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Intermittency and stochastic modeling of hydrodynamic pressure fluctuations in the near field of compressible jets

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ABSTRACT

The intermittent statistics of the pressure fluctuations measured in the near field of a compressible jet are investigated under several flow conditions. An experiment is carried out in a semi-anechoic chamber on a single stream compressible jet at Mach numbers varying from 0.5 to 0.9 and measuring the fluctuating pressure in several positions in the near field. The main quantities analyzed are the intermittent time and the energy amplitude of events that are extracted from the experimental data through a wavelet-based tracking algorithm. As an extension of a previous paper (Camussi et al., 2017), low order statistical moments (mean and variance) and Probability Distribution Functions are parametrized in terms of three relevant quantities characterizing the jet flow physics: the Mach number, the radial distance from the jet axis and the axial position. It is observed that the non-dimensional statistical quantities are weakly dependent upon the flow conditions allowing for simple stochastic models to be introduced on the basis of suitable fittings of averaged statistical properties and of the Probability Distribution Functions.

1. Introduction

The pressure field in the region close to the axis of high-speed subsonic jets is dominated by hydrodynamic fluctuations induced by vortex structures generated by the interaction of the jet flow with the ambient fluid at rest. The flow structures embedded in the jet shear layer not only affects the near field pressure but also represent potential noise sources since they generate pressure waves that propagate to the far field as noise. At high Reynolds numbers (*Re*), turbulence significantly affects the generation, evolution and topology of these flow structures and thus influences the physical mechanisms underlying the generation of noise. From the statistical viewpoint, the action of turbulence is revealed by the non-Gaussian statistics of the pressure fluctuations in the near field that, as shown in Camussi et al. (2017), are characterized by intermittent bursts appearing randomly in time and space as opposed to regions of relatively quiet background. The seminal experiment undertaken by Juve´ et al. (1980) indeed showed that sound producing events in the jet flow are characterized by high levels of intermittency. Several more recent studies (e.g. Guj et al., 2003; Hileman et al., 2005; Kastner et al., 2006; Suponitsky et al., 2010) confirmed the existence and dominant role played by intermittent noise producing events.

Among different turbulent structures existing in the jet shear layer, it is known that a dominant role in sound radiation is played by wavepackets, originated by the Kelvin–Helmholtz instability of the shear layer and convected downstream by the mean flow at a quasi-constant velocity (see, among many, the review provided by Jordan & Colonius, 2013, and the reference therein). Recent studies have shown that simplified wavepacket models provide correct noise level predictions only if the so called space-time jitter is accounted for (e.g. Cavalieri et al., 2011a), a dynamical behavior related to the turbulence-induced intermittency (see also Cavalieri et al., 2013 and Zhang et al., 2014). In a recent paper, Tissot et al. (2017) interpret the non-deterministic dynamics characterizing wavepackets as an effect of background turbulence that acts as an external forcing and affects their evolution through non-linear interactions.

In the Fourier domain, hydrodynamic pressure fluctuations induce large energy in the low frequency region (see e.g. Arndt et al., 1997 and Grizzi and Camussi, 2012). As suggested by Cavalieri et al. (2013) and Jordan and Colonius (2013), the trace of the wavepackets is revealed by the bump around the Kelvin–Helmholtz frequency corresponding to a Strouhal number (*St*) around 0.3. Camussi et al. (2017) have shown that the temporal evolution of the near field pressure around this *St* is non periodic and characterized by an intermittent non-Gaussian statistics, thus confirming the wavepackets non-deterministic dynamics.

The main objective of the present work is to confirm on a different laboratory experiment results achieved by Camussi et al. (2017) and extend their validity to a broader range of flow parameters. A detailed

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statistical characterization of the intermittent events generating energy around the Kelvin–Helmholtz frequency is provided and stochastic models of relevant quantities characterizing intermittency are proposed. As in Camussi et al. (2017), events are extracted through an algorithm based on the wavelet transform of pressure signals measured in the vicinity of a compressible subsonic single-stream jet. The use of wavelet transform is justified by the temporal localization of the events that should be missed by a standard Fourier analysis. The capability of wavelet decomposition to isolate localized events important for the production of sound have been demonstrated in several recent papers (e.g. Cavalieri et al., 2011b,; Grizzi and Camussi 2012; Lewalle et al., 2012; Koenig et al. 2013; Kearney-Fisher, 2015; Mancinelli et al. 2017a) and we refer to the large body of literature for the mathematical background (e.g. Mallat, 1989; Daubechies, 1992; Farge, 1992). We remind to the next section for a brief review of the wavelet-based procedure adopted in the present analysis for the data processing. This section also contains a description of the experimental set up and a summary of the flow conditions analyzed. Results and main conclusions are instead given in Sections 3 and 4 respectively.

2. Experimental set up and post-processing procedure

The experiment has been carried out in the semi-anechoic chamber available at the Laboratory of thermo-fluid-dynamics and aerodynamics of the Department of Engineering of the University Roma Tre of Rome. The flow is generated by a single stream compressible jet powered by compressed air and issuing in still air. The jet is equipped with a contoured nozzle having a contraction ratio of 44.4 and exit diameter of 0.012 m. This set up allows for a maximum Mach number $M = 0.9$ to be reached at stable conditions in terms of pressure, temperature and exit velocity. The facility as well as the jet geometry and the test chamber, are described in details in Grizzi and Camussi (2012). This paper also contains a detailed aerodynamic characterization of the jet flow for flow conditions similar to those considered in the present investigation. Near-field pressure measurements have been carried out using one 1/4" 4135 Bruel & Kjaer microphone installed close to the jet axis on a wooden support and moved using a manual micrometric traversing system. The microphone was calibrated using a B&K 4228 Pistonphone with a sound pressure level (SPL) of 124 dB at 250 Hz. According to the microphones calibration chart, a flat frequency response is achieved up to approximately 100 kHz when used without the caps. The microphone was positioned at normal incidence with respect to the jet axis and installed without the protecting grid. It was connected to a B&K Nexus 2690 signal conditioner that allows to fix the amplification gain and the analogic anti-aliasing filter. The signal was definitely acquired through a Yokogawa Digital Scope DL708E setting the sampling frequency to 500 kHz and the number of samples acquired per each position to 4×10^6.

The frame of reference is chosen with the origin at the jet exit, the x-axis being in the streamwise direction along the jet axis and the radial direction denoted as r. The number of configurations analyzed in the present investigation is 315 and a summary is given in Table 1. It must be noted that the radial positions lie on lines that follow the jet divergence, with an angle of 10° with respect to the jet axis. Therefore the r/D values reported in Table 1 refer to the intercepts of these lines with the nozzle exit plane.

The acquired data are analyzed using standard procedures, including Fourier transform and Probability Density Functions (PDFS) estimation. The latter quantities are always referred to normalized variables obtained by subtracting to the random variable its mean value and dividing it by the standard deviation.

Table 1
Summary of the analyzed flow conditions.

x/D	r/D	M
From 0 to 20 step 1D	From 1 to 3 step 0.5 D	0.5-0.7-0.9

The computation of the power spectra allows for the estimation of the frequency where the energy reaches a maximum. According to the notation adopted in Camussi et al. (2017), this frequency is defined as a Kelvin–Helmholtz frequency f_{kh}. Its non-dimensional counterpart is denoted as a Kelvin–Helmholtz Strouhal number, St_{kh}, where the diameter D and the exit mean velocity have been used to normalize the frequency. The amplitude of the Fourier spectrum at f_{kh} is denoted as A_{kh}. The adopted signal processing algorithm extracts at each position the frequency corresponding to the maximum power and the corresponding amplitude. In order to avoid uncertainties related to the lack of statistical convergence, the spectrum is calculated using the wavelet transform and averaging in time the wavelet scalogram. The wavelet scalogram is given by the square of the wavelet coefficients and it provides a decomposition of the energy contained by the signal onto the time-frequency plane. As reported in Farge (1992), the scalogram provides a localized counterpart of the standard Fourier spectrum that can be recovered by a simple time integration (see Camussi et al., 2017). As pointed out by Farge (1992), Camussi et al. (2017) and Mancinelli et al. (2017b), the integration of the wavelet scalogram allows for an accurate computation of the Fourier spectra that result less affected by uncertainties related to the statistical convergence. To this extent, the wavelet type selected is the Morlet one since it provides the best accuracy in reproducing the Fourier spectrum (Auger et al., 2005).

Fig. 1 reports a series of Fourier power spectra obtained using the wavelet approach. The reported plots refer to the radial position r/D = 1 and the maximum Mach number ($M = 0.9$). According to literature results (e.g. Arndt et al., 1997) the low frequency region exhibits an energy bump that is associated to the Kelvin–Helmholtz instability mechanism. The characteristic frequency decreases for increasing x/D and, as an effect of the increasing turbulent fluctuations, the amplitude A_{KH} increases.

The analysis of intermittency is carried out using the same approach presented in Camussi et al. (2017) and briefly worked out in the following. The key quantity is the scalogram that has been shown in Camussi et al. (2017) to enhance localized amplitude fluctuations modulating the oscillations at the frequency f_{kh}. This property is used to extract the temporal location of the events. The burst tracking is indeed performed by a simple search of maxima of the scalogram at the frequency f_{kh}, each relative maximum providing the temporal location of the event and of its energy content.

The time of appearance of the events as well as the amplitude of their local energy are sequentially collected. Two random variables are then analyzed, the intermittency time Δt, that is the time delay between two successive events, and the event energy amplitude A. As pointed out by Kearney–Fischer et al. (2013), the first parameter provides a direct estimation of the intermittent degree of the physical phenomenon driving the dynamics of the selected events. The second one is a measure of the energy contained by the intermittent events that will be compared to the overall energy contained by the analyzed signal.

The statistical analysis is carried out firstly by analyzing the behavior of low order statistical moments, in particular the mean quantities $<\Delta t>$ and $<A>$ and their standard deviation, the symbol $<\ldots>$ denoting ensemble averaging. Then, higher order statistics are retrieved by computing the Probability Distribution Functions (PDF) of each random variable. The main task of the present analysis is the investigation of the dependence of the statistics upon the flow parameters (axial and radial position and Mach number) and the assessment of analytical approximations that can be used for modeling purposes. Indeed, a detailed knowledge of these statistical properties provides the dynamical parameters to be associated to the wavepacket model to provide more accurate noise prediction.

As was shown in several previous papers (see e.g. Camussi and Guj 1997, and the more recent papers Camussi et al., 2010 and Mancinelli et al., 2017a) the use of an energetic criterion to track events