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Toward source analysis of turbulent coaxial jets in Large-Eddy Simulation

G. Daviller, P. Comte, and P. Jordan

Laboratoire d’Étude Aérodynamiques (LEA) - UMR CNRS 6609, 43, rue de l’Aérodrome 86036 POITIERS CEDEX FRANCE

Abstract:
The energy corollary proposed by Doak [1] and Jenvey [2] based on Helmholtz decompositions of both linear momentum and velocity is applied on a model problem, in order to aspire to provide a clearer interpretational framework for studying the local physical mechanisms which underpin the production of sound energy by turbulence. Initial results show how it is possible to identify the different flow processes (source mechanisms) which lead to the transport of fluctuation energy, as well as the physical mechanisms by which that fluctuation energy is transported away from the source region as propagating sound energy. The final goal of this approach make to investigate the temperature effects on a turbulent subsonic coaxial jet in LES.

1 Introduction
The major part of the jet noise investigations by Large-Eddy Simulation over the last decade have been performed with the aim of explaining the noise generation mechanisms. However, these applications focus on the prediction of the far-field noise [3], and so the dynamics by which subsonic turbulent jets generate sound and propagate it in the farfield is meaningless. Rayleigh’s three classes of fluctuating motion (i.e. vortical, entropic and acoustic), present in the general case an ambiguous system of distinct kinds of fluid motion due to the quadratic interaction which constitutes further sources of excitation for each of the modes [4]. Then, this classification provides an interpretational framework which is invaluable for the obtaining of a mechanistic understanding of the different flow process which underpin energy exchange in compressible turbulent flows. The work of [5] based on Myers’ exact linearized “disturbance energy corollaries” [6], build up a first approach to identify some disturbance energy sources term in turbulent jets, but they shown this decomposition does not separate hydrodynamic and propagative parts of the turbulent motion. Following this idea, we consider a framework which was considered by Doak [1] and Jenvey [2] to be useful to distinguish vortical motion (which they consider synonymous with turbulence) from irrotational motion (which they consider synonymous with acoustic or entropic fields), by a Helmholtz decomposition, applied, respectively, to the momentum and velocity variables. Our objective is to assess this decompositions and the energy corollaries which result, in terms of the physical insight which they are able to provide. We outline here our approach, on a convected wavepacket whose amplitude and solenoidality can be controlled, which constitutes a model problem in order to validate the method and our code. Two different excitations are considered: an irrotational forcing and a non-zero vorticity case. On the other hand, we present large-Eddy Simulations of heated and unheated coaxial jets at Mach number 0.5 and Reynolds number $1.1 \times 10^6$, which complete the experimental work of [7] in the isothermal case. Our idea is to apply the framework described before, in order to investigate the change in the Doak’s [1] energy corollaries when the primary stream of the coaxial jet is heated.

2 Flow decomposition
The response of the two-dimensional Euler equations to a convected wavepacket body-force excitation whose an analytical solution exist [8], is computed (figure 1 (a)). Moreover we can control the amplitude and the vorticity of this excitation. We assess the resulting flow fields using Doak’s energy balance formulations (1) and (2), which are based on a Helmholtz decomposition of the momentum density (i.e. $p \mathbf{u}_1 = \mathbf{B}_1 + \mathbf{B}'_1 + \frac{\partial \psi'}{\partial x_i}$), where $\mathbf{B}$ is the solenoidal vector potential, and $\psi$ is the scalar potential) and which allow the time-averaged energy flux to be expressed as a linear combination of mean-solenoidal ($\mathbf{B}_1$), fluctuating-solenoidal ($\mathbf{B}'_1$) and fluctuating-irrotational ($\frac{\partial \psi'}{\partial x_i}$) components: the terms which correspond to the transport of total fluctuating enthalpy by each of these components of the momentum density are identified.

From the solution of the Euler equations in zero-vorticity case, using a Poisson solver, we first decompose the momentum into solenoidal and irrotational components. In figure 1 (b) can observe that the curves of the analytical result of the acoustic potential and the fluctuating pressure of the simulation are similar. Together
with two of the ICASE-NASA tests case [9], this can be considered as a validation of the code, essentially
designed for aerodynamics [10, 11], for aeroacoustics as well, although its efficiency is significantly less
than high precision codes for CAA [12]. In this case of irrotational body-force, the two first terms of the right-
hand side in equation (1) are equal to zero and so the flow is, according to Doak at a state of local fluctuating
dynamical equilibrium. The budget of the Doak’s energy balance (1) is closed with less than 2% as shown in
Figure 1 (c).

The fluctuating Doak’s energy balance takes the form:

$$\frac{\partial}{\partial x_j} \left( \frac{\partial H'}{\partial x_j} \right) - \frac{\partial}{\partial x_j} \left( \frac{\partial \psi'}{\partial x_j} \right) = \frac{\partial}{\partial x_i} \left( \frac{\partial \psi'}{\partial x_i} \right) - \frac{\partial}{\partial x_i} \left( \frac{\partial \psi'}{\partial x_i} \right) + E_S. \quad (1)$$

where $E_S$ is the energy associated with the body-force excitation.

We then use a further decomposition, as proposed by Jenvey [2], in order to split the fluctuating enthalpy into
irrotational and solenoidal components, $H' = H'_B + H'_A$. The energy balance then becomes

$$\frac{\partial}{\partial x_j} \left( \frac{\partial (H_B' + H_A')}{\partial x_j} \right) = \frac{\partial}{\partial x_i} \left( \frac{\partial \psi'}{\partial x_i} \right) - \frac{\partial}{\partial x_i} \left( \frac{\partial \psi'}{\partial x_i} \right) + E_S. \quad (2)$$

where $H'_B$ and $H'_A$ can be written, to first order, as:

$$H'_B = eM_j(B'_j/\bar{\rho})$$

$$H'_A = (1 - M^2)(p'/\bar{\rho}) - eM_j[(\partial \psi'/\partial x_j)/\bar{\rho}]$$

with $e^2 = \gamma p/\rho$ and the Mach number vector $M_j = v_j/c$, $M^2 = \bar{M}_j\bar{M}_j$

Now we inject vorticity in the body-force excitation, as described in [13], the energy corollary allows the iden-
tification of two further source mechanisms which arise due to a loss of orthogonality between the fluctuating
Lamb vector field and the fluctuating vector fields of the irrotational component (figure 2 (a)) and the solenoidal
components (figure 2 (b)) of the density momentum. Doak referred to such a scenario as one in which the flow
is not in a state of local fluctuating dynamical equilibrium; a silent flow being one in which there does exist
such local equilibrium. In addition to the source mechanisms, the energy corollary allows the identification of
four mechanisms by which fluctuation energy is transported; the two found to dominate in the flows studied
are: term (d) in figure 3 which corresponds to the classical acoustic intensity and term (b) which corresponds
to the scattering of sound by vortical motion. The other terms describe: the transport of solenoidal fluctuation
energy by solenoidal momentum fluctuations (a), and the transport of solenoidal fluctuation energy by sound
(c).

3 LES of compressible turbulent coaxial jet

LES are now performed with the same code, in density-weighted filtered variables, using the macrotemperature
closure [14] and the Filtered-Structure Function subgrid-scale turbulence model [10]. Spatial derivatives are
computed with fourth-order-accurate finite scheme [15] for both the inviscid and viscous portion of the flux
[16]. A second-order predictor-corrector scheme is used to advance the solution in time. In addition, block
decomposition and MPI parallelisation are implemented and the computations were performed on an IBM
power6 machine at IDRIS using 232 processors. The computations presented here are performed with approxi-
ately 90 million grid points, with 1387 points in the streamwise direction, and 342 points along both the
$y$ and $z$ directions, on a computational domain extent to $50D_p \times 32D_p \times 32D_p$ (subscript p denoting the
primary jet). Three dimensional Navier-Stokes characteristic non-reflective boundary conditions (3D-NSCBC),
developed by Lodato & al [17] are applied at the boundaries of the computational domain to account for
convection and pressure gradient in boundary plane. In order to simulate anechoic boundary conditions, in all
directions around the physical portion of the computational domain, the mesh was stretched and a dissipative
term are added to the equations [18]. To promote a natural transition to turbulence from an initially turbulent
mean profile [19] without nozzle in our calculations, we introduce some solenoidal disturbances of amplitude
$\alpha = 0.007$ in a region in the early jet development near the inflow boundary as Bogey & Bailly [20]. In
order to avoid the generation of spurious noise which should drown the physical noise with a sponge layer as in
[21]. The initial mean temperature was calculated with the Crocco-Busemann relation, and the mean initial
pressure was constant.

The flow parameters are summarized in Tab.(1). The acoustic Mach number is in both the heated and unheated
case $M_a = U_p/a_\infty = 0.5$, where $a_\infty$ is the ambient speed of sound. The temperature ratio $T_s/T_p = 0.37$
is chosen as in [22] and the velocity ratio $U_s/U_p = 0.7$ and the mass flux ratio $\beta = \rho_sA_s/\rho_pA_p = 2.153$ as in [7].
The momentum thickness of the secondary jet is $\theta_{os} = 0.044D_p$, and that of the primary jet is $\theta_{op} = 0.028D_p$.

Figure 4 shows a snapshot of the coherent vortices in both the isothermal and heated cases.
4 Conclusion

We have performed simulations of a convected wavepacket and of heated and unheated coaxial jets. Wavepacket results are validated by the closure of the disturbance Doak’s energy budget. In the context of the energy corollaries proposed by Doak [1] and Jenvey [2], we use these decompositions to study the source and energy transport mechanisms which arise in the model flows. The energy corollary allows the identification of two further source mechanisms (which are weak in the low-level excitation we consider), and moreover, underline four fluctuations’ transport mechanisms [23, 13]. First observations seems to indicate that the introduction of non-zero vorticity in the model does not affect so much the total fluctuating enthalpy but increases the turbulent transport of the energy of the acoustic fluctuation (ie scattering of sound by turbulence). Analogous analysis of the coaxial jet results is in progress.

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Références


FIG. 1 – Wavepacket with irrotational forcing: (a) Instantaneous fluctuations pressure field; (b) Analytical solution (—), numerical simulation (—) along \( \vec{x} \) for \( y = 0 \); (c) non-zero term in eq. (1) along \( \vec{x} \) for \( y = 0 \):

\[
\frac{\partial}{\partial x} \left( H' \frac{\partial \psi'}{\partial x} \right) : - - - , \quad \frac{\partial}{\partial y} \left( H' \frac{\partial \psi'}{\partial y} \right) : - - - , \quad \frac{\partial}{\partial x} \left( H' \overline{\vec{B}'} \right) : - - - .
\]

FIG. 2 – Wavepacket with vortical forcing: (a) Instantaneous view of \( \frac{\partial \psi'}{\partial x} \) (in red) and \( (\vec{\Omega} \wedge \vec{u})' \) (in black); (b) instantaneous view of \( \overline{\vec{B}'} \) (in red) and \( (\vec{\Omega} \wedge \vec{u})' \) (in black)
FIG. 3 – Wavepacket with vortical forcing, time averaged transport terms: (a) $\frac{\partial}{\partial x_j} H_B^{\prime} B_j^{\prime}$; (b) $\frac{\partial}{\partial x_j} H_A^{\prime} B_j^{\prime}$; (c) $\frac{\partial}{\partial x_j} H_B^{\prime} \frac{\partial \psi}{\partial x_j}$; (d) $\frac{\partial}{\partial x_j} H_A^{\prime} \frac{\partial \psi}{\partial x_j}$

FIG. 4 – Snapshot of the coherent vortices for coaxial jet by isolines of positive $Q = 0.5(U_s/D_p)^2$ coloured by the streamwise velocity: (a) isothermal case; (b) heated case. We obtain the same decay of the primary jet’s centerline velocity for the isothermal coaxial jet as [7] ($x/D_s \sim 6.0$). Due to temperature ratio, we can observe that the level of turbulence mixing is higher than for the isothermal coaxial jet, and so the potential core is smaller ($x/D_s \sim 5.0$). The exit of the “graphical” nozzle corresponds to the domain inlet.