

Computation of noise generation and propagation for free and confined turbulent flows

C. Bailly

Electricite de France, Clamart

P. Lafon

Electricite de France, Clamart

S. Candel

Paris, Ecole Centrale, Chatenay-Malabry, France

AIAA and CEAS, Aeroacoustics Conference, 2nd, State College, PA, May 6-8, 1996

This paper deals with the application of the SNGR (Stochastic Noise Generation and Radiation) model to compute turbulent mixing noise generated in a duct obstructed by a diaphragm. Two problems must be solved in the framework of an acoustic analogy. First, a wave operator must be derived for sound waves traveling in any mean flow. In the SNGR model, the system of linearized Euler equations is used. An expression of the source term is then deduced from the conservation laws of motion and can be simplified with classical assumptions of aeroacoustics in the case of subsonic mixing noise. Secondly, the knowledge of the turbulence velocity field is required to compute this source term. In the SNGR model, the space-time turbulence velocity field is generated by a sum of random Fourier modes. Finally, the radiated acoustic field is calculated numerically by solving the inhomogeneous propagation system. The method is applied to the case of a 2D duct obstructed by a diaphragm. Numerical results are compared with available experimental ones. Computed noise levels closely match experimental ones and follow the expected U4 law. (Author)

Computation of noise generation and propagation for free and confined turbulent flows

C. Bailly*, P. Lafon†

Département Acoustique et Mécanique Vibratoire
Electricité de France, Direction des Etudes et Recherches
1 av. du Général de Gaulle, 92141 Clamart Cedex, France

S. Candel‡

Laboratoire EM2C, Ecole Centrale Paris
92295 Châtenay-Malabry Cedex, France

Abstract

This paper deals with the application of the SNGR (Stochastic Noise Generation and Radiation) model to compute turbulent mixing noise generated in a duct obstructed by a diaphragm. Two problems must be solved in the framework of an acoustic analogy. First, a wave operator must be derived for sound waves travelling in any mean flow. In the SNGR model, the system of linearized Euler equations is used. An expression of the source term is then deduced from the conservation laws of motion, and can be simplified with classical assumptions of aeroacoustics in the case of subsonic mixing noise. Secondly, the knowledge of the turbulence velocity field is required to compute this source term. In the SNGR model, the space-time turbulence velocity field is generated by a sum of random Fourier modes. Finally, the radiated acoustic field is calculated numerically by solving the inhomogeneous propagation system. The method is applied in this paper to the case of a two-dimensional duct obstructed by a diaphragm. Numerical results are compared with available experimental ones. Computed noise levels closely match experimental ones and follow the expected U^4 law.

Introduction

Aeroacoustic calculations usually require a wave equa-

*Assistant Professor, Member AIAA. Present address: LMFA, URA 263 CNRS, Ecole Centrale de Lyon, 36 av. G. de Collongue, 69131 Ecully Cedex, France

†Research Scientist, Member AIAA

‡Professor, Member AIAA

tion and its source term. It is also necessary to provide some informations about the turbulence in the flow. Classical aeroacoustic approaches based on the Lighthill acoustic analogy generally use the free-space Green's function in order to solve the wave equation, but the application of such techniques to confined configurations are not straightforward. In this paper, we use the Stochastic Noise Generation and Radiation model (SNGR)^{2,4,6,19} which solves the system of linearized Euler equations instead of a wave equation and uses as input a synthesized turbulent field providing the source term.

The equations of the SNGR model are presented in section 2. It is shown in section 3 how one may synthesize a space-time turbulent velocity field with suitable statistical properties. The application to the case of a duct obstructed by a diaphragm is discussed in section 4.

Propagation in nonuniform mean flow

The simplest wave equation that one can exactly derive from the fundamental conservation laws of motion is Lighthill's equation:^{20,21}

$$\frac{\partial^2 \rho}{\partial t^2} - c_o^2 \frac{\partial^2 \rho}{\partial x_i \partial x_i} = \frac{\partial^2 T_{ij}}{\partial x_i \partial x_j} \quad (1)$$

where ρ is the density and T_{ij} is Lighthill's tensor $T_{ij} = \rho u_i u_j + (p - c_o^2 \rho) \delta_{ij} - \tau_{ij}$. In this last expression, u , p , and τ designate the velocity, pressure and viscous stress tensor. Here one assumes that the medium external to the flow is homogeneous and at rest, c_o being the constant speed in

this ambient medium. The free-space Green's function of this wave operator is known allowing easy application of Lighthill's analogy in many studies.^{1-3,7,12-14,25} The method does not account for mean flow effects on acoustic wave propagation. Such effects are known to modify the aerodynamic noise spectrum and directivity. Phillips²⁴ replaced Lighthill's equation by a convected wave equation where a part of the mean flow effects were included in the wave operator rather than in the source term. Introducing the logarithm of the pressure variable $\pi = \ln p$, Phillips' equation reads:

$$\frac{d^2\pi}{dt^2} - \frac{\partial}{\partial x_i} \left(c^2 \frac{\partial \pi}{\partial x_i} \right) = \gamma \frac{\partial u_i}{\partial x_j} \frac{\partial u_j}{\partial x_i} \quad (2)$$

$$+ \frac{d}{dt} \left(\frac{1}{c_v} \frac{ds}{dt} \right) - \frac{\partial}{\partial x_i} \left(\frac{\gamma}{\rho} \frac{\partial \tau_{ij}}{\partial x_j} \right)$$

where $\gamma = c_p/c_v$ is the specific heats ratio. One sees that the main source term for jet noise only contains components of the velocity field unlike Lighthill's source term. At high Reynolds numbers, the viscous stress tensor can be neglected. Furthermore, one assumes viscous dissipation and heat conduction effects are negligible in sound generation and propagation. Then assuming a parallel sheared mean flow: $u_i = U(x_2) \delta_{i1} + u'_i$, Phillips' equation (3) may be written in the form:

$$\frac{D^2\pi'}{Dt^2} - \frac{\partial}{\partial x_i} \left(c_o^2 \frac{\partial \pi'}{\partial x_i} \right) = 2\gamma \frac{\partial u'_2}{\partial x_1} \frac{dU}{dx_2} \quad (3)$$

$$+ \gamma \left\{ \frac{\partial u'_i}{\partial x_j} \frac{\partial u'_j}{\partial x_i} - \frac{\partial u'_i}{\partial x_j} \frac{\partial u'_j}{\partial x_i} \right\}$$

where

$$\frac{D}{Dt} = \frac{\partial}{\partial t} + U \frac{\partial}{\partial x_1}$$

is the convective time derivation operator. It is also known that linearized Euler's equations govern acoustic wave propagation. So, the associated wave equation should be identical to the previous homogeneous equation. But this is not exactly the case.^{10,22} Indeed, assuming a global isentropic relation $dp = c_o^2 d\rho$, the wave equation derived from the linearized Euler's equation is given by:

$$\frac{D^2\pi'}{Dt^2} - \frac{\partial}{\partial x_i} \left(c_o^2 \frac{\partial \pi'}{\partial x_i} \right) - 2\gamma \frac{dU}{dx_2} \frac{\partial u'_2}{\partial x_1} = 0 \quad (4)$$

In order to eliminate the term containing velocity fluctuations of the wave operator, one must again apply the D/Dt operator to the last equation. This finally yields:

$$\frac{D}{Dt} \left\{ \frac{D^2\pi'}{Dt^2} - \frac{\partial}{\partial x_i} \left(c_o^2 \frac{\partial \pi'}{\partial x_i} \right) \right\} + 2 \frac{dU}{dx_2} \frac{\partial}{\partial x_1} \left(c_o^2 \frac{\partial \pi'}{\partial x_2} \right) = 0 \quad (5)$$

This equation shows that Phillips' wave operator does not contain all the terms that appear in (5). On the other hand, in the case of a sheared mean flow, the simplest wave equation for the acoustic variable π' is a third order differential equation. Lilley²² derived such a third order wave equation from Phillips' equation with this idea. Thus, in applying the convective D/Dt operator to Phillips' equation (3), it follows:

$$\frac{d}{dt} \left\{ \frac{d^2\pi}{dt^2} - \frac{\partial}{\partial x_i} \left(c^2 \frac{\partial \pi}{\partial x_i} \right) \right\} + 2 \frac{\partial u_i}{\partial x_j} \frac{\partial}{\partial x_i} \left(c^2 \frac{\partial \pi}{\partial x_j} \right) \quad (6)$$

$$= -2\gamma \frac{\partial u_i}{\partial x_j} \frac{\partial u_j}{\partial x_k} \frac{\partial u_k}{\partial x_i} + \text{other terms}$$

where the viscous contribution and the entropy fluctuations are neglected. The free-space Green function of the Lilley's equation is unknown and it is difficult to solve numerically a third order wave equation, unlike the linearized Euler's equations. Moreover, in the case of a nonuniform mean flow, acoustic and hydrodynamic fluctuations can not be clearly separated to form a wave operator.^{8,23,28} Thus, computation of the acoustic field by solving linearized Euler's equations constitutes an interesting alternative. An analysis of the acoustic analogy associated with linearized Euler's equations was developed.^{2,6} It was found that the following system of two first-order equations has to be retained:

$$\begin{cases} \frac{\partial p'}{\partial t} + u_{j_o} \frac{\partial p'}{\partial x_j} + u'_j \frac{\partial p_o}{\partial x_j} + \gamma p_o \frac{\partial u'_j}{\partial x_j} + \gamma p' \frac{\partial u_{j_o}}{\partial x_j} = 0 \\ \frac{\partial u'_i}{\partial t} + u_{j_o} \frac{\partial u'_i}{\partial x_j} + u'_j \frac{\partial u_{i_o}}{\partial x_j} + \frac{1}{\rho_o} \frac{\partial p'}{\partial x_i} - \frac{p'}{\rho_o^2 c_o^2} \frac{\partial p_o}{\partial x_i} = S_i \end{cases} \quad (7)$$

where the source term reads as follows:

$$S_i = - \left\{ u_{jt} \frac{\partial u_{it}}{\partial x_j} - u_{jt} \frac{\partial u_{it}}{\partial x_j} \right\}$$

The subscript o designates a value of the mean flowfield and the subscript t a value of the turbulent field. u' and p' are the acoustic velocity and pressure. The left hand side of (7) is the system of the linearized Euler's equations around a stationary mean flow (U_o, p_o, ρ_o). The right hand side of this system is the acoustic source term, which is nonlinear in velocity fluctuations. However, the time average of the source term is zero. The previous system (7) is derived under the following assumptions. Acoustic pressure fluctuations are isentropic, the turbulent velocity is incompressible, and only the first order interaction between the mean flow and the acoustic field is retained. In other words, phenomena such as scattering of sound by turbulence are assumed to be negligible.

Finally, to compute the sound field, one carries out the three following steps:

- (i) An aerodynamic calculation of the mean flow is performed by solving the averaged Navier-Stokes equations with a $k - \epsilon$ turbulence closure.
- (ii) A space-time stochastic turbulent velocity field is generated as a sum of random Fourier modes.
- (iii) The propagation system (7) is solved. In the left hand side, one uses values of the mean flow-field calculated in the first step as coefficients of the two first-order differential equations. On the right hand side, the acoustic source term S is calculated from the synthesized turbulent field.

A space-time stochastic turbulent velocity field

A method to simulate a spatial stochastic turbulent velocity field was initially devised by Kraichnan¹⁷ and Karweit.¹⁵ Their Fourier mode approach is used but a space-time evolution of the turbulent field u is introduced by writing that:

$$\frac{\partial u}{\partial t} + U_c \cdot \nabla u = 0$$

where U_c is the convection velocity. In what follows, the subscript t which designates the turbulent velocity field is omitted. The turbulent velocity field is given by the following sum of N modes:

$$u(x, t) = 2 \sum_{n=1}^N \tilde{u}_n \cos [k_n \cdot (x - tU_c) + \psi_n + \omega_n t] \sigma_n \quad (8)$$

where k_n is the wave vector picked randomly on a sphere to ensure a statistical isotropy at time zero. As a consequence of the incompressibility of the turbulent velocity field, $k_n \cdot \sigma_n = 0$ for each mode n . ψ_n is chosen with uniform probability to obtain a homogeneous field.

The amplitude \tilde{u} of each mode is determined from a modified Von Kàrmàn spectrum to simulate the complete spectral range:

$$\begin{cases} \tilde{u}_n = \sqrt{E(k_n) \Delta k_n} \\ E(k) = \alpha \frac{u^2}{k_\epsilon} \frac{(k/k_\epsilon)^4}{[1 + (k/k_\epsilon)^2]^{17/6}} \exp \left[-2 \left(\frac{k}{k_\eta} \right)^2 \right] \end{cases}$$

where $k_\eta = \epsilon^{1/4} \nu^{3/4}$ is the Kolmogorov wave number. The parameters α and k_ϵ of the spectrum are determined from the two integral relations which define k and ϵ :

$$k = \int_0^\infty E(k, t) dk$$

$$\epsilon = 2\nu \int_0^\infty k^2 E(k, t) dk$$

where k is the kinetic energy per mass unit and ϵ the rate of dissipation, that is to say the rate of transfer of kinetic energy per mass unit and per time unit. These two local values of the turbulent field may be used to estimate the integral length scale L :

$$L = \int_0^\infty f(r) dr \simeq \frac{k^{3/2}}{\epsilon}$$

A characteristic angular frequency for the turbulence is given for each mode by the relation:^{5,26}

$$\omega_n = \epsilon^{1/3} k_n^{2/3} \quad (9)$$

Application to the case of a duct obstructed by a diaphragm

The SNGR model was first applied to cases of axisymmetric subsonic jets.^{2,4,6} The configuration of the 2D duct obstructed by a diaphragm (see figure 1) has already been studied²⁷ and we here use the same aerodynamic results.

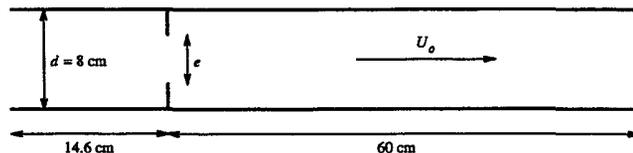


Figure 1: Sketch of the geometry.

Aerodynamic results

The mean flowfield is calculated as a numerical solution of the average Navier-Stokes equations associated with a $k - \epsilon$ turbulence closure. These calculations are carried out with the ESTET code developed by the "Laboratoire National Hydraulique" of the "Direction des Etudes et Recherches d'Electricité de France" and are performed on a grid of 190×83 points. The mesh is finer close to the diaphragm. The smallest mesh size is 1.0×10^{-3} m and the largest is 5.0×10^{-3} m. The computational domain is displayed in figure 2 and a view of the grid close to the diaphragm is shown in figure 3. It is not necessary to discretize a large part of the duct upstream of the diaphragm. The two main parameters for these calculations are the aperture e of the diaphragm and the mean flow velocity in the duct U_0 . The configurations studied are summarized in table 1.



Figure 2: Global view of the computational domain used in the ESTET calculations.

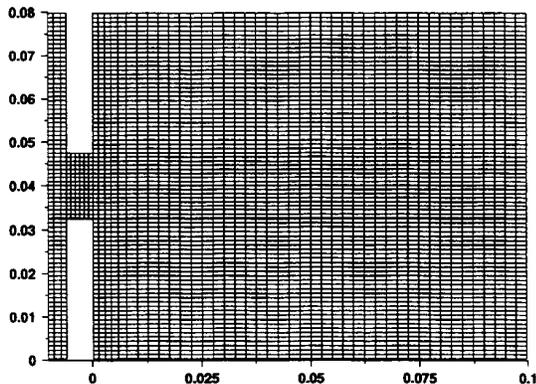


Figure 3: Partial view of the grid used in the ESTET calculations.

Figure 4 shows fields of turbulent kinetic energy for three configurations. For the smallest aperture ($e = 15$ mm), the flows are always non symmetrical. For the largest aperture ($e = 55$ mm), the flows are always symmetrical. For the aperture of 35 mm, the flow is symmetrical up to 14 m/s

Acoustic results

The acoustic propagation computations are carried out with the EOLE code developed by the "Acoustique et Mécanique Vibratoire" Department of the "Direction des Etudes et Recherches d'Electricité de France". The EOLE code solves the Euler linearized Equations using

U_0 (m/s)	14	23	32	55	75
$e = 15$ mm	×	×	×	-	-
$e = 35$ mm	×	-	×	-	×
$e = 55$ mm	-	-	×	×	×

Table 1: Configurations analysed in this study.

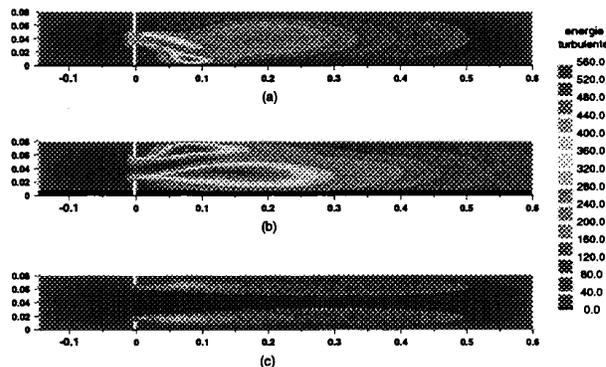


Figure 4: Comparison between turbulent kinetic energy for three configurations: (a) $e = 15$ mm et $U_0 = 14$ m/s, (b) $e = 35$ mm et $U_0 = 32$ m/s, (c) $e = 55$ mm et $U_0 = 55$ m/s.

a fractional step scheme and relies on solutions of one-dimensional propagation problems in terms of a weak formulation.¹¹ Numerical tests indicate that sound wave propagation is calculated with little dispersion and dissipation. Some applications to the propagation in hot jets show that the effects of convection and refraction are retrieved in the predicted sound field.¹⁸

The acoustic calculations are performed on a grid of 601×32 points. The mesh size is constant (3.0×10^{-3} m). The acoustic computational domain is displayed on figure 5 and a view of the grid close to the diaphragm is presented on figure 3.

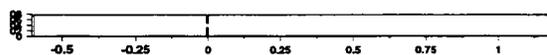


Figure 5: Global view of the computational domain used in the EOLE calculations.

Aerodynamic and acoustic computations require different grids and mesh sizes because:

- local mesh refinements on the aerodynamic grid are needed because of the viscous effects
- larger upstream and downstream discretized domains are needed by the acoustic calculation in order to capture the far field
- the accuracy of the acoustic computation requires a regular grid.

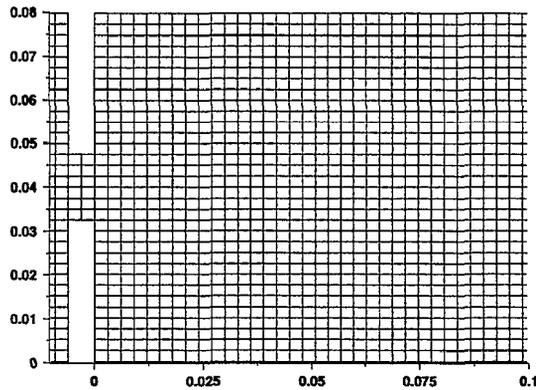


Figure 6: Partial view of the grid used in the EOLE calculations.

- the accuracy of the acoustic computation requires a regular grid.

The isentropic Euler linearized equations bear acoustic fluctuations which are propagative ones but also vorticity fluctuations which are convective ones. It is known that in a mean sheared flow these two modes of fluctuations are coupled. But, even in an uniform flow, vorticity fluctuations will appear if the source term is not irrotational.

In the duct problem, the radiated acoustic power is obtained by recording the pressure fluctuations at both ends of the computation domain. Thus, in the general case, acoustic fluctuations but also vorticity fluctuations would be recorded at the downstream boundary of the domain and the calculation of the radiated acoustic power would be difficult because vorticity fluctuations are much stronger than acoustic fluctuations.

It follows that three kinds of acoustic propagation calculations may be carried out:

- without taking into account the influence of the mean flow in order to avoid the development of the vorticity mode
- taking into account the influence of the mean flow but neglecting in the system of the Euler linearized equations the coupling terms between the two modes. These terms are identified as those containing mean velocity gradients.¹⁹
- solving the full system of the linearized Euler equations.

Results obtained with the first and second methods of calculation are presented in this paper.

Without mean flow

Effects of the mean flow on the propagation are not taken into account but in the low subsonic range we may expect that their influence will not be essential.

Figures 7, 8, 9 present the acoustic power radiated with respect to the mean velocity in the duct. The experimental results obtained in a previous study²⁷ and the expected U^4 law typical of the acoustic radiation in such confined configurations are also plotted.

Figure 10 displays the intensity spectrum for one configuration ($e = 35$ mm and $U_0 = 14$ m/s). Here again the result given by the SNGR model is close to the experimental one and the evolution of the computed levels with respect to the frequency is well retrieved.

With mean flow

In these calculations, the vorticity mode can develop. The simplest way to separate acoustic and vorticity fluctuations is to use their difference in speed of propagation. The computational domain is chosen long enough to be able to record acoustic fluctuations before vorticity fluctuations arrive. Table 2 compares the acoustic results for three configurations with and without mean flow. The differences are quite small.

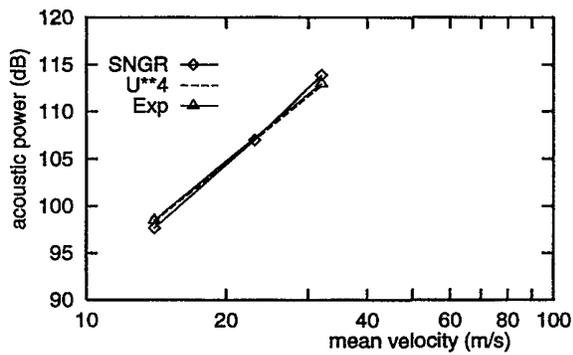


Figure 7: Acoustic power radiated by the diaphragm $e = 15$ mm with respect to the mean flow velocity.

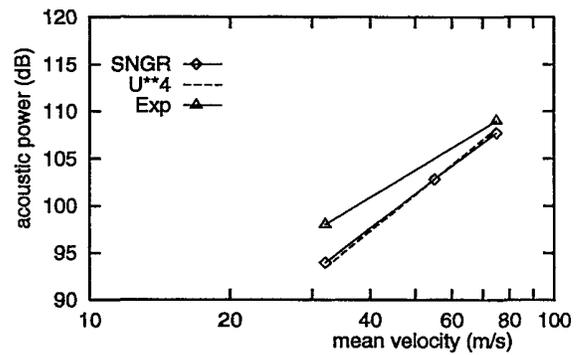


Figure 9: Acoustic power radiated by the diaphragm $e = 55$ mm with respect to the mean flow velocity.

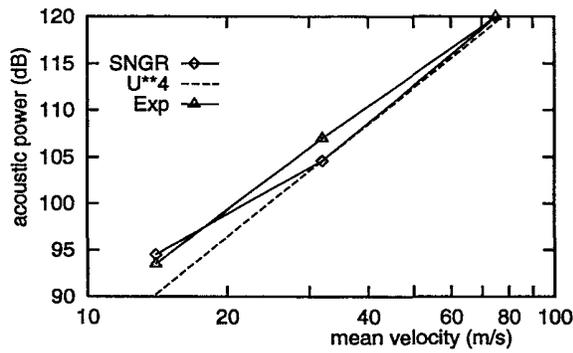


Figure 8: Acoustic power radiated by the diaphragm $e = 35$ mm with respect to the mean flow velocity.

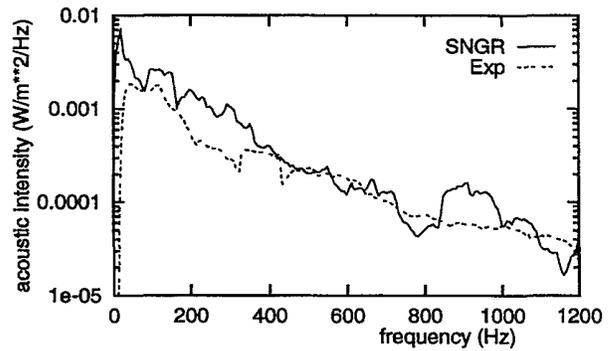


Figure 10: Comparison of acoustic intensity results for the configuration $e = 35$ mm and $U_0 = 14$ m/s

Configuration aperture (mm) velocity (m/s)	acoustic power (dB) without flow	acoustic power (dB) with flow
$e = 15 / U_0 = 23$	107.0	105.3
$e = 35 / U_0 = 32$	104.6	102.8
$e = 55 / U_0 = 55$	102.8	102.9

Table 2: Comparison of acoustic power results obtained with and without mean flow.

Conclusion

The SNGR model was used in a previous study to calculate acoustic radiation from free jets. It is here applied to estimate acoustic radiation in a confined configuration. It is shown that the SNGR model provides useful results with good agreement with experimental data.

The interaction of the mean flow with the acoustic radiation is not clearly highlighted. Numerical and physical problems have to be assessed in order to improve the interpretation of the results given by the SNGR model.

References

- [1] BAILLY, C., BÉCHARA, W., LAFON, P. & CANDEL, S. 1993 Jet noise predictions using a $k - \epsilon$ turbulence model, *15th Aeroacoustics Conference, AIAA Paper 93-4412*, October 25-27, Long Beach, C.A.
- [2] BAILLY, C. 1994 Modélisation du rayonnement acoustique des écoulements turbulents libres subsoniques et supersoniques, Ph.D. thesis, Ecole Centrale Paris, 1994-19.
- [3] BAILLY, C., LAFON, P. & CANDEL, S. 1994 Computation of subsonic and supersonic jet mixing noise using a modified $k - \epsilon$ turbulence model for compressible free shear flows, *Acta Acustica*, **2(2)**, 101-112.
- [4] BAILLY, C., LAFON, P. & CANDEL, S. 1995 A stochastic approach to compute noise generation and radiation of free turbulent flows, *16th Aeroacoustics Conference, AIAA Paper 95-092*, June 12-15, Munich, Germany.
- [5] BATCHELOR, G. K. 1953 The theory of homogeneous turbulence, Cambridge University Press, Cambridge.
- [6] BÉCHARA, W., *et al.* 1994 Stochastic approach to noise modeling for free turbulent flows, *AIAA Journal*, **32(3)**, 455-463.
- [7] BÉCHARA, W., LAFON, P., BAILLY, C. & CANDEL, S. 1995 Application of a $k - \epsilon$ model to the prediction of noise for simple and coaxial free jets, *J. Acoust. Soc. Am.*, **97(5)**, 1-14.
- [8] CHU, B.T. & KOVASZNAV, L.G.S. 1958 Non-linear interactions in a viscous heat-conducting compressible gas, *J. Fluid Mech.*, **3(5)**, 494-514.
- [9] CRIGHTON, D. 1975 Basic principles of aerodynamic noise generation, *Prog. Aerospace Science* **16(1)**, 31-96.
- [10] DOAK, P.E. 1972 Analysis of internally generated sound in continuous materials: 2. A critical review of the conceptual adequacy and physical scope of existing theories of aerodynamic noise, with special reference to supersonic jet noise, *J. Sound Vib.*, **25(2)**, 263-335.
- [11] ESPOSITO, P. 1987 A new numerical method for wave propagation in a complex flow, *5th International Conference on Numerical Methods in Laminar and Turbulent Flow*, Montréal, July.
- [12] FLOWERS WILLIAMS, J.E. 1963 The noise from turbulence convected at high speed, *Philosophical Transactions of Royal Society of London A255*, 469-503.
- [13] GOLDSTEIN, M.E. & ROSENBAUM, B. 1973 Effect of anisotropic turbulence on aerodynamic noise, *J. Acoust. Soc. Am.*, **54(3)**, 630-645.
- [14] GOLDSTEIN, M.E. 1976 *Aeroacoustics*, McGraw-Hill, New York.
- [15] KARWEIT, M., BLANC-BENON, P. JUVÉ D., & COMTE-BELLOT, G. 1991 Simulation of the propagation of an acoustic wave through a turbulent velocity field: A study of phase variance, *J. Acoust. Soc. Am.*, **89(1)**, 52-62.
- [16] KISTLER, A.L. & CHEN, W.S. 1962 The fluctuating pressure field in a supersonic turbulent boundary layer, *J. Fluid Mech.*, **16(1)**, 41-64.
- [17] KRAICHNAN, R.H. 1970 Diffusion by a random velocity field, *Phys. Fluids*, **13(1)**, 22-31.
- [18] LAFON, P. 1989 Propagation acoustique bidimensionnelle. Deux applications du code EOLE, *Direction des Etudes et Recherches d'Electricité de France*, HP 54/89/010.
- [19] LAFON, P. 1995 Application du modèle SNGR de génération de bruit au cas d'un diaphragme en conduit, *Direction des Etudes et Recherches d'Electricité de France*, HP 63/95/032/A.
- [20] LIGHTHILL, M.J. 1952 On sound generated aerodynamically - I. General theory, *Proceedings of the Royal Society of London*, **A211**, 1107, 564-587.

- [21] Lighthill, M.J. 1954 On sound generated aerodynamically - II. Turbulence as a source of sound, *Proceedings of the Royal Society of London*, **A222**, 1148, 1-32.
- [22] Lilley, G.M. 1972 The generation and radiation of supersonic jet noise. Vol. IV - Theory of turbulence generated jet noise, noise radiation from upstream sources, and combustion noise. Part II: Generation of sound in a mixing region, *Air Force Aero Propulsion Laboratory*, AFAPL-TR-72-53.
- [23] Maestrello, L., Bayliss, A. & Turkel, E. 1981 On the interaction of a sound pulse with the shear layer of an axisymmetric jet, *J. Sound Vib.*, **74(2)**, 281-301.
- [24] Phillips, O.M. 1960 On the generation of sound by supersonic turbulent shear layers, *J. of Fluid Mech.* **9(1)**, 1-28.
- [25] Ribner, H.S. 1969 Quadrupole correlations governing the pattern of jet noise, *J. of Fluid Mech.*, **38(1)**, 1-24.
- [26] Tennekes, H., Lumley, J.L. 1972 A first course in turbulence, The MIT Press, Cambridge.
- [27] Van Herpe, F., Crighton, D.G., Lafon, P. 1995 Noise generation by turbulent flow in a duct obstructed by a diaphragm *16th Aeroacoustics Conference*, AIAA Paper 95-035, June 12-15, Munich, Germany.
- [28] Yates, J.E. 1978 Application of the Bernoulli enthalpy concept to the study of vortex noise and jet impingement noise, NASA, 2987.

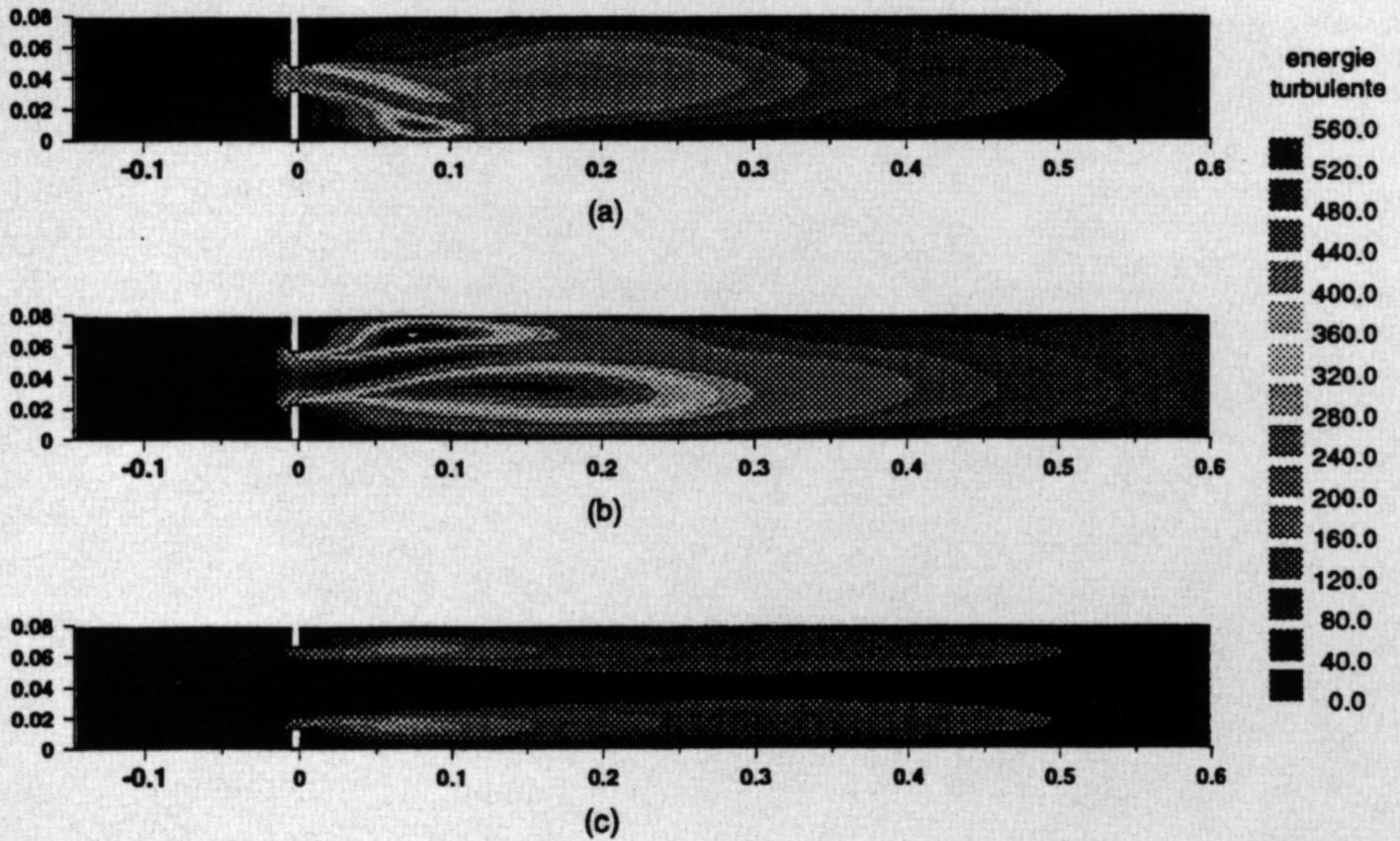


Figure 4: Comparison between turbulent kinetic energy for three configurations: (a) $e = 15$ mm et $U_0 = 14$ m/s, (b) $e = 35$ mm et $U_0 = 32$ m/s, (c) $e = 55$ mm et $U_0 = 55$ m/s.