 4a 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 Figs. 4a and 5a). As reported in Figs. 4b and 5b the mean nondimensional 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 that 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 Figs. 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 Tables 2 and 3, where a summary of the mean values is reported for the original signals and the 0 mode, respectively.

The detailed statistics of the intermittent events are determined by calculating the PDF of Δt and A. The main purpose of this analysis is

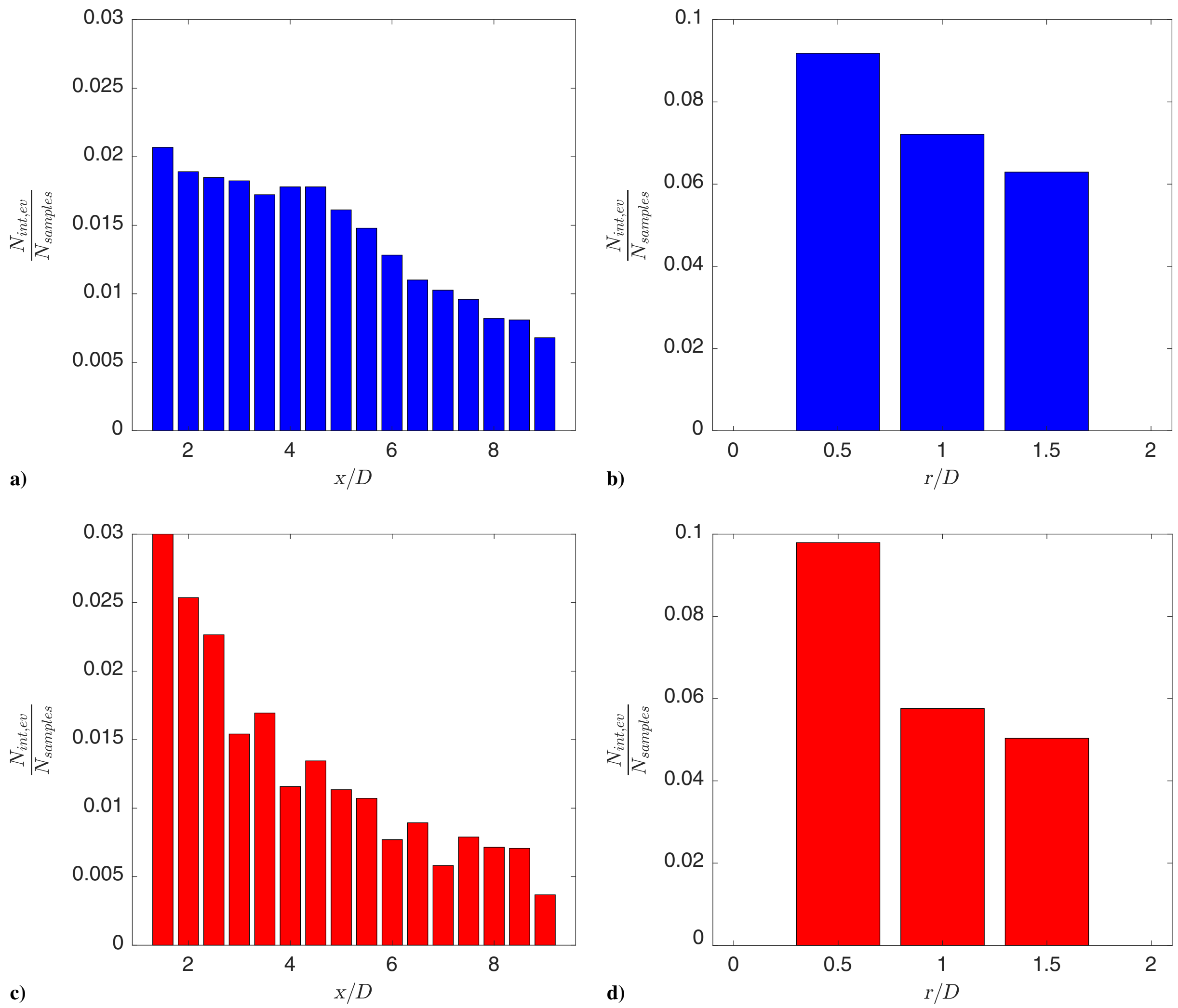

Fig. 2 Number of intermittent events normalized with respect to the total number of samples: a) as a function of x/D for all r/D and Reynolds number 3125; b) as a function of r/D for all x/D and Reynolds number 3125; c) as a function of x/D for all r/D and Reynolds number 10^5; d) as a function of r/D for all x/D and Reynolds number 10^5.

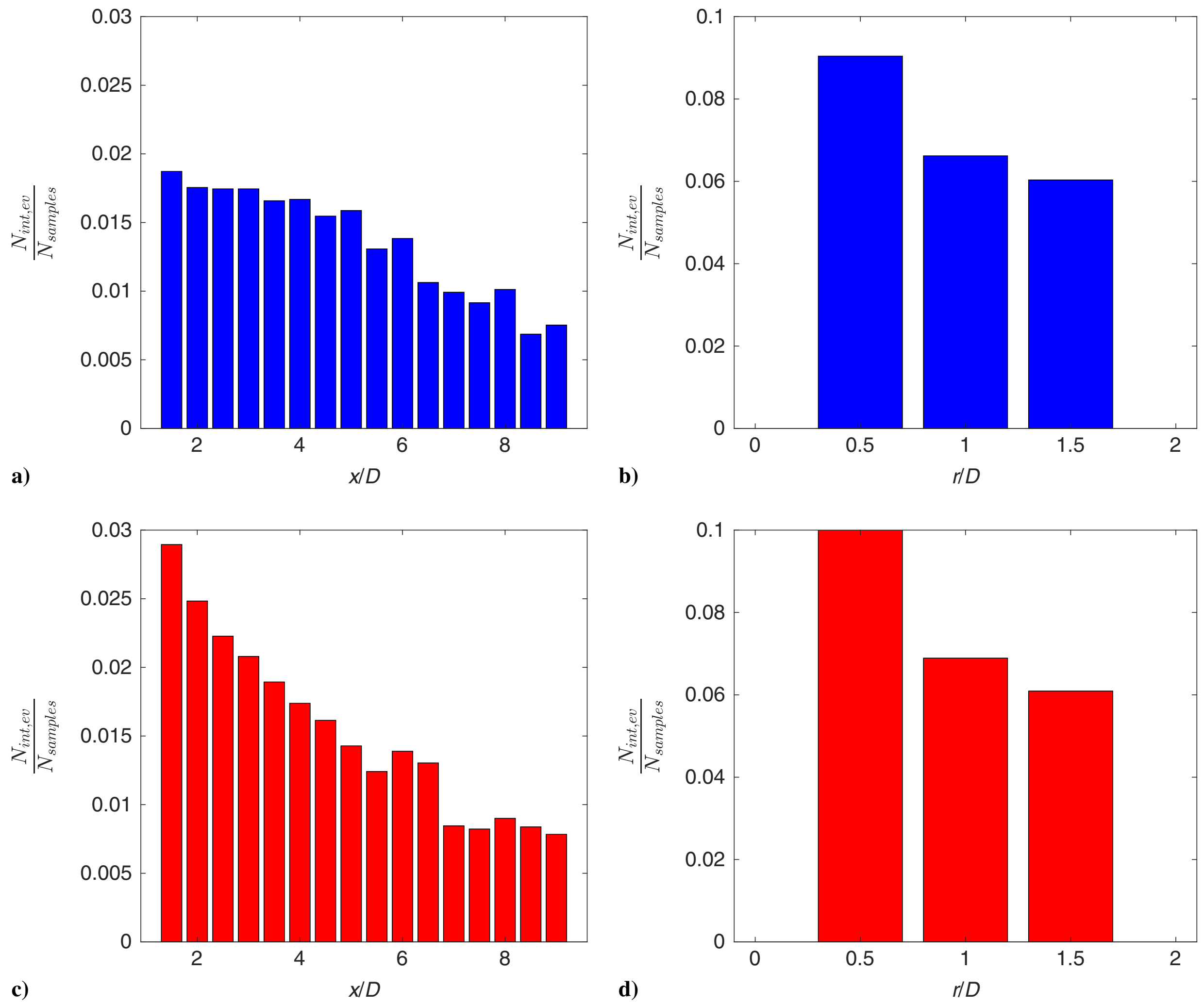

Fig. 3 Same as Fig. 2 but for the 0th mode.

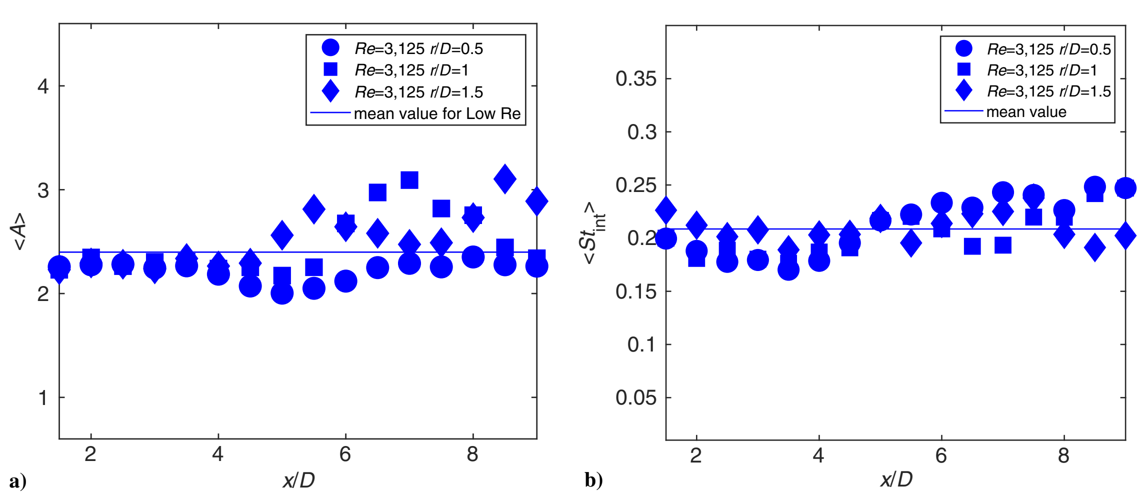

Fig. 4 Axial evolution of a) $\langle A\rangle$ and b) $\langle S_{\mathrm{int}}\rangle$ at the lowest Re and different r/D.

to evaluate the dependence of these PDFs, both for the whole pressure signals and for the 0th mode, upon the considered flow parameters (Reynolds number, axial position, radial distance).

Figures 8a and 8b 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 Figs. 8c and 8d along with the uncertainty interval estimated from the numerical data dispersion. The amplitude of the uncertainty is low, thus

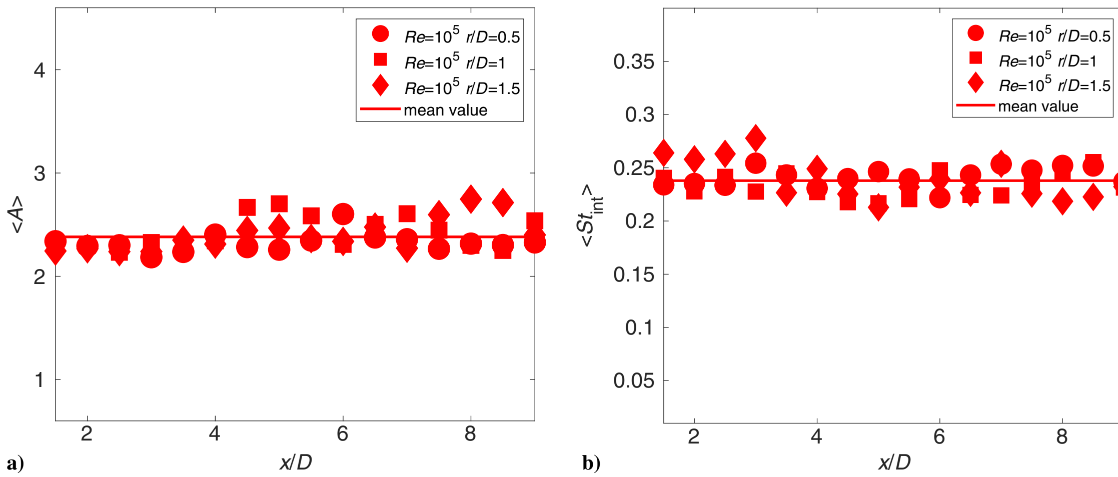

Fig. 5 Same as previous figure but for the highest *Re*.

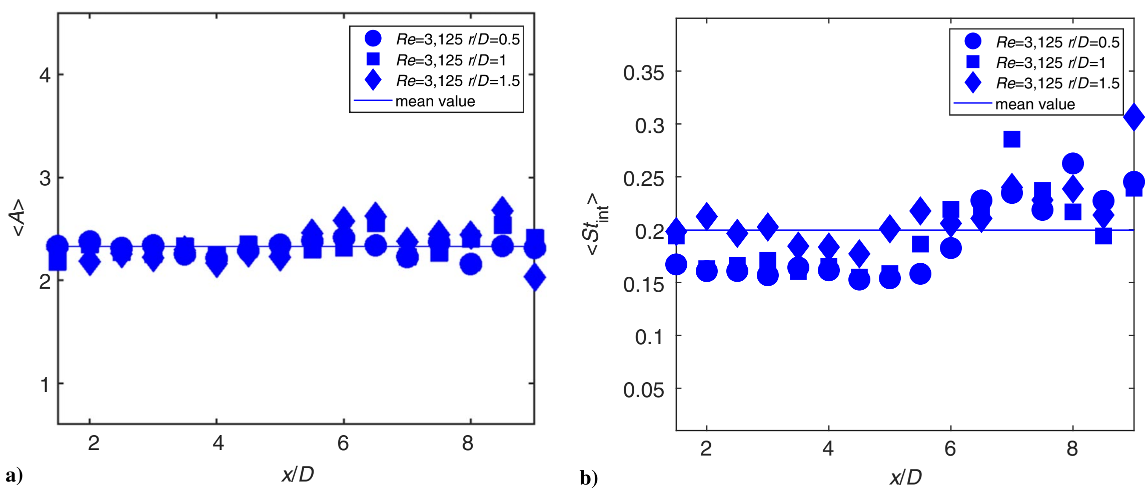

Fig. 6 Axial evolution of a) $\langle A \rangle$ and b) $\langle S_{\mathrm{int}} \rangle$ at the lower *Re* and different r/D for mode 0.

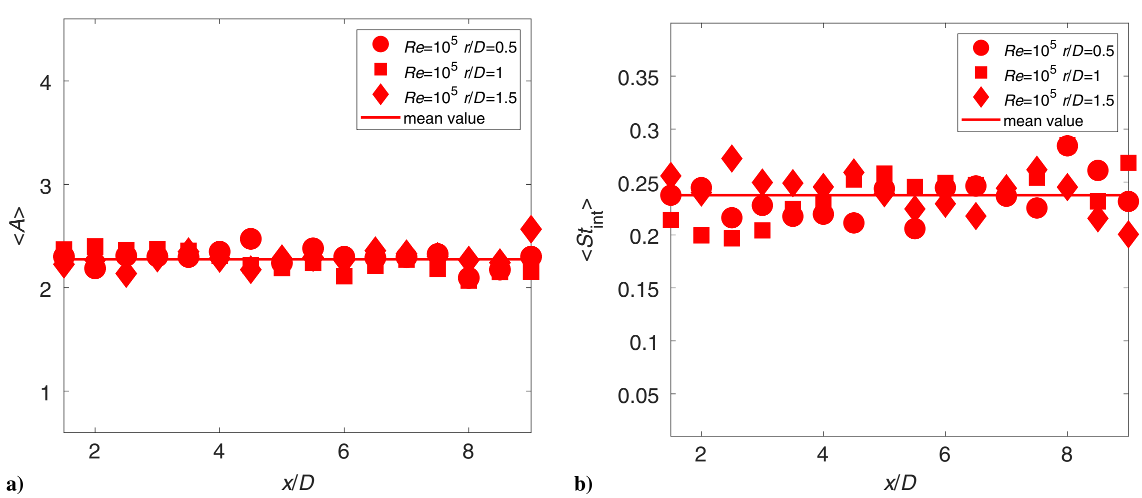

Fig. 7 Same as previous figure but for the higher *Re*.

Table 2 Statistics of the intermittent events identified in the full pressure signals

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

Table 3 Statistics of the intermittent events identified in the 0th mode pressure signals

0th Azimuthal mode	Mean
High Reynolds $\langle St_{\mathrm{int}} \rangle$	0.237
Low Reynolds $\langle St_{\mathrm{int}} \rangle$	0.199
High Reynolds $\langle A \rangle$	2.275
Low Reynolds $\langle A \rangle$	2.329

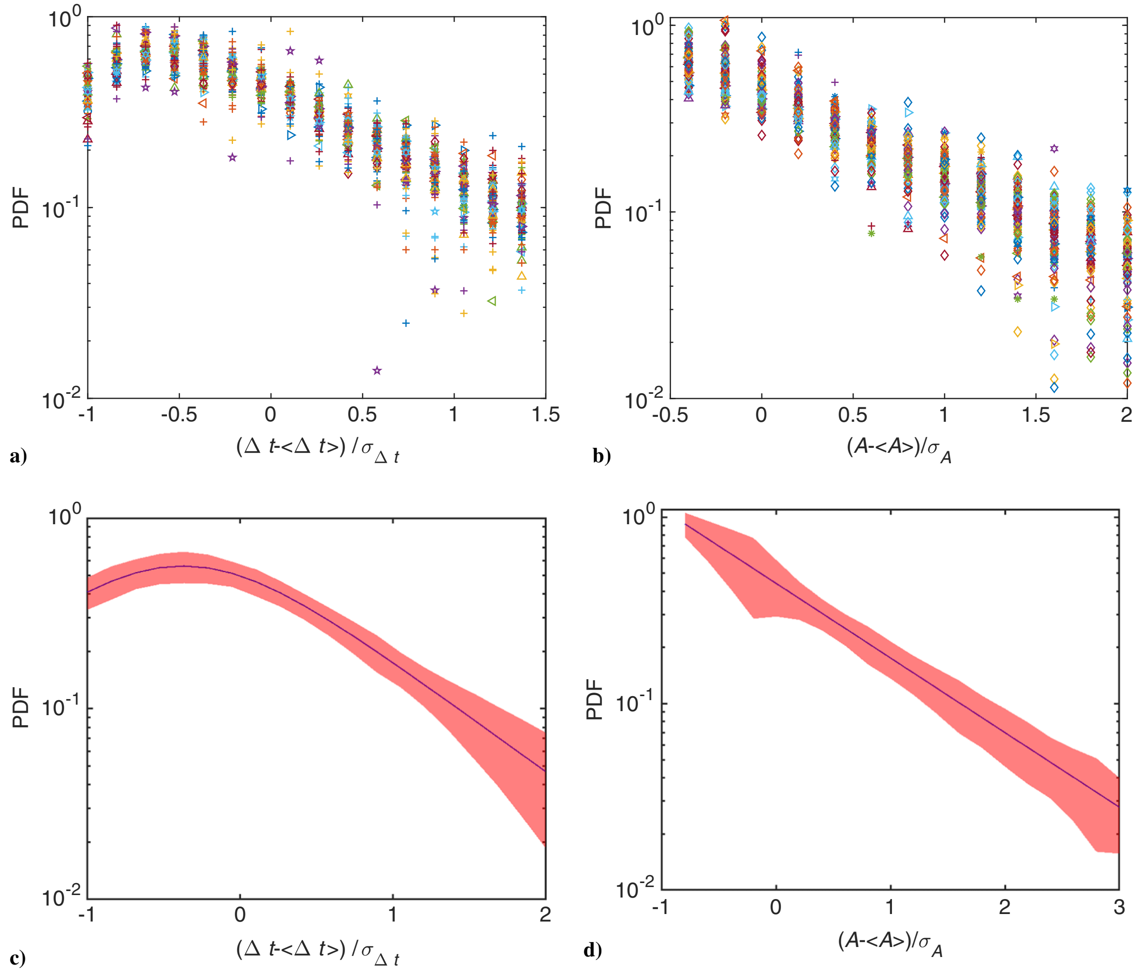

Fig. 8 Probability density functions of the entire database (including both low and high Re): a) Δt; b) A; and c,d) models (5) and (6) with the corresponding uncertainty.

confirming the reliability of the model. According to Eqs. (5) and (6), the coefficients of the approximating functions are $a_1 = 0.56$, $b_1 = 1.337$, $a_2 = 0.44$, and $b_2 = 0.92$, which are very close to those reported in [20].

The analysis is completed with the computation of the statistics of the 0th-mode counterpart. The PDFs are reported in Figs. 9a and 9b, whereas the approximating functions and the corresponding uncertainties are given in Figs. 9c and 9d. The analytical approximations are again those reported in Eqs. (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.

IV. 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 nine diameters in the axial and three 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 K-H mode.

By considering the whole set of available data and following the procedure adopted in [20], a stochastic model 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 0th 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 axisymmetric azimuthal mode. However, the direct estimation of the noise they produce is a nontrivial 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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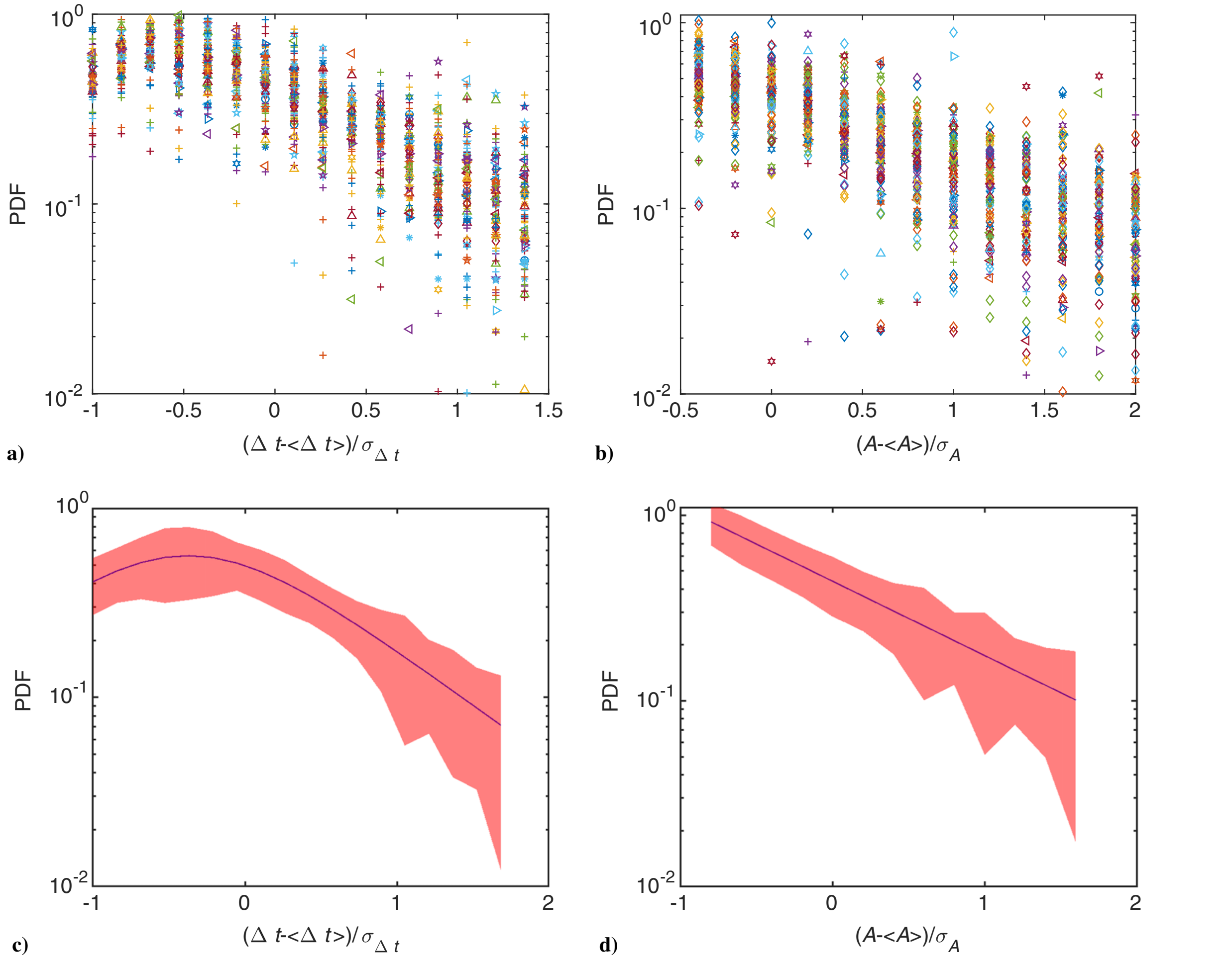

Fig. 9 Probability density functions of the 0th mode for the entire database (including both low and high Re): a) Δt; b) A; and c,d) models (5) and (6) with the respective uncertainty.

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