Response to the Review on the Paper wes-2021-30-RC2

Investigation Into Boundary Layer Transition Using Wall-Resolved LES and Modeled Inflow Turbulence

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Review # 2

We appreciate the effort of the reviewer for evaluating our manuscript in detail. In the following his/her remarks are answered and modifications resulting from his/her comments are explained. Note that in the annotated version of the manuscript all modifications (replacements, additions and deletions) regarding the remarks of reviewer # 2 will be highlighted in blue when the upload of an annotated version is an option.

Response to specific comments:

- **More detailed grid refinement study**
  Figure 1 of this reply shows a comparison of the pressure coefficient between the standard and the refined grid with about three times more grid points. With the refined grid the separation bubble can easily be identified by the flattened c_p curve. The corresponding c_f plot can be seen in Fig. 2 of this reply. Again, some deviations between the results on both grids are visible. However, for the current study, which is focused on the transition phenomena, the standard grid provides a sufficiently accurate resolution with no significant changes observed in the mode of transition as seen in Fig. 1 of the manuscript. Please additionally note that the suction side is of special interest in our study and it has a finer grid resolution than the pressure side. Details are found in Table 2 of the manuscript. Taking into account the goal of the present study and the very high computational costs already necessary for the long-lasting time-consuming predictions on the standard grid, the present resolution is deemed to be sufficient for the purpose of this study.

  In principle it would be possible to include a study of the resolved vs. the modeled turbulence. However, the manuscript is already quite long and the addition of this feature would not provide a lot of useful information to the reader and would also take some time for the computations to be performed. Nevertheless, this is a valuable suggestion and would be something to consider for the higher Re cases. Note that in a recent study by Solís-Gallego et al [1] who have also performed a wall-resolved LES with a grid whose dimensions are coarser than our own standard grid and who have also used the dynamic Smagorinsky subgrid-scale model has investigated this topic. They found that a very small percentage of the turbulent kinetic energy is modeled (between 1 and 8 %) which is below their acceptable threshold of 20 %.

- **Geometry, mesh set-up and boundary conditions**
  Yes, the reviewer is right and the angle of attack is already included in the basic mesh set-up. Therefore, there is no need of any special outflow conditions on the upper boundary.

The domain extends 8 chord lengths upstream of the airfoil and 15 chord lengths downstream of the airfoil. With increasing distance from the airfoil, the grid grows coarser (geometric expansion of the grid spacing). This damps out interfering waves. In addition to the damping due to the grid coarsening, the convective boundary condition on the outflow plane (see line 251 of the original manuscript) has proven itself for LES as it avoids the problem of reflection of pressure waves at the outflow edge and any associated error propagation back into the inner integration domain (see, e.g., [2, 3, 4]). Furthermore, note that there have been various studies that use similar domain dimensions (see, e.g., [1, 5, 6, 7]).

- **Decay of turbulence intensity**

  Definition of the turbulence intensity:
  The decay of free-stream turbulence is plotted using the averaged Reynolds stresses at the end of the simulation period defined as $TI = \sqrt{\frac{1}{3} \times (u'u' + v'v' + w'w')}$, where $u'u'$, etc. are the averaged normal Reynolds stresses in the three principle directions. Future studies will include monitoring points so that the turbulence statistics could be more accurately calculated instead of depending on the averaged statistics.

  Where is the required TI expected to be achieved:
  The required turbulence intensity is expected to be achieved slightly upstream of the airfoil. An analysis of the development of the inflow turbulence was conducted by Breuer [8] for the same inflow turbulence conditions. A development length of about one chord length was found to be sufficient depending on the turbulent length scale. In the present case, the fully developed turbulence is seen at around $x/c =$ -1 to -0.2, which is just upstream of the region influenced by the airfoil.

  Simulations in an empty field for calibration:
  No, simulations without the wing in an empty domain have not been conducted for the purpose of calibration. However, as seen from the plot generated from the averaged Reynolds stresses, it is clear that the TI achieved is of the similar order as that expected, albeit slightly lower which could be due to the averaging of the Reynolds stresses which also includes data prior to the inclusion of inflow turbulence. It must be pointed out that the absolute value of the turbulence intensity is not vital as the simulations study the transition scenario with increasing turbulence. Future studies which include monitoring points will be more accurate.

  Peak in turbulence at the start:
  The peak seen around $x/c =$ -2 (the location of the inflow plane) is due to the way in which the turbulence is injected into the domain. To reduce the required development length of the synthetic turbulence and to avoid discontinuities, the source terms are superimposed in a predefined influence area equal to twice the length scale of the injected turbulence. The center of this influence area is the inflow plane. Based on a Gaussian bell-shaped distribution the source terms are then scaled within this influence area. Further details on the procedure are found in Breuer [8].

  Variations in the data:
  Yes, the data are statistically converged for the mean flow around the airfoil (c_p and c_f was monitored). In all cases, the airfoil seems to influence the expected TI beginning at around $x/c =$ -0.2. An increase in effective TI up to the separation/transition point

(around 50 % chord) is observed before it begins to drop. In the case of $TI = 11.2$ % there is no separation bubble and this seems to be the reason why there is a continuous decay in turbulence (after the small increase above the leading edge of the airfoil as also seen in the other cases). It probably has something to do with the boundary layer being thinner in this case due to the absence of a separation bubble and the fact that the analysis for the calculation of TI is conducted at a height corresponding to the boundary layer thickness at 50 % chord for the $TI = 0$ % case.

- **Comparisons between other studies featuring the SD7003 and NACA0018 airfoils**
  More information comparing the results with other studies is a good suggestion and more information was added to the revised version of the manuscript where appropriate. A short summary is as follows:

  On the relatively thinner airfoil (SD7003) (8.51 %) in the study by Breuer [8], separation takes place close to the leading edge at around 20 % chord and moves downstream with increasing turbulence intensity. Furthermore, a corresponding reduction in the chordwise extension of the separation bubble is seen before it disappears at $TI = 5.6$ %. The time-averaged results showed a decrease in the drag coefficient with increasing TI. A more detailed analysis revealed that the contribution of the pressure component decreased due to the reduction in the length of the separation bubble while that of the friction component increased due to increasing inflow TI. In the current study on the flow around the thicker (20 % thickness) LM45 airfoil, the separation bubble moves slightly downstream with increasing TI before disappearing at $TI = 11.2$ %. However, here the length of the separation bubble does not decrease with increasing TI. The absence of a separation bubble at $TI = 11.2$ % is due to the increased momentum exchange within the boundary layer with the flow being transitional and closer to the turbulent regime than the laminar regime at the location, where it would have otherwise separated. Correspondingly, a resulting increase of the drag coefficient with increasing TI is seen.

  In the study by Breuer [8] a decrease in the lift coefficient is observed with an increase in TI up to 5.6 % before it stays constant. It is known that a separation bubble close to the leading edge could increase the lift coefficient due to the increase in the apparent camber caused by the presence of the separation bubble. With increasing TI and the downstream shift of the separation bubble, the lift coefficient then decreases. In the present study, the lift coefficient increases with increasing TI, however very slightly (a relative change of 3 %) and is likely caused by the slight downstream shift of the separation region, which increases the extent of the laminar flow along the chord.

  A combination of these factors results in an increasing lift-to-drag ratio with increasing TI in Breuer [8], whereas the lift-to-drag ratio in the current study reduces.

  Tangermann and Klein [9] have studied the influence of inflow turbulence with varying intensities and length scales on the NACA0018 airfoil. In this case the separation bubble already originates between 25 and 35% chord length which is further downstream than in our simulations. This can be attributed to the location of the maximum thickness of the airfoil since the adverse pressure gradient favors separation. In case of the NACA0018 airfoil, its maximum thickness is located at 30 % chord while the airfoil studied here has its maximum thickness located at 36 % chord. Tangermann and Klein [9] have also observed the influence of inflow turbulence on the separation bubble with the separation region being delayed in some spanwise regions compared to the case without added turbulence.

- **Brief discussion on the instantaneous state at a TI of 11.2 %**
  There seems to be a misunderstanding. It probably arises on account of line 66 of the first version of the manuscript which states *"The percentage of time, where the spanwise averaged flow on the suction surface is attached, was found to be 59.8 % at a TI of 8 % and 96.6 % at a TI of 10 % which indicates that there were instances of separation even at a high TI of 10 %"*. This statement corresponds to the investigation by Zaki et al. [10].

  In our study we do not see separation either in the mean or the instantaneous flow field, but the data was not as critically analyzed as in the investigation by Zaki et al. [10] to look for possible and very short occurrences of instantaneous flow separation. On line 305 of the first version of the manuscript, it is stated that *"at $TI = 11.2$ % the separation bubble vanishes"* and on line 352 *"For the case with a very high turbulence intensity of 11.2 %, the flow does not separate and spanwise rolls are no longer present while the streaks take over the transition process."* and finally on line 527 this is again stated in the conclusion.

  The manuscript already discusses the instantaneous transition phenomenon at $TI = 11.2$ % with transition being dominated by Klebanoff modes (boundary layer streaks). No further discussion is necessary since the interaction of streaks and the varicose mode of transition has already been thoroughly discussed in Section 4.4 using the case with an inflow TI of 2.8 % as reference. Similar processes are observed at higher inflow turbulence intensities, albeit with relatively more streaks being formed within the boundary layer.

- **Specific comments**
  Figure 1 has been updated and the other errors pointed out have been corrected.

- **Correction to c_p**
  In the first version of the manuscript there was an error in the plotting of the pressure coefficient. The reference pressure was not taken into account and this has been changed in the second version. This does not affect any of the results or calculations other than the plot of the lift-to-drag ratio, which has also been updated.

We gratefully acknowledge the effort of the referee and his/her contributions in enhancing the quality of our paper. Thanks a lot.

B.A. Lobo, A.P. Schaffarczyk, M. Breuer

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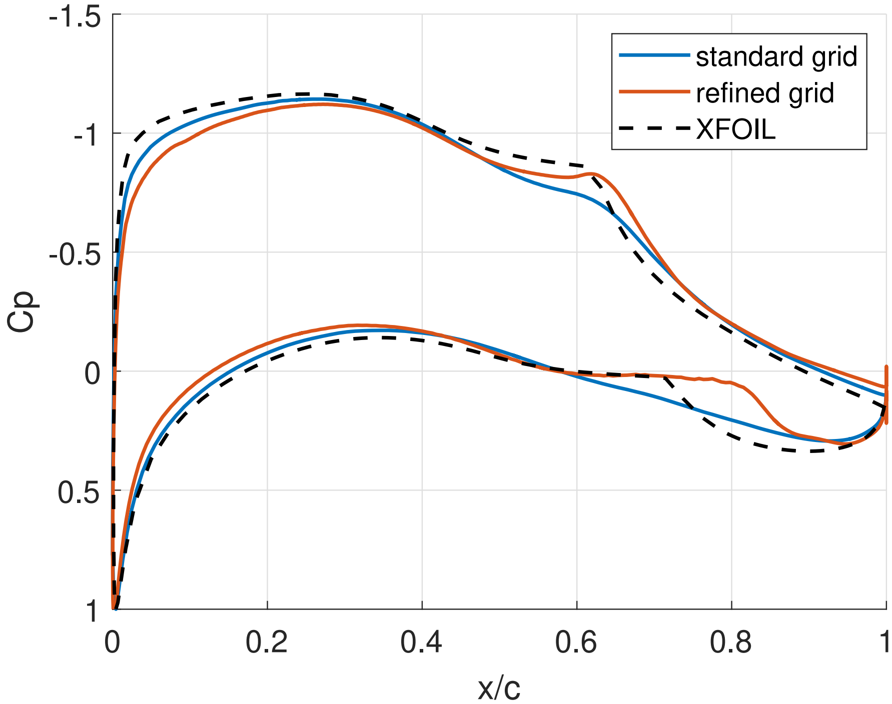

Figure 1: Pressure coefficient of the standard vs. the refined grid at $TI = 0$ %.

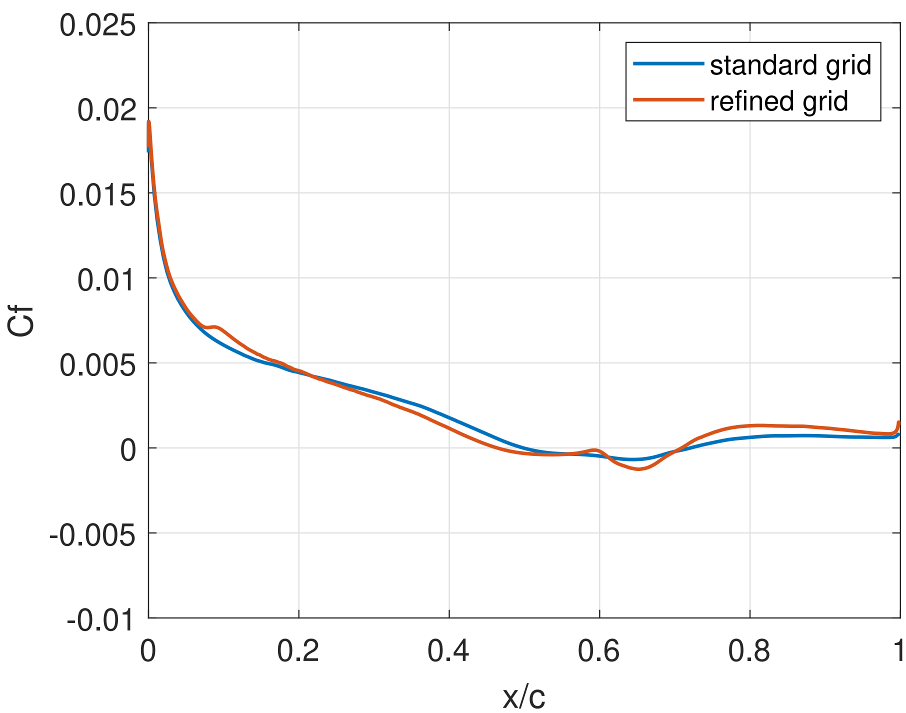

Figure 2: Friction coefficient of the standard vs. the refined grid at $TI = 0$ %.