Large eddy simulation of acoustical propagation in turbulent channel flow

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Introduction

Velocity fluctuations, caused either by imposing sound on a turbulent flow or by pulsating the flow, generate a shear wave at the wall. This shear propagates into the boundary layer and decays within the turbulence equivalence of the laminar Stokes length. Ronneberg & Ahrens [1] related the phase averaging of the wall shear to the loss of acoustical energy and, this way, they determined experimentally the attenuation of the sound wave. At high driving frequencies the damping is not influenced by turbulence. On the contrary, for low driving frequencies turbulence increases the sound attenuation. The rather surprising fact is that for a range of driving frequencies, the damping is reduced by turbulence. This was recovered in Large Eddy Simulation of a pulsating [2], but at too a high a forcing amplitude to be relevant to acoustical propagation. We consider the advection by a turbulent non-pulsating channel flow of a passive scalar with oscillating boundary conditions. In this way, retroaction on the turbulent flow is suppressed and the forcing amplitude is no longer a parameter. We first introduce the numerical method, then we present the main results concerning the scalar flux at the wall and the topology of the scalar field.

Numerical approach

LES of isothermal plane channel flow with advection of a passive scalar oscillating at the walls are carried out. The turbulent flow has the following caracteritics: Reynolds number $R_e = U_b h/\nu$ based on bulk velocity and channel half-height is equal to 3000, the one based on the friction velocity $R_e\tau = u_\tau h/\nu$ is equal to 180; Mach number was set to 0.3 so that compressibility effects are negligeable. We considered the macro-temperature closure of the compressible Navier-Stokes equations in conservation formulation [3], and for the scalar we consider a transport equation. We use the same subgrid-scale model and numerical methods as in [4], namely, the *filtered structure-function model* and an explicit McCormack scheme with 4th order accurate discretisation of the inviscid fluxes. All the calculations have been performed in a domain of size $(L_x/h, L_y/h, L_z/h) = (4\pi, 2, 4/3\pi)$, x and z being directions of homogeneity. Let ω be the pulsation of the scalar oscillation. Then, the diffusivity of the scalar $\kappa = \nu/S_c$ is chosen for $l_s = (2\kappa/\omega)^{1/2}$, the laminar Stokes length or penetration length, to reach a particular location in the flow. Both parameters ω and l_s are made dimensionless with inner variables: $\omega^+ = \omega\nu/u_\tau^2$ and $l_s^+ = \sqrt{2/(\omega^+ S_c)}$.

Results

For the turbulent base flow, we referred to a previous paper: [5]. In addition to the flow validation, in this parper we show the structure of the turbulence likely to interact with the Stokes layer.

Three series of calculations have been performed : the first with a constant penetration length of 30 wall units and the pulsation ω^+ ranging from 0.01 to 0.17. The second and third runs correspond respectively to $\omega^+ = 0.015$ and $\omega^+ = 0.1$ whith l_s^+ ranging from 15 to 30. To reduce the data, we consider first a plane and time averaging ($\overline{c}$), useful in unsteady problems. In addition to plane averaging in the direction of homogeneity, phase averaging ($<\overline{c}>$) is effective in extracting the coherent response of the scalar to the oscillation. Moreover, in all cases, the quantities under consideration show a peak at the forcing frequency, therefore the quantities have been phase-averaged over the period set by the forcing.

$$\overline{c}(y,t) = \frac{1}{L_x L_z}\int_0^{L_z}\int_0^{L_x} c(x,y,z,t)\,dxdz$$

$$<\overline{c}>(y,t') = \frac{1}{N}\sum_{n=1}^{N}\overline{c}(y,t'+nT), t' \in [0, 2\pi/\omega^*]$$

For all cases, $<\overline{c}>$ corresponds to a monochromatic signal $<\overline{c}>(y,t') = A(y)cos(\omega^* t' + \Phi(y))$, for which we have determined the amplitude and the phase shift with a "least squares" method (Levenberg-Marquardt).

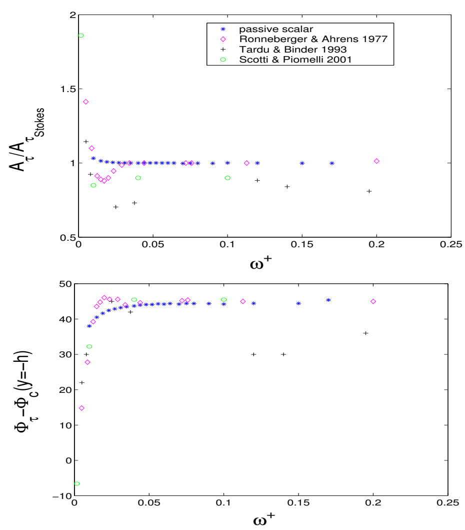

Figure 1: Normalized wall shear impedance as a function of the pulsation ω^+. **Above:** amplitude normalized by the laminar Stokes value $A_{\tau_{Stokes}}$. **Under:** phase shift between the shear and the forcing at the wall. The laminar Stokes solution corresponds to 45°

ω^+	S_c	κ	l_s^+	$\kappa_t(l_s^+)$	$\kappa/\kappa_t(l_s^+)$
0.015	0.5926	$5.62e^{-4}$	15	$2.7e^{-4}$	2.08
	0.4613	$7.22e^{-4}$	17	$3.5e^{-4}$	2.06
	0.1481	$2.25e^{-3}$	30	$1.16e^{-3}$	2.16
	1	$1/R_e$	$\sqrt{2/\omega^+}$	$\nu_t(l_s^+)$	2
0.1	0.5926	$3.7e-3$	15	$1.5e^{-4}$	24.6
	0.0781	$4.8e^{-3}$	17	$2e^{-4}$	24
	0.0222	$1.5e^{-2}$	30	$6.3e^{-4}$	23.6
	1	$1/R_e$	$\sqrt{2/\omega^+}$	$\nu_t(l_s^+)$	25

Table 1: Evolution of the laminar and eddy diffusivity with ω^+ and l_s^+

We considered the mean-averaged scalar transport equation :

$$\frac{\partial <c>}{\partial t} + <v> \frac{\partial <c>}{\partial y} = \frac{\partial}{\partial y}\left[- <v''c''> + \frac{1}{R_e S_c}\frac{\partial <c>}{\partial y}\right]$$

The oscillating boundary condition creates an oscillating shear wave at the wall which generates fluctuations in the turbulent scalar quantities.
By Analogy to sound attenuation or shear stress reduction, we show in Figures 1, the amplitude and the phase of the phase-averaged scalar gradient at the wall $\left\langle (\partial c/\partial y)_w \right\rangle = A_\tau(y) cos[\omega t + \Phi_\tau(y)]$, compared with experimental and numerical counterparts in pulsating flows ([1],[2],[6]). The general trends are recovered, namely, negligible departure from the laminar Stokes solution at high driving frequencies, and increasing shear with decreasing phase shift at low frequencies. The dip of A_τ below its Stokes value, whose origin is still controversial, is not recovered in this approach. We try to explain the low and high frequency regims with an eddy diffusivity assumption. It seems that the eddy diffusivity κ_t ($< v"c" >= -\kappa_t \partial < c > /\partial y$), is defined only as a function of y and ω^+.
In table 1, we actually see that whatever the penetration length is, for a given frequency, the ratio between laminar ($\kappa = \nu/S_c$) and eddy diffusivity is constant. Moreover, this ratio decreases as the pulsation increases. Thus in the high frequency regime, the eddy diffusivity is always nefligible compared to the laminar diffusivity. In the low frequency regime, the eddy diffusivity becomes of the same order of magnitude as the laminar diffusivity, and turbulence is no more negligible. We still miss the particular case, currently in progress, corresponding to both critical pulsation and critical penetration length. Thus we can not yet conclude concerning the critical zone. Nevertheless, with our linearized approach, we are abble to capture some turbulence effects. The low and high frequency regimes are recovered : as the forcing frequency is lowered, turbulence as time enough during one period to affect the scalar field. This increasing sensibility to turbulence as the freqency is lowered is also observed in the topology of the scalar field. Instantaneous scalar fields actually show a streamwise striation very similar to the one of the turbulent temperature fluctuations, as can be seen on Figures 2. Moreover, the level of the scalar fluctuations, normalized with the wall concentration is lower for the higher frequency.

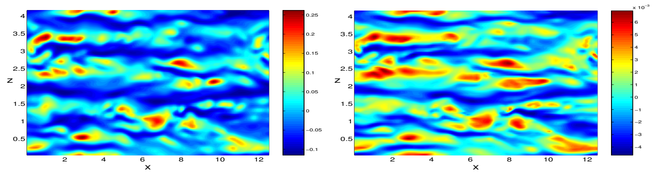

Figure 2: Section of scalar and temperature fluctuations at $y^+ = 5$. **Left:** scalar fluctuation c" for ($\omega^+ = 0.01$,$l_s^+ = 30$). **Right:** temperature fluctuation

Conclusions

In order to clarify the study of pulsatile channel flow with small amplitudes of oscillation, relevant for the sound propagation study, we performed LES of advection/diffusion of a passive scalar oscillating at the wall. The oscillating passive scalar obeys the laminar Stokes law at high driving frequencies and exhibits increasing wall shear at decreasing frequency, in agreement with experimental and numerical results in pulsating shear flows. These trends seem to correspond to the variation of the eddy diffusivity as a function of the pulsation. The established albeit controversial subrange of reduced shear is not recovered with this linearized scalar approach for the ranged tested. Although it seems that the laminar to eddy diffusivity ratio is independant of the penetration length, we still miss the specific case corresponding to both critical pulsation and critical penetration length to conclude. Future work will consist in the study of the coupled problem of pulsatile turbulent channel flow with acoustical wall treatements. The results will be compared to an experimental study realised at the same time in the Laboratoire d'Acoustique de l'Université du Maine at Le Mans.

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