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A fully synthetic turbulent boundary condition with a homogeneous vortex distribution

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ABSTRACT

Temporally and spatially resolved simulations of turbulent flow need realistic inlet velocity fluctuations. The vortex method, described and implemented in this work, adds vortices to the inlet mean flow profile. The vortices are randomly distributed over the inlet and they move across the extent of the inlet with a finite life-time. The initial vortex sizes, strengths, as well as their developing motion and life-times, are determined by the inlet mean velocity and turbulence distributions. In contrast to previous studies of the vortex method, the inlet mean velocity and turbulence distributions are in the present work theoretically determined, and thus form an explicit part of the boundary condition. This makes the method independent of precursor RANS simulations. Special care has been taken to distribute the vortices evenly across the inlet. The tangential velocity of the vortices is randomly initialized and the spatial and temporal correlation is preserved. An edge bouncing mechanism is implemented at solid boundaries.

The boundary condition is applied to a DNS simulation of pipe flow at a Reynolds number of 5300, based on pipe diameter, aiming at reaching fully developed conditions at a short distance from the inlet. The results are compared with those using cyclic boundary conditions, and with two DNS results found in the literature. It is shown that a good agreement is reached for the mean velocity profiles five pipe diameters downstream from the inlet. Also the resolved velocity fluctuations at that location are reasonable. It is concluded that the present implementation of the vortex method boundary condition, based on theoretical mean velocity and turbulence profiles, gives an inlet flow that is sufficiently realistic to reach a well-resolved fully developed turbulent pipe flow at five pipe diameters downstream the inlet.

1. Introduction

Time-resolved Computational Fluid Dynamics (CFD) requires realistic and efficient inlet boundary conditions to get accurate and cost effective results. There are some well-established turbulent boundary condition methods in use today.

One method is to make precursor simulations and use those results as input to another simulation [1]. That method requires large amounts of free disk space, and the reading of the input files at each time step takes a significant time. The precursor simulation itself also takes a lot of time, and it may not be possible to make it ideal for the case to be studied.

Another approach is to use streamwise cyclic boundary conditions [2], where the inlet inherits the unsteadiness at the outlet and a fully developed and cyclic turbulent flow is reached. That kind of condition is not generally applicable since it presumes that also the geometry is cyclic in the streamwise direction, which otherwise distorts the cyclic flow. A special cyclic variant is the *mapped* boundary condition [3], where the inlet flow inherits the flow properties at an arbitrary sampling plane at some distance downstream the inlet. A schematic description of the streamwise cyclic and mapped boundary conditions is given in Fig. 1. The arrows indicate how the flow field is transferred back to the inlet. For the mapped boundary condition, the distance between the inlet and the sampling plane must be large enough to ensure a negligible correlation between the internal fluctuations and those at the inlet, just as for a pure cyclic case. As for the cyclic case, the mapped condition does not prescribe the inlet mean velocity profile. Although the geometry between the inlet and the sampling plane may be cyclic in itself, the mean velocity distribution from the mapped condition is also distorted by the pressure distribution downstream the sampling plane. Both these cyclic methods are very accurate for cases where they are applicable. They are,

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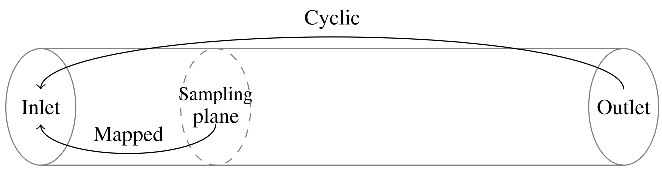

Fig. 1. Schematic view of streamwise cyclic and mapped boundary conditions.

however, computationally expensive since the "inlet boundary condition" in fact requires a solution of the full equations in a large portion of the computational domain. Further, the mean profiles are not specified, so the solution must first propagate until a fully developed state is reached.

A third method is the addition of stochastic fluctuations to a prescribed mean flow profile. Contrary to the previously discussed methods, this does not require any full solution of the flow equations. If the mean flow profile is chosen carefully, the flow should become fully developed in a short distance downstream the inlet. It is however well-known that stochastic fluctuations without temporal and spatial correlation are rapidly extinguished [4,5]. Some synthetic boundary conditions are realized by superposition of harmonic modes that have spatial correlation. A blending filter enforces the temporal correlation [6]. This type of boundary condition creates fluctuations with zero divergence, which have suitable characteristics to trigger the onset of turbulence within the flow.

The vortex method, used in the present work, is a development of an alternative method of adding stochastic fluctuations. It generates temporally and spatially correlated fluctuations in the form of vortices of appropriate sizes and strengths and adds them to a mean inlet flow profile. The vortices are initially randomly distributed at the inlet, and are then moved across the inlet during their finite life-time. New vortices are created as the old ones are extinguished. A general description of a vortex method for vorticity generation and dispersal, was first published by Chorin [7]. A specific adaptation to inlet boundary conditions, based on the vortex method, was published by Sergent [8]. It has been implemented by Benhamadouche et al. [9] in Code Saturne and by Mathey et al. [10] and Mathey [11] for ANSYS Fluent®. Jarrin [12] refers to the same type of inlet condition as the Synthetic Eddy Method (SEM). These publications all have in common that the estimation of the mean velocity and turbulence distributions are based on precursor RANS data, while the present study uses a fully theoretical approach.

The current work implements the vortex method in a boundary condition for the OpenFOAM® CFD tool, and evaluates it for turbulent pipe flow, a well investigated application where reliable studies for validation are available. Special care is taken to make the vortex distribution homogeneous across the inlet patch. The translational directions of the vortices are initiated randomly, and a spatial and temporal correlation is preserved. A boundary edge bouncing mechanism is incorporated.

The inlet condition is made independent of precursor simulations, by the use of theoretical mean profiles of velocity, turbulent kinetic energy, and turbulence dissipation. The versatile theoretical approach enables effective working methods when focusing on parametric studies. For cases where a fully developed flow at a circular inlet is applicable, the present method is convenient for parametric studies of the flow at various Reynolds numbers. It eliminates the need for a precursor simulation for each Reynolds number. This reduces the overall time, and simplifies the process. It does not put any restraints on the configuration of the downstream domain, which makes it useful in numerous applications.

Example applications could span from small needle valves [13], via investigations of mid range flow metres [14], up to large scale Francis turbines [15], i.e. wherever the theoretical profiles hold. In cases where asymmetries in the inlet profile are expected, another approach, such as the utilization of an additional precursor RANS simulation, may be favourable to find suitable average profiles.

The vortex length scales are calculated based on the local flow properties at their randomized initial position. First-order statistics in terms of RMS-values for streamwise, radial and circumferential fluctuations are presented. Two-point correlations and energy spectra are investigated. The results are compared with those of a fully cyclic approach, using the same code, and with results found in the open literature.

The theory, upon which the vortex method is based, is described in Section 2. A brief overview of the numerical schemes is given in Section 3. A description of the investigated case is found in Section 4, together with a summary of the cases used for the validation. Section 5 presents the results and validation. Concluding remarks are found in Section 6.

2. Methodology

The implementation of the new inlet boundary condition is inspired by the methodology described by Sergent [8], which is based on superimposed vortices on a mean flow profile. The present work includes a detailed method description to highlight the similarities as well as the differences to earlier publications. Section 2.1 describes the decomposition of the inlet velocity field into a mean velocity distribution, and fluctuating components tangential and normal to the inlet plane. The derivation of the mean velocity distribution is left to Section 4.1.1, since it is case-dependent. Section 2.2 presents how spatially correlated fluctuations tangential to the inlet plane are generated by randomly distributed vortices. Section 2.3 describes how the fluctuation normal to the inlet plane is approximated. Section 2.4 describes how the movement of the vortices is implemented and how their trajectories are reflected on boundary edges. Section 2.5 explains the lifetime calculation of each vortex. Finally, in Section 2.6, a graphical state chart summarizes the methodology.

2.1. Decomposition of the inlet velocity field

Turbulent flow consists of vortices of various sizes. The methodology used in the present work superimposes vortices to the inlet mean velocity profile. The vortex method boundary condition decomposes the instantaneous inlet velocity field as

$$\boldsymbol{u}(\boldsymbol{x}) = \overline{\boldsymbol{u}}_z(\boldsymbol{x}) + \boldsymbol{u}'_z(\boldsymbol{x}) + \boldsymbol{u}'_t(\boldsymbol{x}), \quad (1)$$

evaluated in $\boldsymbol{x} \in S$, where S represents the surface of the inlet patch. Here, $\overline{\boldsymbol{u}}_z$ is the mean streamwise velocity, while $\boldsymbol{u}'_z$ represents the streamwise velocity fluctuations. Subscript z is used to achieve an analogy with the notation of the investigated cases of the current work. It is assumed that the mean velocity is normal to the inlet patch. Fluctuations tangential to the inlet patch are referred to as $\boldsymbol{u}'_t$.

2.2. Tangential fluctuations

The tangential velocity fluctuation vector, $\boldsymbol{u}'_t$, is derived from vorticity point sources (vortices) across the inlet boundary. This section describes the derivation of $\boldsymbol{u}'_t$ and its constituents. Stokes [16] states that the velocity field of an incompressible 2D vector field, in this case $\boldsymbol{u}'_t$, can be expressed as the curl of a divergence-free vector field, $\boldsymbol{\psi}$, as

$$\boldsymbol{u}'_t = \nabla \times \boldsymbol{\psi}. \quad (2)$$