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GENERATION OF TURBULENT INFLOW DATA WITH A PRESCRIBED SHEAR-STRESS PROFILE

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1. Background and objectives

Simulation of spatially developing turbulent flows using DNS or LES requires specification of unsteady inflow data. Several methods for generating turbulent inflow data for wall-bounded flows have been proposed which introduce a temporal periodicity (e.g. [1, 2, 11, 13]) on a time-scale of $\mathcal{O}(10)\ \delta_{99}/U_\infty$ that can interfere with low-frequency flow dynamics. This might not be an issue in a spatially evolving mixing layer, since it was found by [9] that the temporal correlation introduced by the inflow generation decayed quickly with streamwise distance from the domain inlet. However, in flows involving separation from a smooth surface it has been observed that the periodicity of the inflow signal can trigger the unsteady behavior of the detachment point of a separation bubble [1].

Other inflow generation methods which are based on specification of random numbers at the inlet plane avoid the issue of temporal periodicity [7, 8]. However, they are known to require an extended spatial development region to reach equilibrium and the integral properties of the developing boundary layer are difficult to control with this approach.

Here, we propose a new method which avoids certain drawbacks of the former approaches. The method is based on random numbers and therefore avoids long-range temporal correlations. By introducing body forces in the framework of closed-loop control we are able to (i) accelerate the adjustment process towards equilibrium turbulence and to (ii) precisely control integral properties of the boundary layer.

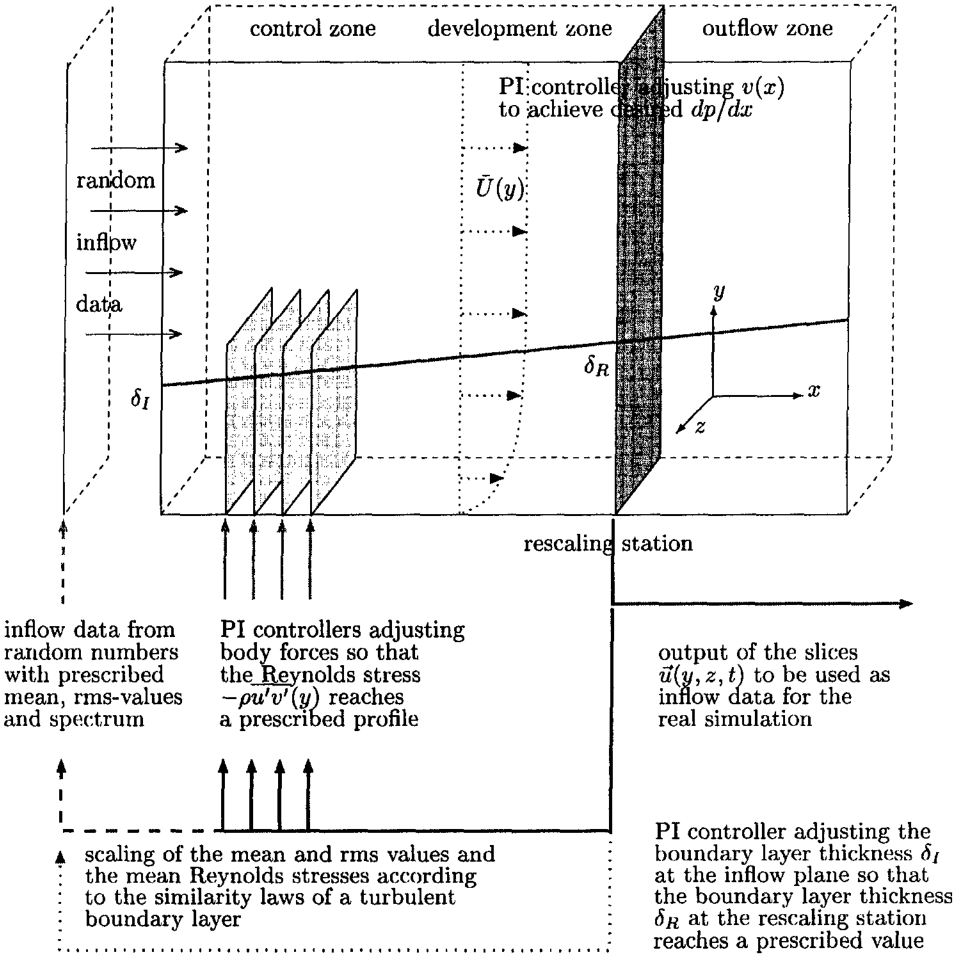

Figure 1. Sketch of the computational domain and outline of individual steps of the method.

2. Method

Similarly to [11], we demonstrate the proposed new inflow generation method for a Navier-Stokes simulation (DNS or LES) of a spatially developing turbulent boundary layer in a rectangular computational domain, see Fig. 1. At the inlet plane, we specify mean flow $U(y), V(y)$ and superimposed fluctuations $u'(y,z,t), v'(y,z,t), w'(y,z,t)$, generated from random Fourier coefficients similarly to [7]. The amplitudes of the coefficients follow a prescribed spectrum ($k < k_p$: $E(k) \sim k^2$; $k > k_p$: $E(k) \sim k^{-5/3}$) and the profiles of $u'_{rms}(y), v'_{rms}(y), w'_{rms}(y)$ match those obtained after time-averaging and rescaling the instantaneous flow obtained at the "rescaling station", which is located at x_R at the end of the development zone. Since it is impossible to provide *a priori* the correct phase relation between individual Fourier modes, turbulence decays downstream of the inlet plane.

In the control zone the flow is subject to a body force f acting in the wall-normal direction according to

$$\frac{\partial \vec{u}}{\partial t} + (\vec{u} \cdot \vec{\nabla})\,\vec{u} = -\vec{\nabla}p + \frac{1}{Re}\,\Delta\,\vec{u} + f\vec{e}_y.$$

The rationale behind this approach is the observation that $-\overline{v'v'}dU/dy$ forms the dominant production term in the balance equation for the shear stress $-\rho\overline{u'v'}$. The body forces act simultaneously in several x, z-planes which are $\mathcal{O}(1)\delta_{99}$ apart in the streamwise direction.

The magnitude of the body force at a streamwise location x_0 is adjusted via a PI–controller with the goal to achieve a prescribed shear-stress profile $g(x_0, y)$. The target shear stress $g(x_0, y)$ is obtained by upstream extrapolation based on a similarity hypothesis using the mean stress $-\rho\overline{u'v'}^{\,z,t}(y)$ at the rescaling station as in Lund's method [11]. Here, $\overline{()}^{\,z,t}$ denotes averaging in the spanwise direction and over $\mathcal{O}(10)\delta_{99}/U_\infty$ in time. The use of a "rescaling" station is not mandatory, since the target profile $g(x_0, y)$ might also come from an experiment or from a RANS calculation – possibly carried out simultaneously with the LES.

The input of the PI controller at the location x_0, the error signal e, is computed as

$$e(y,t) = -\rho\overline{u'v'}^{\,z,t}(x_0,y,t) - g(x_0,y)\,.$$

With the amplitude

$$r(y,t) = \alpha\, e(y,t) + \beta \int_0^t e(y,t')\,\mathrm{d}t',$$

the instantaneous body force is computed as

$$f(x_0,y,z,t) = r(y,t)[u(x_0,y,z,t) - \overline{u}^{\,z,t}(x_0,y)].$$

In order to prevent stimulation of unrealistic large shear stress 'events', f is only applied if the following constraints for the instantaneous, local correlation $u'v'(x_0,y,z,t)$ and the fluctuations $u'(x_0,y,z,t)$ and $v'(x_0,y,z,t)$ are met:

$$|u'| < 0.6\,U_\infty,\ |v'| < 0.4\,U_\infty,\ u'v' < 0 \quad \text{and} \quad |u'v'| > 0.0015\,U_\infty^2.$$

The parameters α, β of the PI controllers are chosen in order to decrease the error signal sufficiently fast without causing instabilities.

A closed-loop controller is used to control the boundary layer thickness δ_I at the domain inlet until δ_{99} at the rescaling station reaches a target value δ_R. Similarly, $v(x)$ at the top of the domain is adjusted via a feedback loop in order to obtain a desired streamwise pressure gradient, e.g. $dp/dx \approx 0$. The adjustment times for reaching approximately steady values are of $\mathcal{O}(100)\delta_{99}/U_\infty$.

The incompressible Navier-Stokes equations for primitive variables u, v, w, p are solved on a staggered mesh. The non-linear term is discretized in the skew-symmetric form, guaranteeing conservation of kinetic energy in the absence of viscosity [12, 6, 5]. Spatial derivatives in the wall-parallel directions (x, z) including the pressure gradient and the continuity equation are approximated with 6th-order compact (Hermitian) differences. Explicit second order differences are used in the non-equidistant wall-normal direction. The pressure Poisson equation is solved via Fourier transform in the spanwise periodic direction and via cosine transform in the streamwise direction where the pressure satisfies a von Neumann boundary condition. At the outflow plane we specify a convective outflow boundary condition. The Smagorinsky model accounts for the sub-grid-stresses with the model constant determined via the dynamic procedure [4] in the formulation of Lilly [10]. The test filter is approximated with the trapezoidal rule, filtering is limited to the wall-parallel directions, and the ratio of test and grid filter width is $\widehat{\Delta}/\Delta = 2.0\sqrt{3/2}$.

3. Results

The method has been applied in an LES in a domain of size $18\delta_0 \times 3.5\delta_0 \times 2.2\delta_0$. The reference length δ_0 corresponds approximately to the 99%-thickness of the boundary layer at the "rescaling" station which is located at $x_R = 12\delta_0$. There, integral properties of the turbulent boundary layer are $\theta/\delta_0 = 0.129$, $\delta^*/\delta_0 = 0.187$, $c_f = 0.00353$, and $H_{12} = 1.44$. This corresponds to $Re_\theta = 1816$, $Re_{\delta^*} = 2616$, and $Re_\tau = u_\tau\delta_{99}/\nu = 780$. The domain is discretized into $144 \times 55 \times 48$ cells. At the rescaling station, the grid spacing normalized in wall-units is $\Delta x^+ = 98, \Delta y^+_{min} \approx 1.2$, and $\Delta z^+ = 36$. Body forces act at three stations located at $x/\delta_0 = 2$, 3.75, and 5.5. In the wall-normal direction they are limited to the region $0.05 < y/\delta_0 < 0.5$. Results are compared with the random-phase method of [7] where no adjustment by body forces takes place.

Fig. 2 and 3 show the results in terms of 'streamwise' evolution of skin friction coefficient $c_f = \rho u_\tau^2/(0.5U_\infty^2)$, shape factor $H_{12} = \delta^*/\theta$ and velocity derivative skewness coefficient $S_{\partial u/\partial x} = \overline{(\partial u/\partial x)^3}/\overline{(\partial u/\partial x)^2}^{1.5}$.

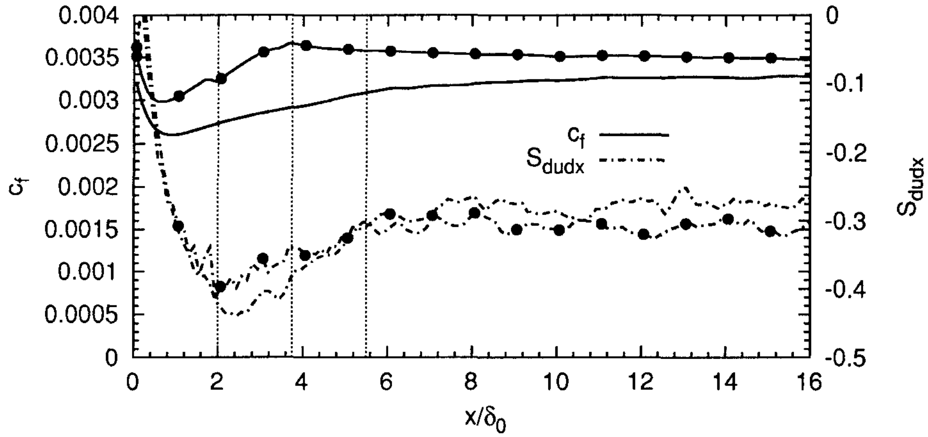

Figure 2. Streamwise development of friction coefficient c_f (left axis) and velocity derivative skewness $S_{\partial u/\partial x}$ (right axis). Lines corresponding to the forced case are marked with additional dots. Vertical lines denote the three forcing locations.

Inflow generation by random numbers causes a strong deviation of statistics from equilibrium values due to the lack of proper correlations. Obviously, with body forces the development length needed for reaching a statistical equilibrium is shortened considerably. This can be seen from the quicker recovery of c_f and $S_{\partial u/\partial x}$, the latter being an indicator for the onset of non-linear energy transfer. Comparison with experimental data in Fig. 3 reveals, that the auxiliary body forces are beneficial for driving the boundary layer closer to an equilibrium state.

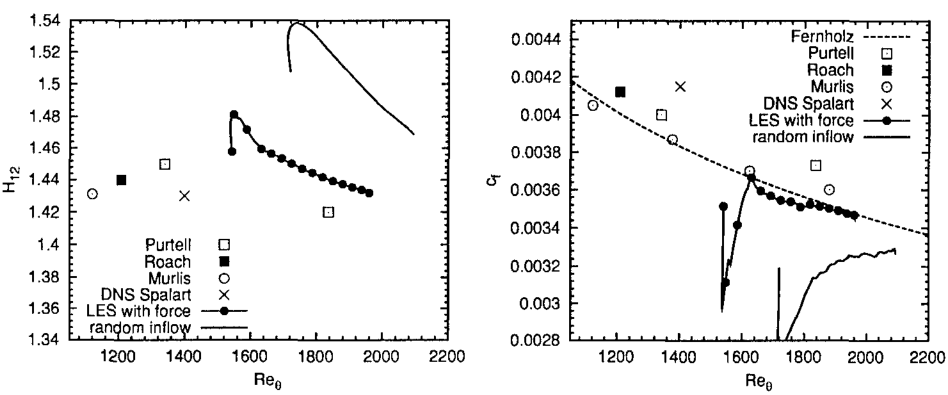

Figure 3. Shape factor H_{12} and skin friction coefficient c_f as function of Re_θ. For comparison we include DNS and experimental data, for the references see Fernholz & Finley (1996).

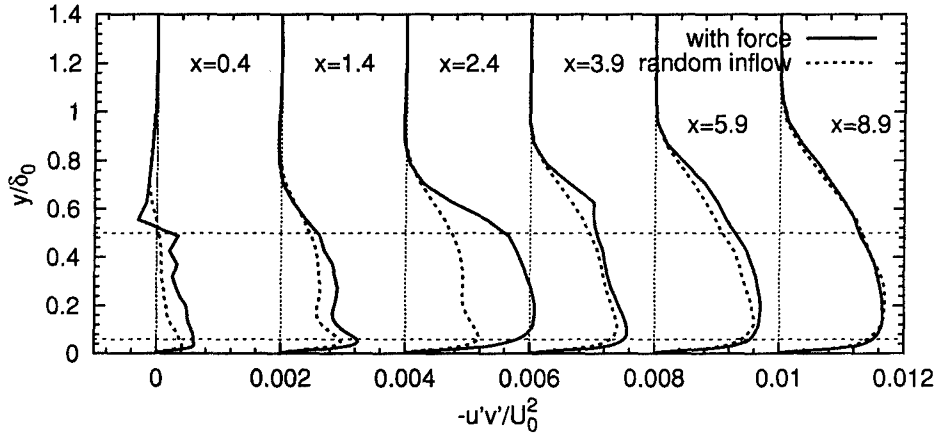

Figure 4. Profiles of shear stress $-\overline{\rho u'v'}$ at several stations as indicated in the plot for the new method (———) and the random method (- - - -). Horizontal lines indicate the zone in which the body forces act.

Fig. 4 shows the streamwise development of the shear-stress profile. Ahead of the first forcing station, shear-stresses are too small due to lack of proper correlation between u' and v' fluctuations at the domain inlet. Without body forces, recovery of the profiles proceeds quicker near the wall than in the outer part of the boundary layer. The addition of body forces at $x/\delta_0 = 2$ has some influence on the flow upstream. At $x/\delta_0 = 2.4$ we observe the largest difference between forced and unforced cases. The forcing at the first station results in an overshoot in the shear-stress magnitude. As a consequence, body-forces at the second station – located at $x/\delta_0 = 3.75$ – counteract the wall-normal fluid motion, thereby reducing the shear-stress to the desired levels. The amplitude of the force decreases nearly an order of magnitude from the first to the last station.

Downstream of the forcing zone the flow recovers into an equilibrium state. The mean flow profile follows the standard log-law, see Fig. 5. We observe a pronounced wake which does not seem to be connected with the forcing since it is also visible in the unforced case. Rms-profiles of the resolved velocity fluctuations are in good agreement with DNS data.

For a coarse-grid DNS at $R_\theta \approx 340$ carried out in a domain of size $10\delta_{99} \times 3\delta_{99} \times 3\delta_{99}$, the new method was compared with Lund's [11] approach. The rescaling station was located at $x_R/\delta_{99} = 6.3$. Power spectra recorded inside and outside the boundary layer are shown in Fig. 6. Whereas Lund's method exhibits peaks at frequencies U_∞/x_R and its higher harmonics, spectra from the new method are smooth in the low-frequency range. Thus, the proposed method is capable of generating inflow turbulence without introducing a quasi-periodicity at low frequencies.

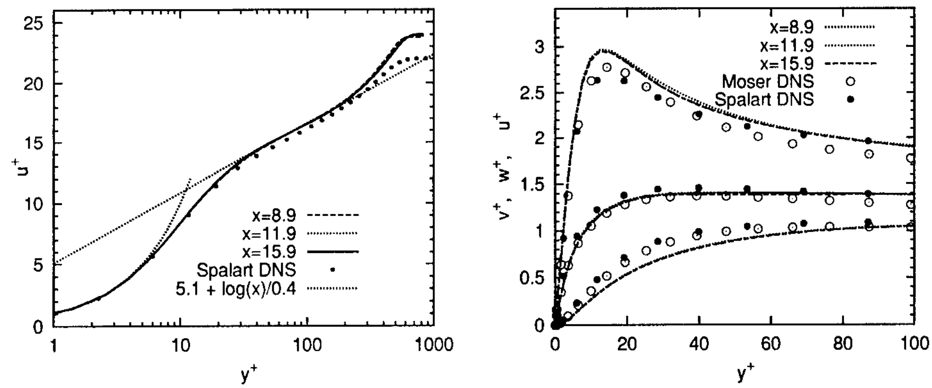

Figure 5. Mean flow profile and turbulence statistics scaled in inner variables at several downstream locations.

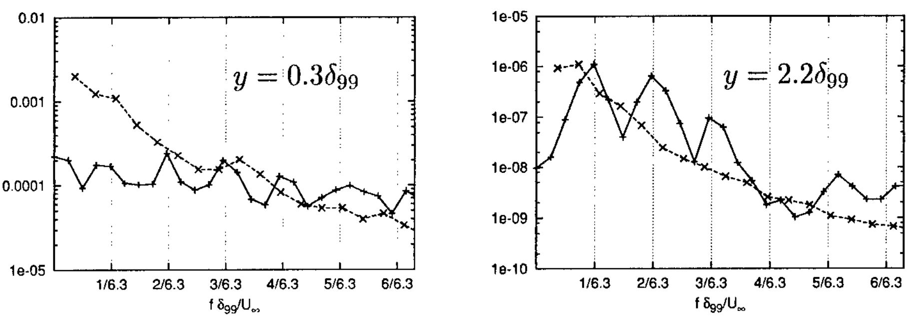

Figure 6. Power spectra Φ_{uu} at x_R inside (left) and outside (right) of the boundary layer using Lund's method (———) and the new approach (········) for a coarse-grid DNS at $R_\theta \approx 340$.

4. Conclusions and perspectives

We propose a new method for the generation of turbulent inflow data which avoids a long-range temporal correlation in the artificial velocity signal. It turns out that the method is fairly robust with respect to several of the parameters which can be chosen. These include the spectrum of the random turbulence introduced at the domain inlet, the streamwise extent of the control zone, the number of x, z-planes where body-forces are applied, the streamwise spacing between stations, and the vertical extent of the forcing zone.

The method is not restricted to equilibrium situations since turbulence is forced to follow a prescribed target profile. The method is capable to both enhance and damp existing fluctuations in order to achieve a desired target, e.g. the shear stress $\overline{u'v'}$. The method can easily be extended to consider other targets such as $\overline{U}$ or rms profiles. Possibly, the occurence of "adverse" forces at later stations could be avoided entirely by correcting only part of the "error" at the first station.

Similar strategies might be applied in the context of hybrid RANS/LES approaches, where zones exist in which the grid is too coarse for resolving a sufficient range of energy containing eddies, e.g. near the wall. There, the generation of "supporting" stresses induced by body forces might be useful in order to achieve a smooth transition between regions which are modeled via RANS and via LES, respectively.

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