Consistent boundary conditions for integrated LES/RANS simulations: LES inflow conditions

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1. Motivation

Currently, a wide variety of flow phenomena are addressed with numerical simulations. Many flow solvers are optimized to simulate a limited spectrum of flow effects effectively, such as single parts of a flow system, but are either inadequate or too expensive to be applied to a very complex problem.

As an example, the flow through a gas turbine can be considered. In the compressor and the turbine section, the flow solver has to be able to handle the moving blades, model the wall turbulence, and predict the pressure and density distribution properly. This can be done by a flow solver based on the Reynolds-Averaged Navier-Stokes (RANS) approach. On the other hand, the flow in the combustion chamber is governed by large scale turbulence, chemical reactions, and the presence of fuel spray. Experience shows that these phenomena require an unsteady approach (Veynante and Poinsot, 1996). Hence, the use of a Large Eddy Simulation (LES) flow solver is desirable.

While many design problems of a single flow passage can be addressed by separate computations, only the simultaneous computation of all parts can guarantee the proper prediction of multi-component phenomena, such as compressor/combustor instability and combustor/turbine hot-streak migration. Therefore, a promising strategy to perform full aero-thermal simulations of gas-turbine engines is the use of a RANS flow solver for the compressor sections, an LES flow solver for the combustor, and again a RANS flow solver for the turbine section (figure 1).

2. Interface

The simultaneous computation of the flow in all parts of a gas turbine with different flow solvers requires an exchange of information at the interfaces of the computational domains of each part. Previous work has established algorithms, which ensure, that two or more simultaneously running flow solvers are able to exchange the information at the interfaces efficiently (Shankaran *et al*, 2001, Schlüter *et al*, 2002).

The necessity of information exchange in the flow direction from the upstream to the downstream flow solver is self-explanatory: the flow in a passage is strongly dependent on mass flux, velocity vectors, and temperature at the inlet of the domain. However, since the Navier-Stokes equations are elliptic in subsonic flows, the downstream flow conditions can have a substantial influence on the upstream flow development. This can easily be imagined by considering that, for instance, a flow blockage in the turbine section of the gas turbine can determine and even stop the mass flow rate through the entire engine. This means that the information exchange at each interface has to go in both, downstream *and* upstream, directions.

Considering an LES flow solver computing the flow in the combustor, information on the flow field has to be provided to the RANS flow solver computing the turbine as

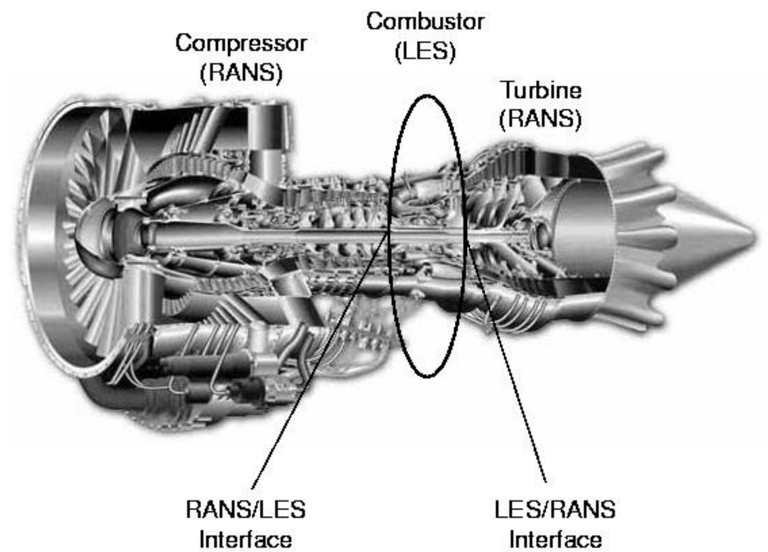

FIGURE 1. Gas turbine engine

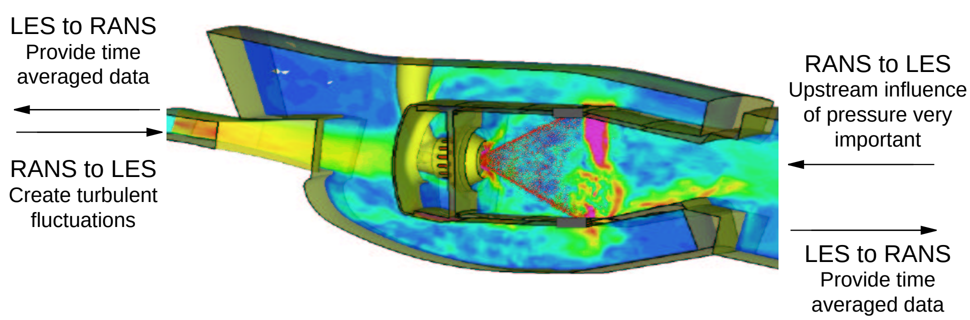

FIGURE 2. Gas turbine combustor with interfaces. (LES of combustor from Mahesh *et al*, 2001)

well as to the RANS flow solver computing the compressor, while at the same time, the LES solver has to obtain flow information from both RANS flow solvers (figure 2). The coupling can be done using overlapping computational domains for the LES and RANS simulations. For the example of the compressor/combustor interface this would imply that inflow conditions for LES will be determined from the RANS solution at the beginning of the overlap region, and correspondingly the outflow conditions for RANS are determined from the LES solution at the end of the overlap region.

However, the different mathematical approaches of the different flow solvers make the coupling of the flow solvers challenging. Since LES resolves large-scale turbulence in space and time, the time step between two iterations is relatively small. RANS flow solvers average all turbulent motions over time and predict ensemble averages of the flow. Even when a so-called unsteady RANS approach is used, the time step between two ensemble-averages of the RANS flow solver is usually larger by several orders of magnitude than that for an LES flow solver.

The specification of boundary conditions for RANS from LES data is relatively straightforward. The LES data can be averaged over time and used as boundary condition for the RANS solver.

Since LES computations have shown to be sensitive to outflow conditions (Moin, 1997, Pierce & Moin, 1998a), the adjustment of the LES solution near the outlet to the RANS solution of the downstream computation is of importance. Previous work investigated in detail LES outflow conditions (Schlüter and Pitsch, 2001, Schlüter *et al*, 2002). A virtual body force is employed to drive the LES mean velocity field to the RANS solution in an overlap region. The turbulent quantities and the pressure field adjusts accordingly to the mean velocity field.

In the present study, the boundary conditions provided from an upstream RANS flow solver to a downstream LES flow solver is investigated. The inflow conditions have to be created such, that the time-averaged mean values of all computed quantities match the RANS solution at a given plane and meaningful turbulent fluctuations are added. LES computations of validation test cases are performed to assess the influence of the inflow boundary conditions.

3. Inflow Boundary conditions

The following section presents some possible LES inlet conditions, which are tested for use in integrated RANS-LES computations

3.1. *Creation of database from auxiliary LES computation*

The formulation of LES inflow conditions from time-averaged RANS data is similar to the definition of LES inflow conditions from experimental data, which is usually given in time-averaged form. An established procedure to create inflow boundary conditions is to perform an auxiliary LES computation prior to the actual LES of the desired domain (Pierce & Moin, 1998b). The auxiliary LES computation computes a periodic pipe and uses virtual body forces inside the domain to drive the flow to the desired velocity profiles. The time history of one plane of this computation is written into a database. The actual LES computation of the desired geometry then reads this database and uses its transient velocity field to define its own inlet velocity field.

This method is a well established procedure and shows good results in reproducing experiments (e.g. Duchamps & Pitsch, 2000, Schlüter, 2001). Hence, it will be used as a benchmark for all following proposed boundary conditions.

The advantage of this method is that the representation of the inlet turbulence is taken from a fully developed turbulent flow, which means all temporal and spatial correlations of the turbulent fluctuations are actual representations of eddies. The energy spectra in time and space have a natural energy distribution especially in the long wave range.

The creation of the database implies additional computational costs. However, using flow solver specialized to this task, the auxiliary computation usually takes less than an hour wall-clock time on a single processor, which is less than 1% of the computational costs for the LES of the actual geometries used in the current investigation.

The disadvantage of this procedure is that the mean velocity field at the inlet has to be known prior to the LES computation. In integrated RANS-LES computations the mean velocity field at the inlet of the changes in time, and hence, is unknown. This makes it impossible, to apply this procedure in this form for integrated RANS-LES computations.

3.2. *No-fluctuations inflow conditions*

The most simple way to define the inflow boundary conditions from RANS data is to neglect the turbulent fluctuations entirely. The velocity field at the inlet is then defined by the ensemble-averaged mean profiles of the RANS computation. This means, the incoming flow is laminar, but the shape of the velocity profiles is still that from a turbulent flow. It is easy to adapt this inflow condition during the LES computation to take variations of the ensemble-averaged flow field delivered by the RANS computation into account.

3.3. *Random fluctuations*

Early work in LES inlet boundary conditions report the usage of random fluctuations superposed to the mean velocity field at the inlet to simulate inflow turbulence. However, due to the lack of correlations in space and time of the fluctuations, these lack the energy in the long wave range. As a result of that, the fluctuations are usually in the high wave spectrum and hence, dissipated very quickly. The few tests in the current investigation which were made with this inlet condition agree with these findings. The flow laminarizes quickly behind the inlet and flow fields obtained with this inlet condition were indistinguishable from the flow fields obtained with the no-fluctuations inflow condition. Hence, they will not be shown here.

3.4. *Mean velocity profiles with turbulent fluctuations from database*

The method proposed here for integrated RANS-LES computations, uses the mean flow field from the RANS solution and adds meaningful turbulence from a database created by an auxiliary LES computation. This allows to vary the mean flow field during the LES computation in order to take temporal variations of the RANS solution into account. As for the inlet condition proposed in section 3.1, an auxiliary LES computation of a pipe flow is performed to define the turbulent fluctuations. The inlet condition is then defined as:

$$u_{i,\mathrm{LES}}(t) = \underbrace{\bar{u}_{i,\mathrm{RANS}}}_{I}(\tau) + \underbrace{(u_{i,\mathrm{DB}}(t) - \bar{u}_{i,\mathrm{DB}})}_{II} \cdot \underbrace{\frac{\sqrt{\overline{u'^2_{(i)}}_{\mathrm{RANS}}}(\tau)}{\sqrt{\overline{u'^2_{(i)}}_{\mathrm{DB}}}}}_{III} \tag{3.1}$$

with RANS denoting the solution delivered by the RANS computation and DB properties delivered by the database. The time-scale t is the time-scale used by the LES computation, and τ the time-scale used by the RANS computation. The RANS time-step $\Delta\tau$ is usually much larger than the LES time-step Δt, which means, that multiple LES inlet conditions are computed before the RANS solution is updated.

Term II of Eq. 3.1 computes the velocity fluctuation of the database. This turbulent fluctuation is scaled to the needed value with term III. Here, it is assumed that the value of $\overline{u'^2_{(i)}}_{\mathrm{RANS}}(\tau)$ is a known quantity. However, most RANS turbulence models do not compute the single components of the Reynolds-stress tensor, but more general turbulent quantities such as the turbulent kinetic energy k. In this case, the axial components of the Reynolds-tensor have to be approximated by:

$$\overline{u'^2_{(i)}}_{\mathrm{RANS}} = \frac{2}{3}k \tag{3.2}$$

Once the turbulent fluctuation is computed, it is then added to the time-averaged velocity field (term I) and a meaningful inlet velocity field is recovered.

The quality of the database can be measured in the necessity of term III to scale the

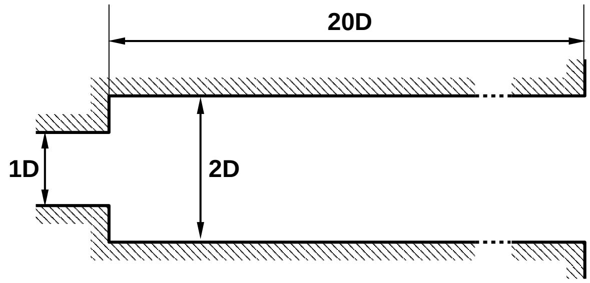

FIGURE 3. Geometry of test case

turbulent fluctuation. Since this scaling is linear, it is desirable, that the scaling factor is close to unity. Hence, in the creation of the database it is important to reproduce the expected inlet condition as closely as possible in order to keep scaling in the bounds of the validity of a linear extrapolation.

In the following test cases, inlet conditions computed with eqn. 3.1 are using databases with flow statistics strongly different from the desired values. This is solely to prove the robustness of the method and not advisable for the final application.

4. Validation test case

In order to validate the influence of different inflow boundary conditions, LES computations of a confined jet with and without swirl were performed. The considered geometry corresponds to the experiments of Dellenback (Dellenback, 1986, Dellenback *et al*, 1988). The experiment investigates the flow at an axi-symmetric expansion (figure 3). Measurements upstream of the expansion allow a proper description of the inflow statistics and multiple measured velocity profiles downstream of the expansion give a good picture of the flow development.

Three different flow configurations are computed:
(a) no swirl ($S = 0.0$) at a Reynolds-number $Re = 30,000$
(b) strong swirl ($S = 0.6$), at $Re = 30,000$ and
(c) weak swirl ($S = 0.3$), at $Re = 20,000$
with the swirl number S defined as:

$$S = \frac{1}{R} \frac{\int_0^R r^2 \bar{u}_x \bar{u}_\phi \, dr}{\int_0^R r \bar{u}_x^2 \, dr} , \qquad (4.1)$$

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

For the first two cases measurements are available and LES predictions can be compared with experimental data. For the last case, no measurements are available.

The computational meshes contain 1.58 million points (1.52 million cells) and are identical for all LES computations.

5. LES flow solver

In order to investigate the effects of different inflow boundary conditions, the various boundary conditions were implemented in an LES flow solver and tested. For this task, the LES flow solver developed at the Center for Turbulence Research (Pierce & Moin,

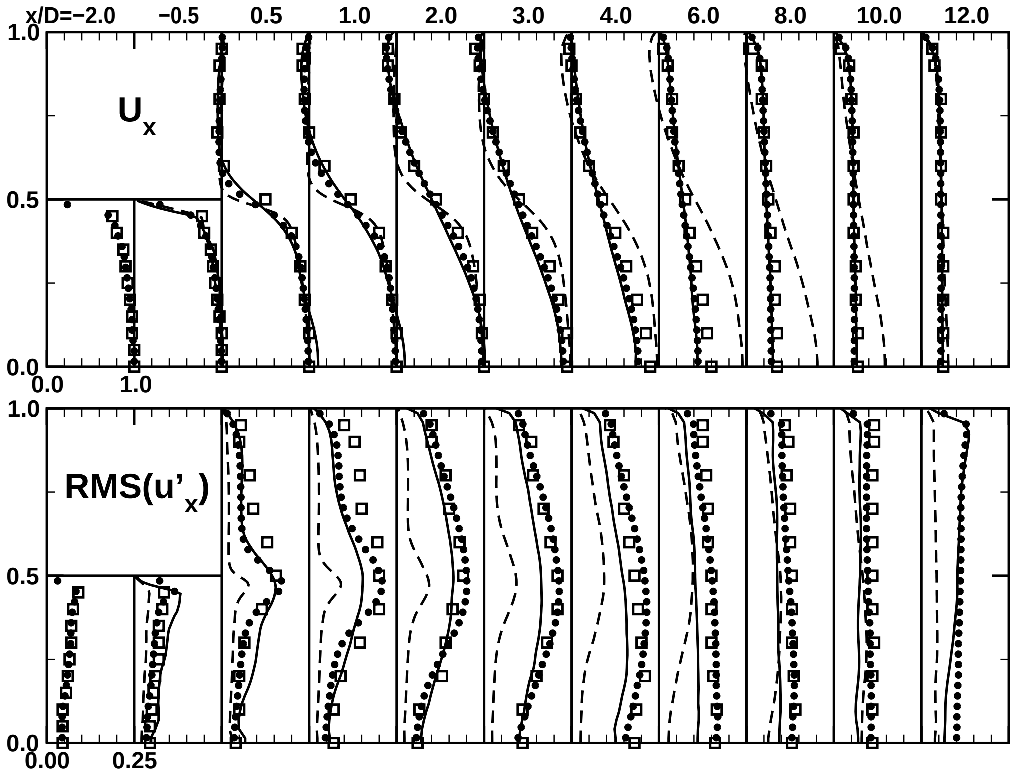

FIGURE 4. LES results for a confined jet. Squares: experiment; Dots: LES with inflow entirely from database (section 3.1); Dashed line: LES with no-fluctuations inflow (section 3.2); Solid line: LES with mean-flow + fluctuations from data-base (section 3.4)

1998a) has been used. The flow solver solves the filtered momentum equations with a low-Mach number assumption on an axisymmetric structured mesh. A second-order finite-volume scheme on a staggered grid is used (Akselvoll & Moin, 1996).

The subgrid stresses are approximated with an eddy-viscosity approach. The eddy viscosity is determined by a dynamic procedure (Germano *et al*, 1991; Moin *et al*, 1991).

6. Validation

6.1. *Confined jet without swirl*

The first test of the inlet boundary conditions is made for a confined jet without swirl. It is well known, that the spreading rate of the jet is dependent on the turbulence present in the jet flow.

Figure 4 shows the velocity fields obtained for this case. Experimental results are shown as square symbols. The two velocity profiles on the left are taken upstream of the step, and the leftmost profile defines the inlet conditions for the LES computations.

The first LES computation (black dots in figure 4) determines the inlet conditions entirely from a database (compare section 3.1). The database was created by an auxiliary computation with body forces driving the mean velocity field to the desired inlet velocity profile on the left. The usage of this boundary condition is possible in this case, since the time-averaged velocity field defining the inlet condition does not vary in time. It can be seen, that this LES computation reproduces the experimental data well in mean values and turbulent fluctuations. The reattachment of the flow behind the step is well captured.

The second LES computation uses no-fluctuations inflow conditions (compare section 3.2). Since 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 penetrates much further into the chamber (dashed lines in figure 4). The reattachment length is overestimated. As a result of the neglect of turbulence at the inlet, the axial turbulent fluctuations are underestimated throughout the domain.

The third LES computation uses the mean velocity field and turbulent fluctuations from a database (compare section 3.4). The database used is the database created for a swirling flow (first LES computation of the following chapter, section 6.2) and hence, is not adapted to this particular case. The correction of Eq. 3.1 is used to obtain the desired mean statistics. The results of this computation (solid lines) show a good agreement with the experiment and the first LES computation in the mean values. There are some discrepancies in turbulent fluctuations between this LES computation and the LES computation using a matching database due to the different description of turbulence at the inlet. However, both LES results are reasonably close to the experimental data.

This test case shows, that the proposed inflow condition (Eq. 3.1) is capable of reproducing the desired flow field, even when a low-quality database is used. The importance of turbulent fluctuations at the inlet is underlined with the failure of the no-fluctuations inlet condition to reproduce the flow field properly.

6.2. *Confined jet with strong swirl*

As a second test case a swirl flow at an expansion with a swirl number $S = 0.6$ is considered. Swirl flows with high swirl ($S > 0.25$) create central recirculation zones, and, as a result of that, flows with high shear are created which have a high level of turbulence production.

Figure 5 shows the results of this series of computations. The LES computation using a data-base with matching inlet velocity statistics (black dots) agrees well with the experiments (square symbols).

Surprisingly, the LES computation using the no-fluctuations inflow conditions (dashed lines) yields a comparable flow field and, despite some discrepancies, agrees reasonably well with the experiments. This can be explained with the fact, that the level of turbulence production is very high behind the expansion. The origin of the inner recirculation zone in highly swirling flows is fixed at the location of the expansion. This means, the zones of the turbulence production – the shear layers created by the recirculating fluid and the issuing jet – is well determined and independently of the inflow conditions. The turbulence level is then nearly entirely defined by the turbulence production behind the step.

The third LES computation uses a combined approach and the database from the previous test case of the flow *without* swirl (section 6.1). The particular shape of the axial velocity profile and the entire swirl component is imposed using Eq. 3.1. The LES computation recovers the LES solution using a matching database exactly.

This second test case shows, that situations exist, where the inlet turbulence plays a minor role, 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.

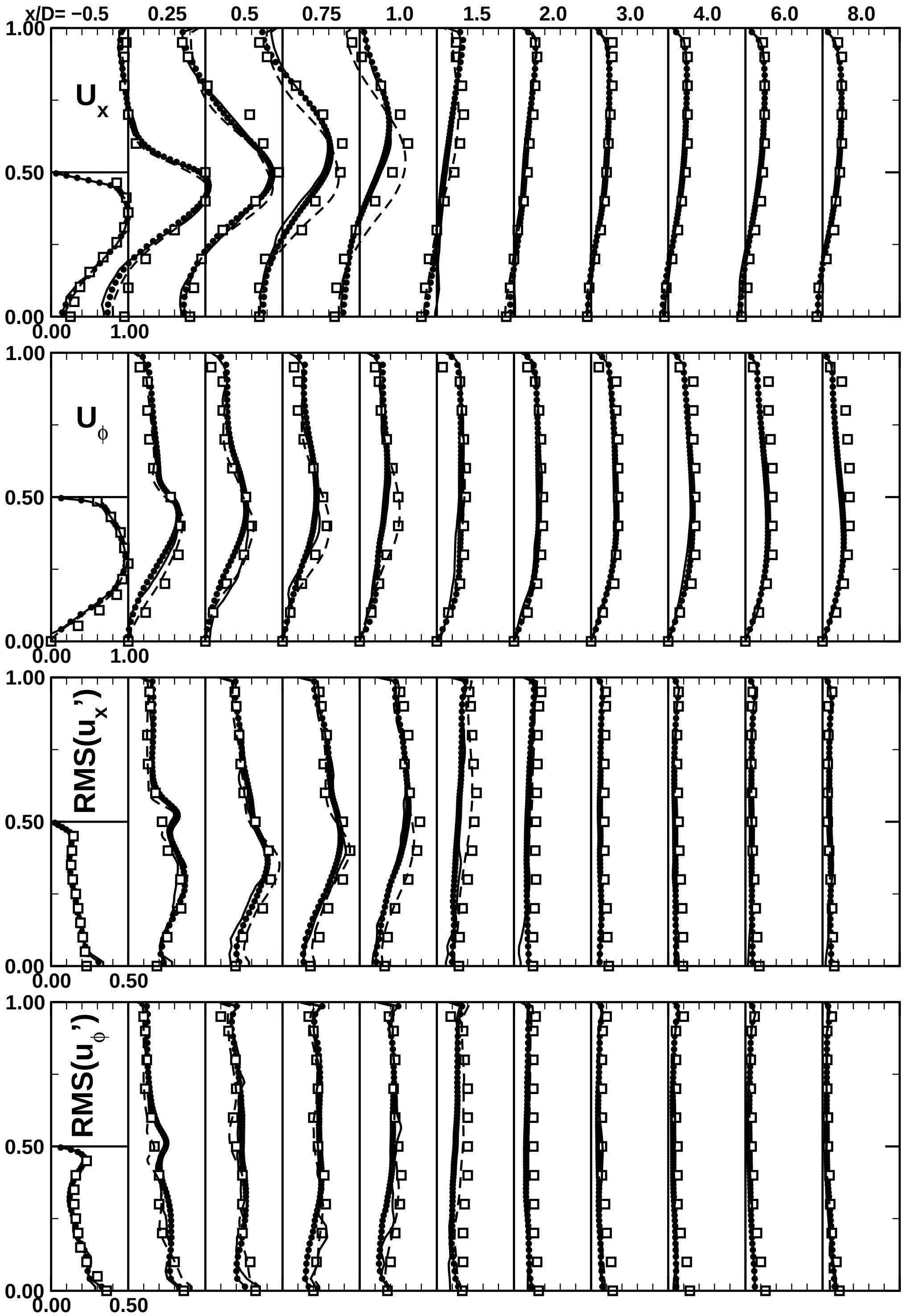

FIGURE 5. LES results for a jet with strong swirl ($S = 0.6$). Squares: experiment; Dots: LES with inflow entirely from database (section 3.1); Dashed line: LES with no-fluctuations inflow (section 3.2); Solid line: LES with mean-flow + fluctuations from data-base (section 3.4)

6.3. *Confined jet with weak swirl*

While in the previous case the strong swirl ensured a certain universality of the extent of the recirculation zone, weakly swirling flows are much more sensitive to inflow conditions (Gupta *et al*, 1984). Since 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 over the swirler, these kinds of flows are of particular interest for industrial applications. Hence, a proper definition of LES inflow boundary conditions is crucial 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 develops. Unfortunately, no experimental measurements are available for this case, but since the traditional method of generating inflow conditions by an auxiliary LES computation was very successful in the previous two cases, the results of this computation can be used as a reference.

Figure 6 shows the results of this series of LES computations. The LES computation with a database with matching mean flow statistics (black dots) shows the onset of the recirculation zone near the location of the expansion.

Using the no-fluctuations inflow condition (dashed lines), the location and extent of the recirculation zone changes dramatically. As a result of that, the mean flow field differs substantially from the previous LES computation. Due to the neglect of turbulence at the inlet, the turbulent fluctuations are underestimated throughout the near field of the expansion. As a result of the displacement of the zones of turbulence production, not even the shape of the profiles of turbulent fluctuations is reproduced.

Using Eq. 3.1 and the non-swirling database from the test case in section 6.1 (solid lines), all flow features are recovered. The origin and the extent of the recirculation zone are identical to the LES with the matching database. As a result of that, the turbulence production is also well represented and the prediction of turbulent fluctuations coincide.

This last test case shows most dramatically how the choice of LES inflow boundary conditions may alter the results of a computation. While the previous test case of the strongly swirling flow was remarkably robust to different inflow conditions, the present case shows that only a little change in flow parameters, the decrease of the swirl number, may result in flow configuration much more sensitive to inflow conditions.

7. Conclusions

The definition of LES inflow conditions from time-averaged statistical data has been subject of research for some time. The current investigation focuses on LES inflow boundary conditions for integrated RANS-LES computations, where the LES inflow conditions are prescribed by the solution of an upstream RANS solver. Here, the flow statistics, which have to be prescribed at the inlet of the LES domain, may vary in time.

A modification of the already widely used procedure, where an auxiliary LES computation creates a database for inflow conditions, was proposed. This inflow condition uses the unsteady mean velocity profiles at the inlet and superposes turbulent fluctuations from a database.

The proposed inflow condition was validated on three different flows. While one case, a strongly swirling flow, was surprisingly robust against different inflow conditions, the other two cases, a confined jet and a weakly swirling flow, underlined the necessity of a proper turbulence description at the inlet.

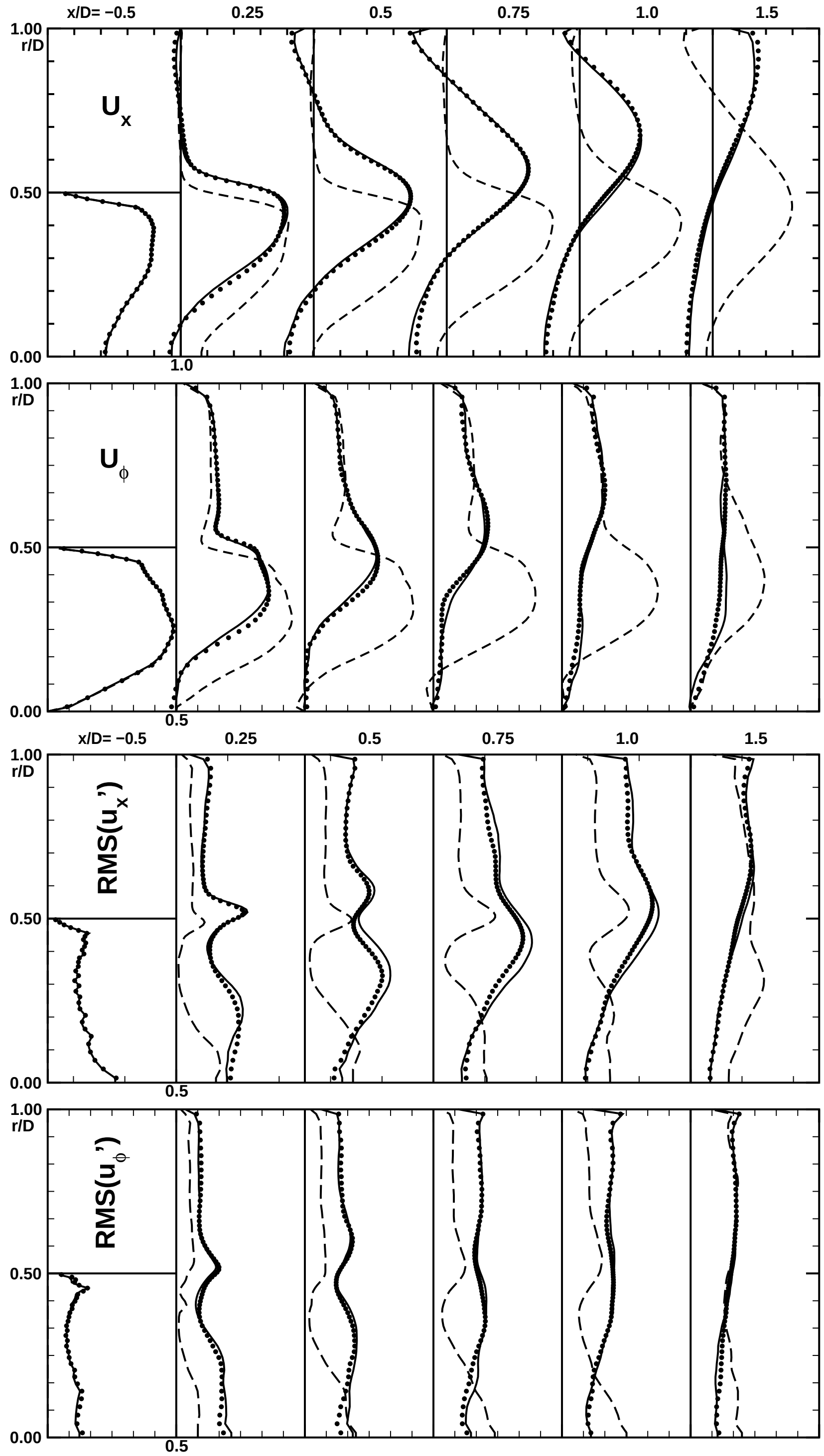

FIGURE 6. LES results for a jet with weak swirl ($S = 0.3$). Dots: LES with inflow entirely from database (section 3.1); Dashed line: LES with no-fluctuations inflow (section 3.2); Solid line: LES with mean-flow + fluctuations from data-base (section 3.4), no experimental data available

The inflow boundary condition proposed in the present study shows equivalent results to the commonly applied procedure using a database from an auxiliary LES computation. Its advantage over other methods is its flexibility to accommodate for time-dependent flow statistics at the LES inlet.

The definition of LES inflow boundary conditions for integrated RANS-LES computations is an important step towards integrated flow computations.

8. Acknowledgments

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