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Large Eddy Simulation Inflow Conditions for Coupling with Reynolds-Averaged Flow Solvers

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Hybrid approaches using a combination of Reynolds-averaged Navier–Stokes (RANS) approaches and large eddy simulations (LES) have become increasingly popular. One way to construct a hybrid approach is to apply separate flow solvers to components of a complex system and to exchange information at the interfaces of the domains. For the LES flow solver, boundary conditions then have to be defined on the basis of the Reynolds-averaged flow statistics delivered by a RANS flow solver. This is a challenge, which also arises, for instance, when defining LES inflow conditions from experimental data. The problem for the coupled RANS–LES computations is further complicated by the fact that the mean flow statistics at the interface may vary in time and are not known a priori but only from the RANS solution. The present study defines a method to provide LES inflow conditions through auxiliary, a priori LES computations, where an LES inflow database is generated. The database is modified to account for the unsteadiness of the interface flow statistics.

I. Introduction

A WIDE variety of industrial flow applications is currently assessed by numerical predictions. These flow predictions are usually based on the Reynolds-averaged Navier–Stokes (RANS) approach, or, more recently, on large eddy simulations (LES). Both approaches have their advantages and drawbacks.

RANS simulations benefit from the relatively low computational costs involved. In this approach, ensemble-averaged flow variables are computed and all turbulent fluctuations are modeled with a turbulence model. These flow simulations show good results in standard applications, such as turbulent channel flows, but have difficulties in predicting flow separations because the turbulence model is not able to take complex vortical motions into account.

LES simulations on the other hand are resolving the large scales of turbulence and are modeling only the smallest scales, which tend to be more universal and hence easier to model. These simulations have much greater success in predicting detached flows but result in much higher computational cost. In the case of turbulent boundary layers, LES is usually too expensive because the small turbulent scales, which have to be resolved near the wall, require very fine meshes and very small time steps.[1]

A way to overcome the drawbacks of both approaches is to combine both and perform hybrid RANS–LES computations. The approach that has probably drawn most attention is the detached eddy simulation approach.[2] Here, the near wall region uses a RANS model, whereas detached flow turbulence is resolved with LES. Another hybrid LES–RANS approach is the limited numerical scales approach, which allows embedded zones of LES in a RANS domain.[3] All of these approaches have special advantages in high-Reynolds-number flows.

A different approach to combine LES and RANS methodologies is to use two separate flow solvers, one based on the LES approach and the other on the RANS approach. Each of these flow solvers computes certain parts of a flow domain. The flow solvers run simultaneously and exchange information at the interfaces. The goal of this kind of coupled RANS–LES computations is the flow prediction in very large systems, where one approach may be suitable for a portion of the system but inaccurate or too expensive for another portion.

As an example, the flow through a gas turbine can be considered (Fig. 1). The flow in the turbomachinery parts, the compressor and the turbine, is characterized by mostly attached flows around the blades. Currently, RANS flow solvers are widely used to predict these flows. With adapted turbulence models, computations of entire turbo-machinery sections is feasible.[4]

On the other hand, the flow in the combustor is characterized by detached flows, chemical reactions, and fuel spray. Experience shows that an unsteady approach such as LES has major advantages in predicting these flows. The moderate Reynolds number in the combustor allows the use of a pure LES approach in this domain. LES flow solvers for combustion applications are currently under development and show success in the prediction of real engine combustors and complex reacting flows.[5–7]

A promising approach to compute the unsteady flowfield in an entire gas turbine would be to decompose the flow domain into several discrete domains, such as the compressor, the combustor, and the turbine, and to apply an appropriate approach in each of these domains. These coupled RANS–LES computations deliver a solution, which would not have been feasible with a single approach.

This methodology to use several flow solvers simultaneously meets two major challenges. The first is the practical problem of running these flow solvers simultaneously and establishing a real-time communication between the codes. Previous work has established algorithms, which allow an information exchange of two or more parallel running flow solvers.[8–10]

The second major challenge is to specify meaningful boundary conditions on the basis of the exchanged data (Fig. 2). In the case of the RANS flow solver, this is relatively straightforward. The LES flow solver delivers a filtered solution,[11] which can be used directly at the boundaries. Problems arise in the proper definition of RANS boundary conditions for the turbulence models. This will be left for future work.

Boundary conditions are more demanding for the LES flow solver because the LES flow solver has to reconstruct the resolved turbulence according to the statistical data delivered by the RANS flow solver. In the case of the LES outlet, body forces are used to drive the LES solution to the statistical data computed by a RANS flow solver downstream of the LES domain, while preserving the turbulent fluctuations computed inside the LES domain.[12,13]

The present study investigates the remaining boundary condition: the LES inflow boundary.

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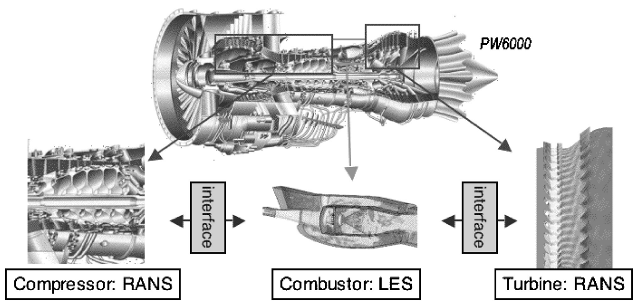

Fig. 1 Domain decomposition for a gas turbine engine (turbine computation from Ref. 4, combustor computation from Ref. 7).

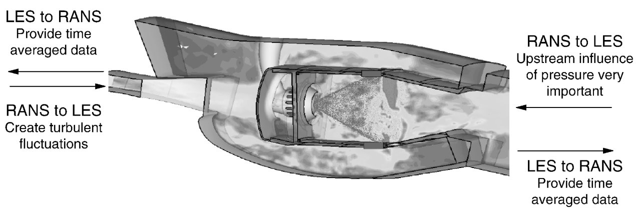

Fig. 2 Boundary conditions at the center piece of a gas turbine computation.

II. RANS Data for LES Inflow Boundary Conditions

Before attempting to define the LES inflow, it is useful to have a closer look at the data delivered by the RANS flow solver. Assuming a low-Mach-number flow and no chemical reactions at the interface, the density, temperature, and total energy play a minor role and can be assumed constant over the interface. What is left are the momentum flux across the interface and the turbulence statistics.

In a RANS solution, the momentum appears as an average. In a steady computation, this would be the time-averaged solution. In unsteady computations this converts to a phase average for periodic problems or more generally to an ensemble average. This implies that the mean values of the momentum are subject to temporal changes.

In a RANS approach, all turbulence motions are approximated with a turbulence model. From the point of view of the LES flow solver, it would be most convenient to use a full Reynolds-stress model for the RANS flow solver, where each of the Reynolds stresses is modeled by its own transport equation. However, the most popular turbulence models for RANS computations are two-equation models based on the eddy viscosity approach. One of the equations models k, the turbulent kinetic energy of the turbulent fluctuations, and the other either ϵ, the dissipation, or other similar variables. The deficiency of the eddy viscosity approach, especially for free turbulence, leaves only k as a useful quantity. Assuming homogeneous isotropic turbulence, the normal stresses of the Reynolds tensor can be recovered by

$$\overline{u'^2_{(i)}}_{\text{RANS}} = \tfrac{2}{3}k, \qquad \text{with} \qquad i = 1, 2, 3 \tag{1}$$

with (i) denoting that no addition of the components is made. The shear stresses cannot be recovered from the RANS computation.

The definition of LES inflow boundary conditions has to be done in a way that allows temporal fluctuations of the mean momentum and to add meaningful turbulent fluctuations according to the statistics delivered by the RANS turbulence model.

III. Inflow Boundary Conditions

In this section we present some possible ways to specify LES inflow conditions. These are then tested for use in integrated RANS–LES computations

A. Turbulent Inflow Conditions Without Fluctuations

The simplest way to define the inflow boundary conditions from RANS data is to neglect the turbulent fluctuations entirely. The velocity field at the LES inlet is then defined by the ensemble-averaged mean profiles from the RANS computation. This means that the incoming flow is laminar in a sense that the velocity does not fluctuate, but the mean profiles of the velocity are still those of a turbulent flow. We will refer to this approach as the quasi-laminar method. An advantage of this method is that it can easily accommodate inlet conditions, which are unsteady in the mean. Because the inflow conditions here are provided by a coupled, simultaneously computed, upstream, unsteady RANS simulation, these are usually unsteady.

B. Turbulent Inflow Conditions with Random Fluctuations

Early studies applying LES have often used inlet boundary conditions based on mean profiles with random fluctuations added such that the inflow has the correct turbulent kinetic energy, which is specified, for instance, from experimental data. However, because these fluctuations have no correlations in space and time, they cannot resemble turbulence. In turbulence, large-scale turbulent structures initiate the cascade of turbulent kinetic energy from large to small scales, which is not reflected in random fluctuations. As a result, random fluctuations have more energy in the high wave numbers and dissipate very quickly without sustaining or initiating real turbulence. The fluctuations can therefore act only as initial disturbance, which could be important for a natural transition to a turbulent flow. This method will be called the random-fluctuation method. An example for this approach and its deficiencies will be given.

C. Turbulent Inflow Conditions from Separate Periodic LES

A well-established procedure, often used in LES of experimental configurations, is to create inflow boundary conditions from the knowledge of the flow rate or the bulk velocity and swirl number, by performing a separate, periodic, preprocessed LES computation reflecting the inflow conditions and geometry of the particular experiment.[14] In such computations, a periodic channel or pipe is considered, and virtual body forces inside the domain are used to drive the flow to the desired mean velocity profiles. Because the geometry is periodic, a fully developed turbulent flow will be established if the Reynolds number is high enough. The time history of one cross-sectional plane of this computation is recorded in a database. If the desired mean flow is swirling or the desired mean profiles are not fully developed, a body-forcing method as described by Pierce and Moin[14] can be used. This database will then be used in an LES of the actual geometry to provide time-dependent, fully turbulent inflow conditions. In the subsequent evaluation of the different procedures, this method will be referred to as the matching database method.

The matching database method has been successfully used in several LES studies.[15,16] This method will hence be used as a benchmark for all other methods of providing inflow boundary conditions discussed in this paper.

The advantage of this method is that the representation of the inlet turbulence is taken from a fully turbulent flow, which means that all temporal and spatial correlations of the turbulent fluctuations are not artificial but actually represent real turbulence. This also implies that the distribution of the turbulent kinetic energy in wave number space follows the well-known decay. Although the additional LES used to create the database requires additional computing, this takes usually only a small fraction of the LES of the actually investigated configuration and can be performed on a workstation in an overnight computation if a flow solver is used that is specialized for this task.

The main disadvantage of this procedure, however, is that the inflow is assumed to be fully developed and constant in the mean. In integrated RANS–LES computations, the mean velocity field at the LES inlet is provided by an unsteady RANS calculation and might be neither fully developed nor steady in the mean. This makes it impossible to apply this procedure without further modifications in integrated RANS–LES computations.

D. Turbulent Inflow Conditions from Mean Velocity Profiles with Fluctuations from Database

The method proposed here to specify velocity inflow conditions for integrated RANS–LES computations is similar to the matching database approach to generate periodic pipe simulations with arbitrary, specified mean profiles. Here, we use the mean flowfield from the RANS solution or the experimental data and add meaningful turbulence from a database created by an additional preprocessed LES computation as it was described in the preceding section. This allows one to vary the mean flowfield and the level of turbulence during the LES computation in order to take temporal variations of the RANS solution into account. The turbulence database is generated from a periodic LES, for the present example that of a pipe flow, which is performed at conditions similar to but not necessarily the same as what is expected to be specified from the RANS solution. If the ensemble-averaged mean profiles of the database are equal to the RANS solution, then the matching database method, described in the preceding section, is recovered.

The LES inflow conditions can then be defined as

$$u_{i,\mathrm{LES}}(t) = \underbrace{\bar{u}_{i,\mathrm{RANS}}(t)}_{\mathrm{I}} + \underbrace{[u_{i,\mathrm{DB}}(t) - \bar{u}_{i,\mathrm{DB}}]}_{\mathrm{II}} \cdot \underbrace{\frac{\sqrt{\overline{u'^2_{(i)}}_{\mathrm{RANS}}(t)}}{\sqrt{\overline{u'^2_{(i)}}_{\mathrm{DB}}}}}_{\mathrm{III}} \qquad (2)$$

with the subscript RANS denoting the solution obtained from the RANS computation and where quantities with subscript DB are from the database. Here, t is the time, u_i stands for the velocity components, and the $\bar{u}_i$ is the ensemble average of the velocity component u_i.

Term II of Eq. (2) is the velocity fluctuation of the database. This turbulent fluctuation is scaled to the desired value by multiplication with term III, which ensures that the correct level of velocity fluctuation is recovered.

Here, it is assumed that the value of $\overline{u'^2_{(i)}}_{\mathrm{RANS}}(\tau)$ is a known quantity. However, because most RANS turbulence models do not compute the single components of the Reynolds-stress tensor but use lower order approximations for the turbulence, the trace of the Reynolds-stress tensor has to be approximated by Eq. (1).

It is readily seen that, taking the ensemble average of Eq. (2), the second term on the right-hand side goes to zero, leading to $\bar{u}_{i,\mathrm{LES}}(t) = \bar{u}_{i,\mathrm{RANS}}$. On the other hand, if first $\bar{u}_{i,\mathrm{RANS}}$ is substracted from both sides of Eq. (2) and then the equation is squared and subsequently ensemble averaged, then term II cancels with the denominator of term III, and it remains that $\bar{u}'^2_{(i),\mathrm{LES}} = \bar{u}'^2_{(i),\mathrm{RANS}}$. This demonstrates that Eq. (2) leads to the desired mean quantities. However, it is also obvious that only three variance conditions can be satisfied. If, for instance, the entire Reynolds-stress tensor is known from the RANS simulation or the experiment, the application of Eq. (2) is not unique. Instead of the autocorrelation functions used in term III, the cross correlations also could be used, but in addition to the mean velocities only three of six independent correlation functions can be enforced in the LES inflow conditions.

Because the RANS time step is usually much larger than that of the LES, the RANS solution has to be interpolated for all intermediate LES time steps.

The quality of the database can be measured in the necessity of term III to scale the turbulent fluctuation. Because this scaling is linear, it is advisable that the scaling factor be close to unity. Hence, in the generation of the database it is important to reproduce the expected inlet condition as closely as possible in order to keep the approximation in the bounds of the validity of a linear approximation and to ensure that the turbulent length scales are comparable to the length scales of the upstream flow in the RANS domain.

In the following test cases, inlet conditions computed with Eq. (2) are using databases with flow statistics, which are very different from the desired target values. This is done only to demonstrate the robustness of the proposed method and to show that the proposed LES inflow boundary condition is insensitive to numerical alterations. In an actual application of this method, the database can be generated with conditions closer to the expected RANS solution, which then provides even better accuracy. In the discussion of these simulations we will call this approach the adjusted database method.

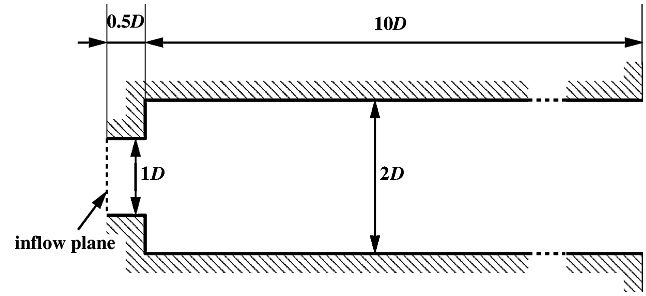

Fig. 3 Geometry of test case.

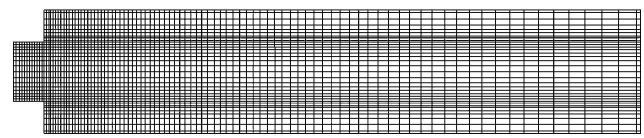

Fig. 4 Mesh for all LES computations; every fourth mesh line shown.

IV. Validation Test Cases

To validate the influence of different inflow boundary conditions, LES computations of a confined jet with and without swirl have been performed. The considered geometry corresponds to the experiments of Dellenback[17] and Dellenback et al.[18] The experimental configuration consists of a flow at an axisymmetric expansion as shown in Fig. 3. Measurements upstream of the expansion allow for a proper description of the mean inflow quantities and, for the present study, will replace the upstream RANS computation. In addition, the experiment provides measured mean velocity and velocity fluctuation profiles at several stations downstream of the expansion.

Three different flow configurations are computed: 1) no swirl ($S = 0.0$) at a Reynolds number $Re = 3 \times 10^4$, 2) strong swirl ($S = 0.6$) at $Re = 3 \times 10^4$, and 3) weak swirl ($S = 0.3$) at $Re = 2 \times 10^4$ with the swirl number S defined as

$$S = \frac{1}{R} \frac{\int_0^R r^2 \bar{u}_x \bar{u}_\phi dr}{\int_0^R r \bar{u}_x^2 dr} \qquad (3)$$

where u_x is the axial velocity component, u_ϕ is the azimuthal velocity component, and R is the radius of the nozzle.

For test cases 1 and 2, measurements are available and LES predictions will be compared with these data. For test case 3, experimental data are not available.

The computational mesh used for all simulations consists of a $384 \times 64 \times 64$ cylindrical single-block mesh (Fig. 4) adding up to approximately 1.5 million cells, with the smallest cell next to the edge of the jet. The cell size near the wall upstream of the expansion is approximately $y^+ = 25$, which means that the boundary layer is still underresolved. The outlet boundary condition corresponds to a convective outflow condition. The time step is limited by the Courant–Friedrich–Lewy condition and is approximately $\Delta t^* = 0.0015$ with $t^* = t \cdot D_{\mathrm{ref}}/U_{\mathrm{ref}}$, with D_{ref} the diameter of the jet nozzle and U_{ref} the maximum velocity of the axial velocity component. The choice of the reference parameter was done in conformance with the experimental data.[18]

V. LES Flow Solver

To investigate the effects of different inflow boundary conditions, the various boundary conditions were implemented in an LES flow solver and tested under the conditions described earlier. A structured LES flow solver developed by Pierce and Moin[19] and Pierce[20] has been used. The code solves the filtered momentum equations with a low-Mach-number assumption on an axisymmetric structured nonequidistant mesh. A second-order, finite volume scheme, staggered in space and time, is used.[20,21] The subgrid stresses are computed with an eddy-viscosity approach, where the eddy viscosity is determined using the dynamic procedure.[22,23]

VI. Validation Results

A. Confined Nonswirling Jet

The first test of the inlet boundary conditions is performed for a confined jet without swirl for which it is well known that the jet spreading rate is dependent on the turbulence present in the jet inflow.

Figure 5 shows the velocity fields obtained for this case. Experimental results are shown as square symbols. The leftmost velocity profile is located upstream of the expansion and defines the inlet condition for the LES.

First a database for turbulent fluctuations is created. The first database is created to match the inflow profile exactly. The auxiliary LES computation is created using body forces to drive the flowfield in a turbulent periodic pipe to the measured profile upstream of the expansion. Because no detailed information on the boundary layer is available here, the flow near the wall is unaltered and develops naturally according to the flowfield imposed away from the wall. The auxiliary LES computation to create the database for this case used about 3% of the computational costs of the actual LES computation.

The filled circles in Fig. 5 denote the simulation with the inlet conditions from this matching database method. Note that this method to specify inflow boundary conditions can here be used because the mean inflow profiles do not change with time. It can be seen that the simulation reproduces the experimental data well for both mean profiles and turbulent fluctuations. The reattachment of the flow behind the step is also well predicted.

The second LES computation uses the quasi-laminar method for the inflow boundary condition (dashed lines in Fig. 5). Because the initial turbulence in the flow does not reach the desired level near the step, the spreading rate of the jet is underestimated and the jet core penetrates much too far into the chamber. The reattachment length is overestimated. As a result of neglecting turbulent fluctuations at the inlet, the axial turbulent fluctuations are underestimated especially in the initial spreading of the shear layer. It should also be noted that the random-fluctuation method essentially leads to the same results. The imposed velocity fluctuations decay immediately downstream of the inlet plane, and the quasi-laminar solution is recovered.

The third computation was performed specifying the velocity inflow conditions using the adjusted database method. To demonstrate the robustness of the method, a database that does not correspond to the investigated flow has to be chosen. Here, the database created for a strongly swirling flow, test case 2, is used, whereas the presently computed flow is nonswirling. The results of this simulation are given by the solid lines in Fig. 5. Compared with the experimental data and the LES using the matching database method, the results from the adjusted database method show excellent agreement for the mean velocity fields. There are some small differences in the turbulent fluctuations due to the different description of the turbulence at the inlet, but the overall agreement is still very good.

This test case demonstrates that the adjusted database method is capable of reproducing the desired flowfield, even when the flow conditions applied in generating the database are rather different from those of the investigated case. The importance of a proper description of the turbulence in the inlet boundary conditions is emphasized by the strong discrepancies in the results obtained from the quasi-laminar and the random-fluctuation methods.

B. Confined Strongly Swirling Jet

As a second test case, a swirl flow at an expansion with a swirl number $S = 0.6$ is considered. Swirl flows at high swirl numbers ($S > 0.25$) create central recirculation zones, which lead to high shear regions and, hence, to high levels of turbulence production.

Figure 6 shows the results of this series of computations. As before, the LES applying the matching database method (filled circles) agrees very well with the experimental data (squares).

Surprisingly, the LES computation using the quasi-laminar method to specify inflow conditions (dashed lines) also yields a comparable flowfield and, despite some discrepancies especially in the jet spreading rate, agrees reasonably well with the experimental data. The explanation is that the level of turbulence production in this type of flow is rather high behind the expansion. The location of the inner recirculation zone in highly swirling flows is essentially fixed at the location of the expansion. This means that the regions of high turbulence production and the shear layers created by the recirculating fluid and the issuing jet are well determined and basically independent of the inflow conditions. High levels of turbulence are then generated in the shear layers behind the step, which make the flow almost independent of the initial turbulence intensity.

The third computation uses the adjusted database method, where the database has been taken from the preceding test case, the nonswirling flow. The mean inlet velocity profiles and the velocity fluctuations are then imposed using Eq. (2). Although a database for a

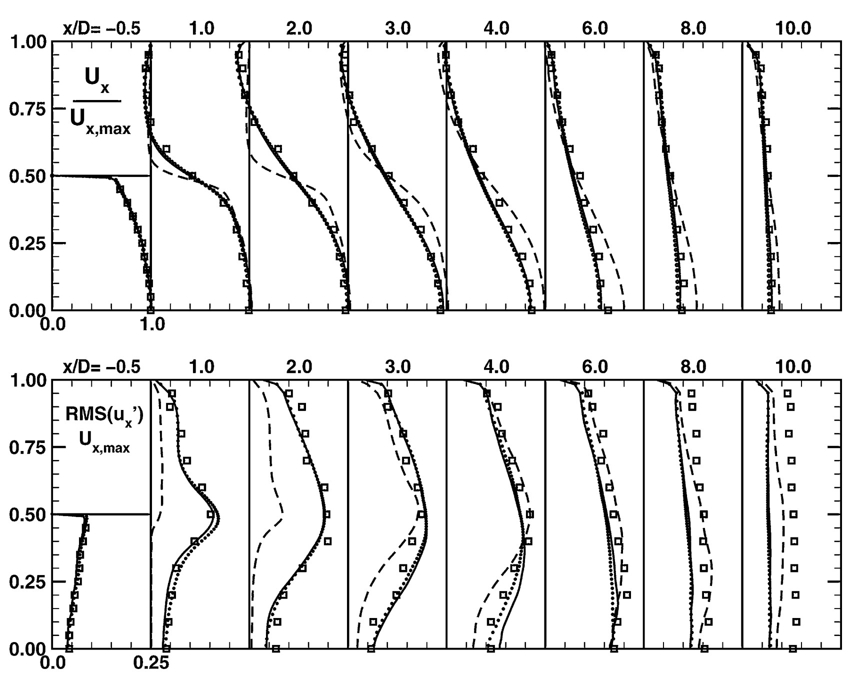

Fig. 5 LES results for a confined nonswirling jet with inflow conditions from ●, matching database method; – – –, quasi-laminar method; and ——, adjusted database method compared with □, experimental data.

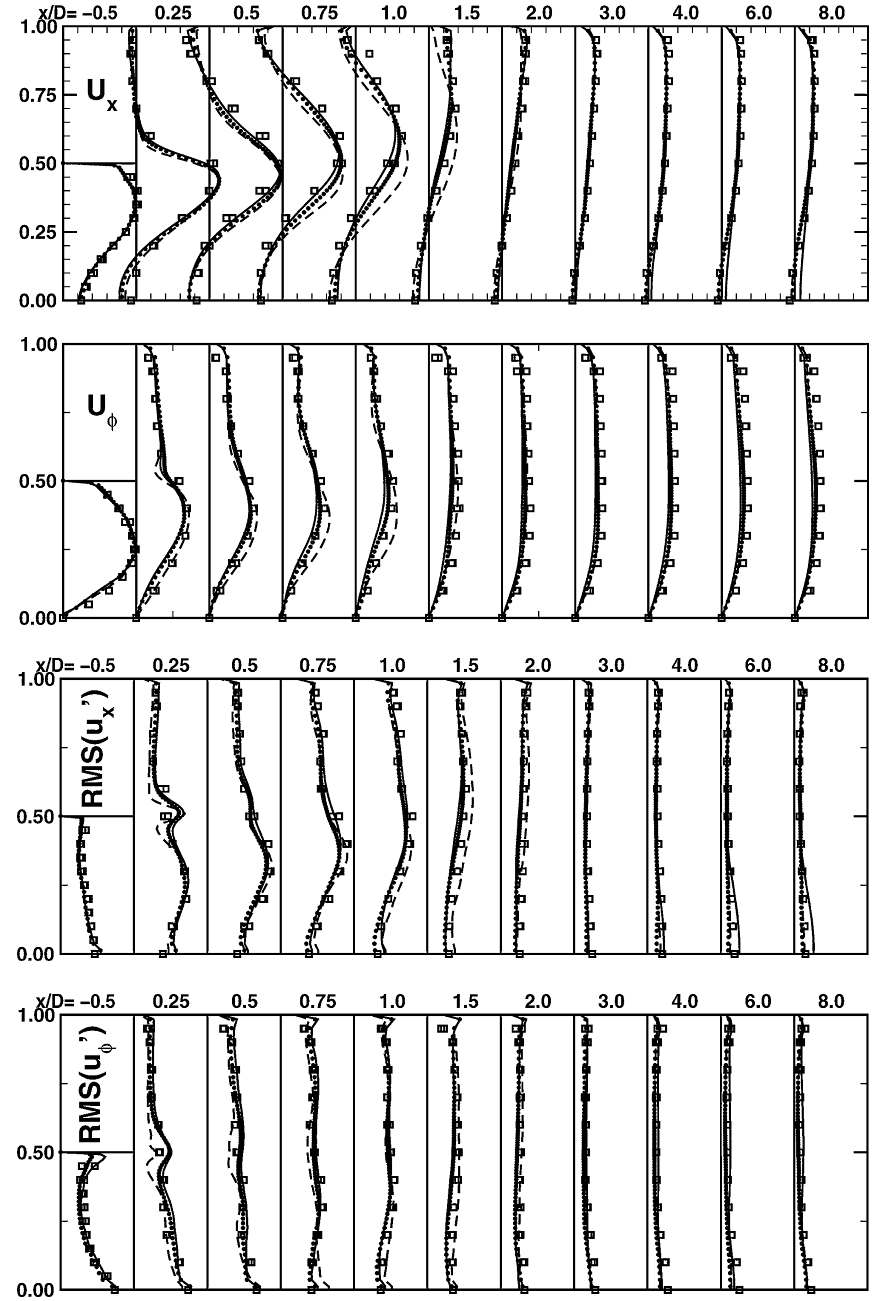

Fig. 6 LES results for a confined strongly swirling flow (S = 0.6) with inflow conditions from ●, matching database method; – – –, quasi-laminar method; and ——, adjusted database method compared with □, experimental data.

nonswirling flow has been applied here to a swirling flow, the results are in very good agreement with experiments and the results obtained using the matching database method.

Similar results can also be observed in the axial profiles of the turbulent kinetic energy, shown in Fig. 7. Even though the quasi-laminar and the random-fluctuation methods overpredict the turbulent kinetic energy in the region between approximately one and two nozzle diameters downstream of the expansion, the development for all methods is essentially similar. However, it is interesting to note that the random-fluctuation method starts with k at the same level as the database methods. Then the turbulent fluctuations decay rapidly to the level that is already obtained by the simulation with the quasi-laminar conditions and also downstream remain very comparable to those of that simulation. This demonstrates that the use of random fluctuations does not improve the results as compared with the quasi-laminar method. Similar results are obtained for the other test cases.

This second test case shows that situations where the inlet turbulence plays a minor role exist, even when complex flow configurations are considered. In this special case, the high level of turbulence production inside the LES domain is dominant and its location and level are not determined by the inlet conditions. Yet the use of proper inlet boundary conditions delivered more satisfactory results.

C. Confined Weakly Swirling Jet

Whereas in the preceding case the strong swirl ensured a certain universality of the extent of the recirculation zone and hence of the location and strength of the turbulence generating shear layers, weakly swirling flows are much more sensitive to inflow conditions.[24] Because it is desirable for most flow applications, e.g., for gas turbine combustors, to keep the swirl number low in order to minimize the pressure drop through the swirler, these kinds of flows are of particular interest for industrial applications. Hence, a proper definition of LES inflow boundary conditions is crucial

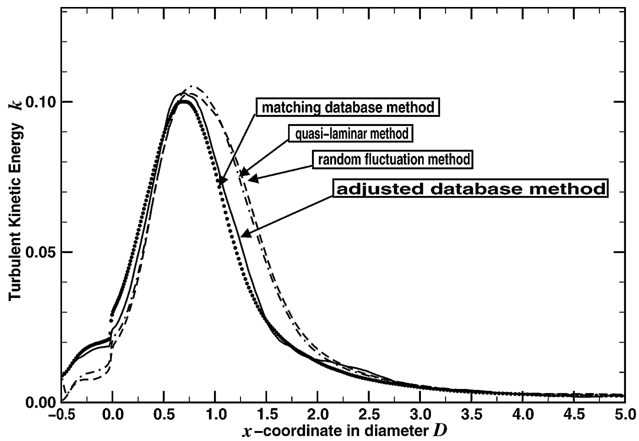

Fig. 7 Turbulent kinetic energy along centerline from the LES of a confined strongly swirling flow (S = 0.6) with inflow conditions from ●, matching database method; –·–, quasi-laminar method; – – –, random fluctuation method; and ——, adjusted database method.

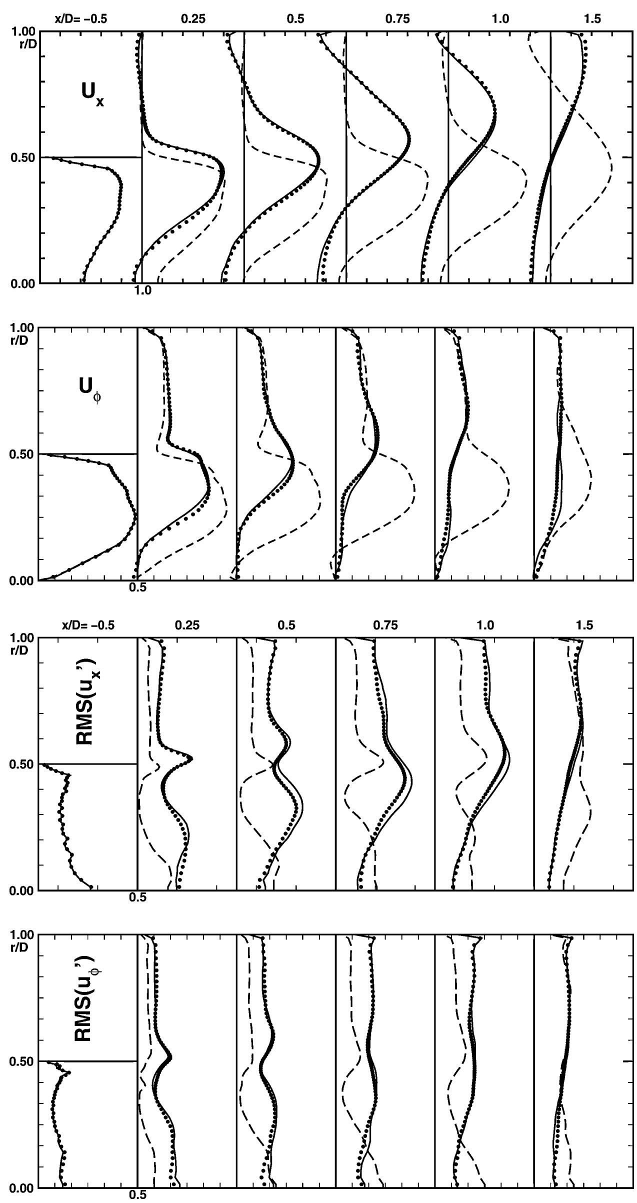

Fig. 8 LES results for a confined weakly swirling flow with inflow conditions from ●, matching database method; – – –, quasi-laminar method; and ——, adjusted database method.

for the prediction of these flows and the optimization of swirler geometries.

The third test case considered in this investigation is a weakly swirling flow at a swirl number $S = 0.3$. The swirl number is just supercritical, meaning that an inner recirculation zone should develop. Unfortunately, no experimental measurements are available for this case. We will therefore use the matching database method as a reference solution because this method has been shown to yield accurate results for the first two test cases.

Figure 8 shows the results for this test case. The LES using the matching database method (filled circles) shows the onset of the recirculation zone near the location of the expansion.

Using the quasi-laminar inflow condition (dashed lines), the location and extent of the recirculation zone changes remarkably. As a result, even the mean flowfield differs substantially from the LES when the matching database method is used. Because the turbulence at the inlet has been neglected, the turbulent fluctuations are underestimated throughout the near field of the expansion, which leads to the displacement of the shear regions, where the main turbulence production occurs, and consequently not even the shape of the profiles of the turbulent fluctuations is reproduced.

Applying the adjusted database method using Eq. (2) with the database from the nonswirling test case (solid lines), all flow features are recovered, as shown by the solid lines in Fig. 8. The origin and the extent of the recirculation zone are identical to the results of the LES with the matching database method. The good predictions of the turbulent fluctuations also indicate that the turbulence production and, hence, the strength of the shear layers are well reproduced.

This test case demonstrates most convincingly the importance of the proper representation of the inflow boundary condition in LES. Whereas the preceding test case of the strongly swirling flow was remarkably robust with respect to different inflow conditions, the present case shows that only small changes in flow parameters, for the present case the decrease in the swirl number, may result in flow configurations much more sensitive to inflow conditions.

VII. Conclusions

The proper formulation of boundary conditions for LES from time- or ensemble-averaged quantities has been a subject of research for many years. The current investigation focuses on LES inflow boundary conditions for application in integrated RANS–LES computations, where the LES inflow conditions are prescribed from the solution of an upstream unsteady RANS solver. Hence, the flow statistics, which have to be prescribed at the inlet of the LES domain, may vary in time. Turbulent inflow conditions are often prescribed from a precomputed, periodic LES, which has been shown to yield good predictions for most situations. However, this method assumes that the flow is steady in the mean, which for coupled RANS–LES simulations is usually not the case.

Here, a modification of this procedure is proposed, where the velocity data from the database, which has been generated from the periodic LES, are modified to result in the desired mean velocity and velocity fluctuation profiles, which are obtained from the coupled, upstream RANS simulation. The method to provide inflow conditions has been validated for three different flows and compared with other methods for prescribing inflow boundary conditions. Whereas one of the test cases, a confined strongly swirling flow, is surprisingly robust with respect to different methods to prescribe inflow conditions, the remaining two cases, a confined nonswirling jet and a confined weakly swirling flow, reveal strong differences among the different approaches.

The method for prescribing the inflow boundary condition proposed in the present study yields results in good agreement with results from the commonly applied procedure using the database method with the experimental data. The advantage of the present method is its flexibility to accommodate inflow conditions, which are unsteady in the mean.

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