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Short communication

A simple extension of digital filter-based turbulent inflow to non-uniform structured grids

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ABSTRACT

The digital filter-based turbulence generator is one of the widely used synthetic turbulence inflow boundary conditions for large-scale-resolving flow simulations. However, the requirement of using uniformly-spaced Cartesian meshes and the limitation of enforcing a constant integral length scale along a given direction restrict the applicability of the method severely. The current paper describes an easy-to-implement and computationally inexpensive approach to extend the digital filter-based inflow to non-uniform structured meshes, using a mapping between the physical curvilinear mesh and a computational uniformly-spaced Cartesian mesh. The method also allows a limited control on the variation of integral length scales over the inflow plane. A zero-pressure-gradient, flat plate turbulent boundary layer is simulated using the proposed method and the distance required by the generated fluctuations to adapt into realistic turbulence is estimated to be about 10 boundary layer thicknesses. The method was developed for and has been used in simulations of turbulent boundary layers along nozzle walls for jet noise applications.

1. Digital filter-based turbulent inflow

For synthetic turbulence inflow boundary conditions, it is both essential and challenging to introduce realistic spatial coherence in the fluctuating inflow quantities. Not prescribing any energy carrying large length scales at the inflow results in an immediate annihilation of such synthetic fluctuations within the flow domain [1]. One effective way of prescribing desired length scales in a random signal is through application of properly designed digital filters [2]. This method has become one of the widely used synthetic turbulence boundary conditions in the last decade (see [3] for a recent review) and a short description of its formulation is provided in this section.

For illustration purposes, consider a 2-D computational domain having a 1-D line discretized in $N-1$ intervals as the inlet. A random number r, picked from a normal distribution with unit variance, is assigned to each of the N grid points. The filtering operation generates correlated length scales in this random signal. A 1-D filter function is given by

$$\grave{u}_k = \sum_{a=-W}^{W} b_a r_{k+a}, \tag{1}$$

where b_a are the filter coefficients and W is the filter stencil half-width. $\grave{u}_k$ represents the filtered velocity fluctuation for a particular velocity component u at the location indexed k. It can be shown that the two-point correlation function for this filtered velocity component takes the following form [2]:

$$R_{\grave{u}\grave{u}}(p\,\Delta s) = \frac{\overline{\grave{u}_k \grave{u}_{k+p}}}{\overline{\grave{u}_k \grave{u}_k}} = \left(\sum_{a=-W+p}^{W} b_a b_{a-p} \right) \Big/ \left(\sum_{a=-W}^{W} b_a^2 \right), \tag{2}$$

where $(p\,\Delta s)$ is the separation in terms of p intervals of uniform grid spacing Δs. The overbar indicates an average over all points on the 1-D inlet line, from $k=1$ to $k=N$. Note that Equation (2) does not use index notation and k is simply the location index of a grid point. The filter has to be designed in such a way that the correlation established by Equation (2) matches in form with the correlation observed in the physical flow to be simulated, thus prescribing a realistic integral length scale in the $\grave{u}$ fluctuations. The details of the filter design, extension to 3-D domains, and additional processing to enforce a desired Reynolds stress tensor are

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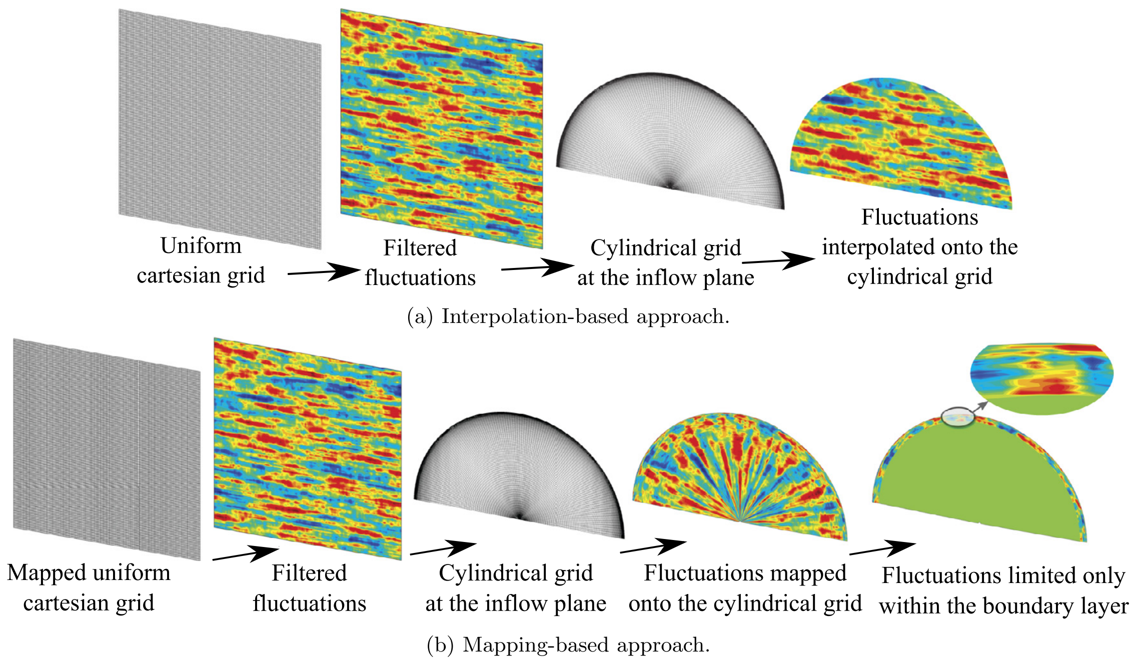

Fig. 1. Different approaches for extension of the digital filter-based turbulent inflow to curvilinear structured grids (reproduced from [3]).

not included in this paper for the sake of brevity. A complete description of the procedure used by the authors can be found in [4].

2. Extension to non-uniform grids

The filtering operation described in section 1 is limited to uniformly-spaced Cartesian grids and cannot be readily applied to inlet planes in curvilinear grids, which is highly desirable for most practical applications. For example, in large eddy simulations performed to study the noise produced by turbulent jets issuing from different nozzle designs, a realistic turbulent boundary layer is desired on the inner nozzle walls. This turbulent boundary layer gives rise to a turbulent shear layer in the free jet and is crucial for the downstream flow dynamics and the associated noise generation. The most common nozzle cross-section shape is circular and a cylindrical grid provides optimum resolution of the initial jet shear layer. However, the digital filter-based inflow cannot be applied in such a cylindrical grid. Another shortcoming of the digital filter-based technique is the limitation of using a constant integral length scale in a particular direction. This is especially important in wall-bounded flows where the integral length scale is supposed to reduce to zero towards the wall.

For use in curvilinear grids, the usually recommended procedure [5,6] is to generate a separate uniformly-spaced Cartesian grid larger than or equal in extent to the actual curvilinear inlet grid. The filtering operation is first performed on the uniform grid and then interpolation is used to transfer the fluctuations to the actual inlet. This method involves additional computational effort for interpolation, as well as complicates the implementation, especially for parallel solvers.

To vary the integral length scale over the inlet plane, one approach is to vary the filter coefficients spatially, although a strong variation through change of the filter coefficients can result in deviation of the correlation function from its prescribed shape [2]. As an alternative, a zonal approach has been proposed by Veloudis et al. [7] to allow integral length scales to vary over the inflow plane. In their approach, the inlet plane is split into several uniformly-spaced Cartesian grids. The filtering operation is performed in each zone separately with different filter coefficients, thus resulting in different integral length scales in separate zones. A stepwise variation in length scales is possible with this approach, although it suffers from discontinuities in fluctuations at the zone boundaries. Also, in general curvilinear grids, the two-step process of generating fluctuations on several uniform zones and then interpolating the fluctuations onto the actual inlet is both complicated to implement in parallel and requires more computational effort. In certain curvilinear geometries, such a zonal approach cannot be readily applied to have a desired length scale variation over the inlet plane. For example, in a pipe flow simulation, the length scales are required to decrease radially towards the wall. A Cartesian zone-based approach cannot handle such requirements.

In the current work, a different way of introducing the digital filter-based fluctuations in curvilinear grids is suggested. This approach does not involve the excessive computational cost of interpolation and allows smoother variation in length scales, albeit with some limitations. When the governing equations are solved on a structured curvilinear grid with finite-difference discretization, the physical mesh is mapped onto a uniformly-spaced Cartesian computational mesh. The filtering operation can be performed on such a mapped mesh which is uniformly-spaced by definition. Parallelizing this operation is straightforward compared to the implementation of interpolation-based methods. The required length scales are specified in terms of intervals on this mapped grid. After filtering establishes these length scales, the resulting velocity fluctuations are simply mapped back onto the physical grid. If a smooth grid stretching is employed on the physical grid, it causes the imposed length scales to vary in an equivalent smooth manner.

The difference between the current approach and the interpolation-based approach is demonstrated in Fig. 1, for a case where turbulent fluctuations are required on a 2-D cylindrical grid, such as a pipe flow simulation. It is clear from Fig. 1(a) that the interpolation-based approach is not capable of enforcing the correct orientation of the length scales on the cylindrical mesh. The grid is generally designed to be finer closer to a wall to resolve the boundary layer, and therefore the mapping-based approach will inherently produce decreasing length scales towards a wall. This desirable property is seen in Fig. 1(b) in the radial direction towards the outer wall boundary. However, mapping produces undesirable results when the grid density does not directly correspond to the integral length scales in a region. This effect can