Deliverable D3.1-03

"Report on test case F1:
Turbulent Flat Plate Boundary Layer"
.

Date of issue

07 January 2014

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The work described in this document was performed as part of the Go4Hybrid project (Grey Area Mitigation for Hybrid RANS-LES Methods) which is funded by the European Union under Grant Agreement No. 605361.

The project is a collaboration between CFDB, NTS, DLR; FOI, NLR, ONERA, and UniMAN, with Bombardier Transportation, GE Global Research, NUMECA, EDF, PSA Peugeot-Citroen, Rolls-Royce Deutschland, SAAB, ANSYS and Volkswagen AG as observers.
EADS CASSIDIAN and Eurocopter Deutschland GmbH are associate partners, not belonging to the consortium directly.

The opinions, findings and conclusions expressed in this report are those of all partners, and do not necessarily reflect those of the European Commission.

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1 Introduction-physical phenomena and modelling

Spatially developing boundary layers at high Reynolds numbers play a key role in many engineering applications *e.g.* for determining friction drag on a body moving relative to a fluid. This enables performance prediction (*e.g.* fuel consumption).

In contrast to the rich literature concerning channel flows, there exists only very few publications where hybrid RANS/LES results are compared with experimental/DNS data in the case of a spatially developing flat plate boundary layer. This may appear surprising since the capability to simulate a spatially developing boundary layer is a mandatory milestone of a hybrid RANS/LES method intended to simulate complex flows of practical interest. Nevertheless, the capability to simulate accurately such flows in WMLES mode is definitely a challenging issue.

The problem of zonal or embedded hybrid coupling is equivalent to a multi-resolution decomposition of the problem and can take several forms as illustrated in Figure 1.

1. Whilst non-zonal methods aim at covering the entire boundary layer in the URANS mode, embedded methods aim at covering only the inner part of the boundary layer. Consequently, LES content has to be generated in the outer part of the boundary layer. This first type of problem is sometimes referred to as Wall-Modelled LES (WMLES).
2. The second type of RANS/LES coupling aims at representing a turbulent inflow especially when a LES domain is located downstream a RANS domain. In this case, synthetic turbulent structures have to be generated to match statistical characteristics provided by the RANS side.
3. The most general multi-domain/multi-resolution problem concerns the case where a local LES simulation is embedded into a global RANS simulation.
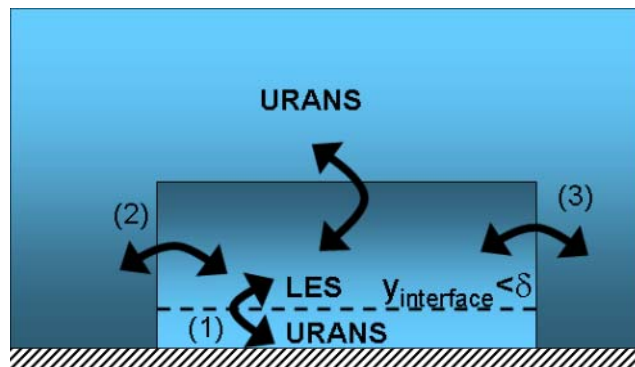

Figure 1: Several configurations of zonal RANS/LES coupling: (1) Wall-Modelled LES (WMLES) – (2) Turbulent inflow condition – (3) Embedded.

In all cases, the spatial derivatives across the RANS/LES interface of the averaged flowfield are discontinuous and synthetic turbulence must be generated at the inflow of the LES domain when it is located downstream a RANS region. This test case (referred to as F1 in the following) has been designed to address the aforementioned issues.

2 Flow and inflow boundary condition

The test case is a spatially developing zero-pressure gradient turbulent boundary layer over a smooth flat plate. The free-stream velocity is U_0=70 ms^{-1}, the static pressure is set to P_0=99120 Pa, the temperature equals 287 K leading to a Reynolds number per meter Re=4.72×10^6 m^{-1}.

The initial boundary layer thickness is δ_0=5.8mm so that the Reynolds numbers based respectively on the momentum thickness θ_0 and the friction velocity $u_{\tau 0}$ at the inlet are respectively:

$$\mathrm{Re}_{\theta 0} = \frac{U_0 \theta_0}{\upsilon} = 3040 \text{ and } \delta_0^+ = \mathrm{Re}_{\tau 0} = \frac{u_{\tau 0}\delta_0}{\upsilon} = 1065$$

Implementation of inflow conditions for LES is a serious and still open problem. Indeed, using the RANS field alone to generate inflow data for the LES domain cannot be sufficient: additional modelling which includes further assumptions on local length scales, time scales and energy distribution is required to recover an efficient inlet condition for LES.

As the knowledge of the whole Reynolds stress tensor is often lacking, Laraufie and Deck [1] assessed several methods to generate these quantities from a RANS calculation. The method M2 of Ref. [1] (based on Wilcox's hypothesis) has been retained to generate the inlet profiles gathered in Table 1 and plotted in Figure 2 and Figure 3. It is important to note that the provided quantities are given in the frame of a cell-centered approach.

Name of the file	Content	Units
u_v_mutmu_inlet_ONERA.dat	y, μ_t/μ, <u>, <v>	y in [m], <u> and <v> in [m/s]
Rij_inlet_ONERA.dat	y, <u'^{2}>, <v'^{2}>, <w'^{2}>, <u'v'>, <u'w'>, <v'w'>	<u'$_i$u'$_j$> in [(m/s)^2]

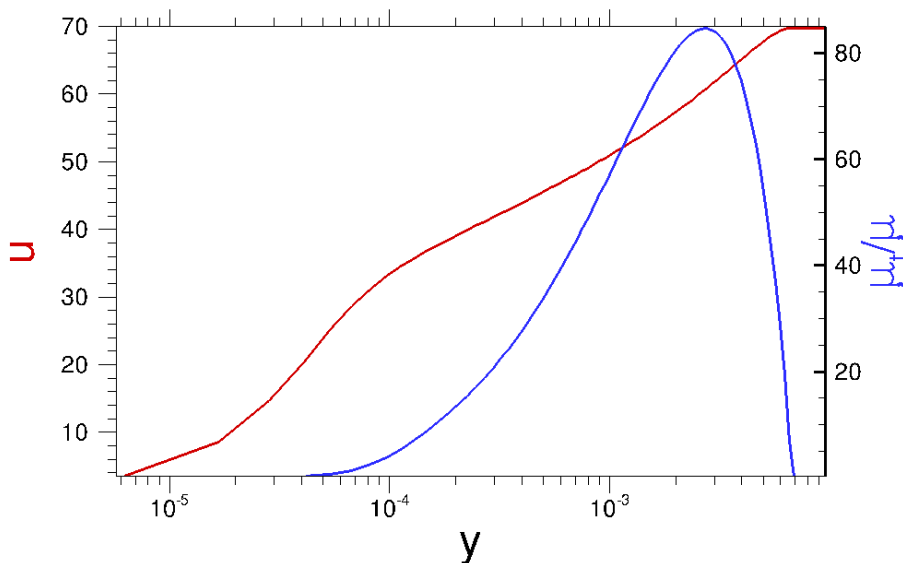**Table 1: Inlet velocity and Reynolds stresses profiles.**

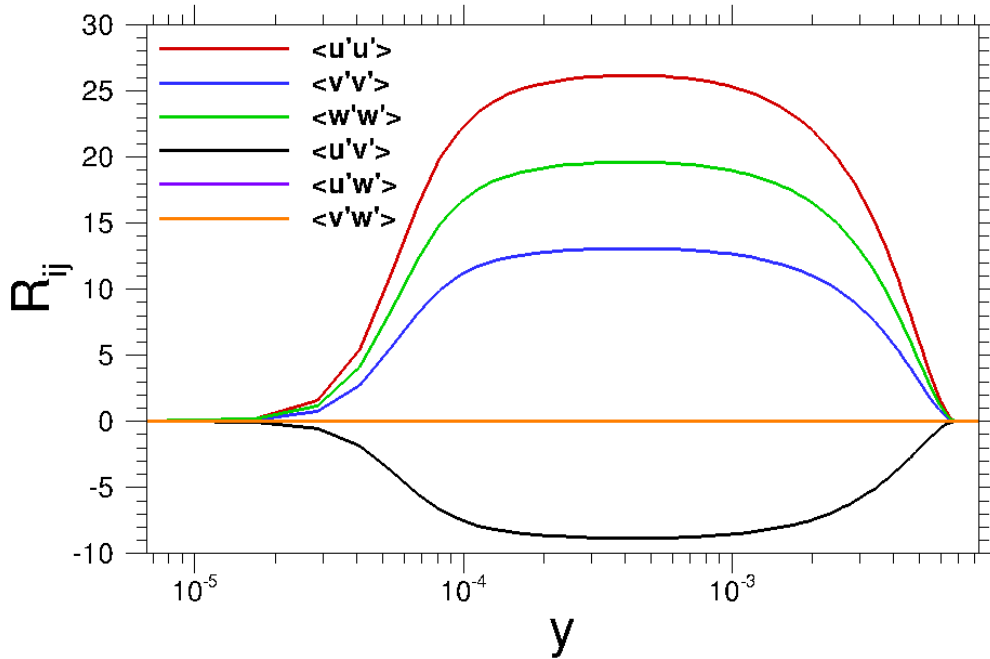**Figure 2: Velocity and eddy viscosity profiles at the inlet**

Figure 3: Reconstructed Reynolds stresses profiles at the inlet

3 Geometric description and mandatory grid

A mandatory structured grid was designed for the purposes of the project. The computational domain sizes in the streamwise, spanwise and wall-normal directions are respectively $L_x= 113\ \delta_0$, $L_z=5\ \delta_0$ and $L_y=52\ \delta_0$ so that the range of Reynolds number covered by the simulation is $3040 \leq Re_\theta \leq 6100$ (or $1065 \leq Re_\tau \leq 2095$).

A visualisation of the computational domain is displayed in Figure 4. Note that for $x/\delta_0>77$, mesh cells are stretched in order to progressively damp the turbulent fluctuations. This procedure is common to ensure that the domain of interest is free from wave reflections.
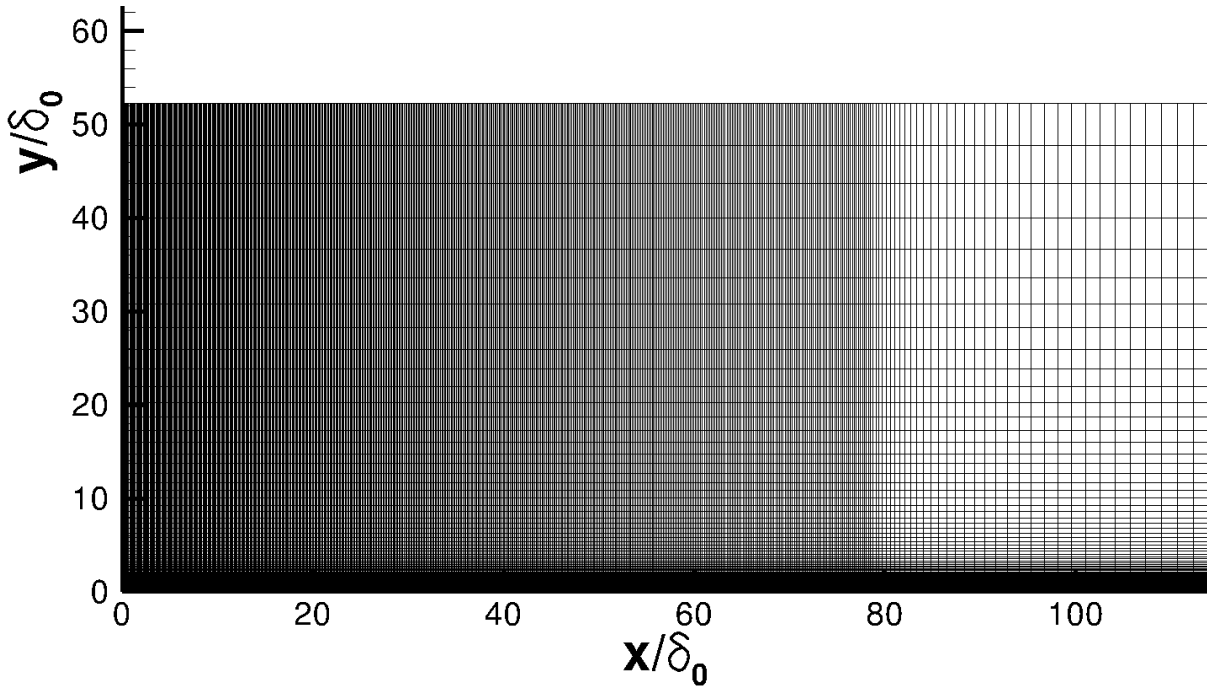
Figure 4: Computational domain of the mandatory grid

The major parameters of the grid resolution are gathered in Table 2 as well as in Figure 5 and correspond to classical grid resolutions used in the framework of WMLES approach whose objective is to describe the outer part of the boundary layer. Note that the first cell is at $y^+=1$ in the framework of a cell-centered code (i.e. $y^+=2$ in the framework of a cell-vertex code). The grid distribution in the streamwise direction is not uniform in order to maintain $\Delta x/\delta \approx 0.1$ in the region of interest. Conversely, the grid in the spanwise direction is constant so that $\Delta z = \Delta x_{min}/2$. Finally the total number of points is $N_{xyz}=7.8\ 10^6$ points.

Δx^+	Δy^+	Δz^+	$\Delta x/\delta$	Δz	$N_x \times N_y \times N_z$	N_{xyz}
100^+-200^+	2	50	0.092-0.1	$\Delta x_{min}/2$	$587 \times 127 \times 103$	$7.8\ 10^6$

Table 2: Parameters of the mandatory grid. N_x, N_y and N_z are the grid sizes along the axes and the Δs are the corresponding resolutions expressed in both wall unit $\bullet^+$ and inlet boundary layer thickness unit (δ_0).
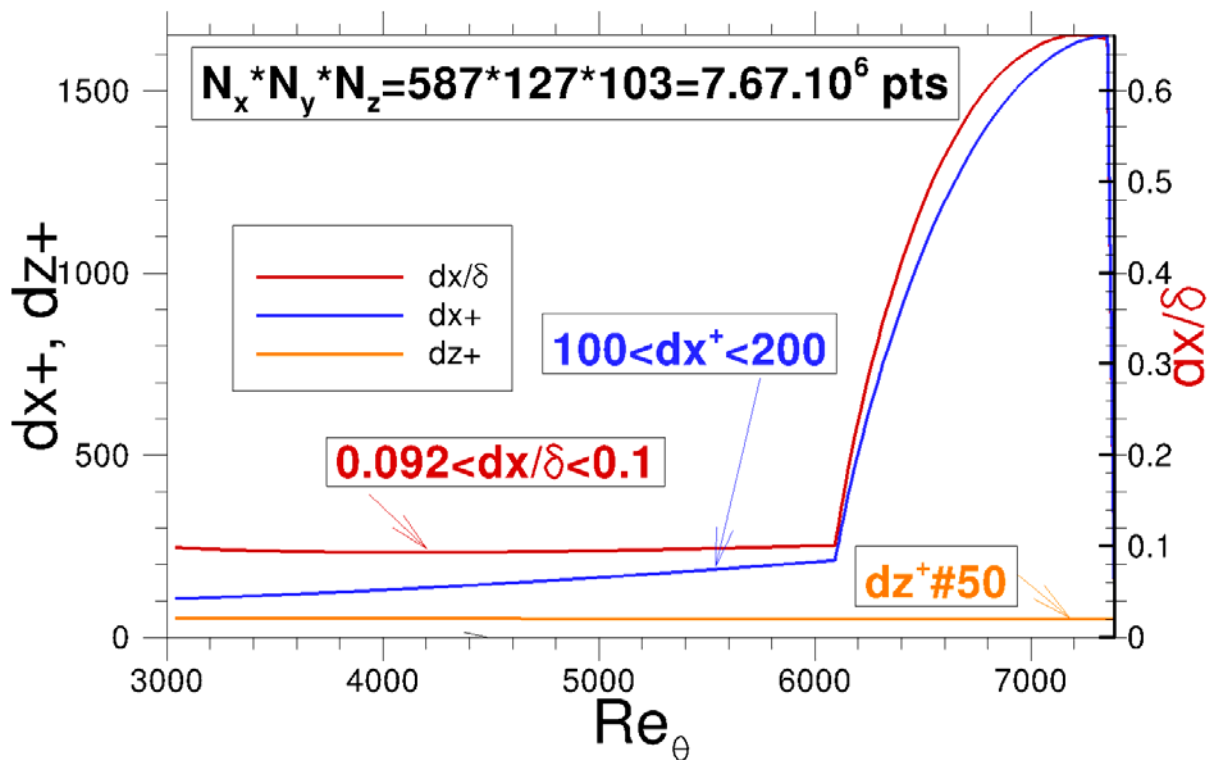
Figure 5: Streamwise evolution of the mesh resolutions

The grid is provided in TECPLOT ASCII format (see Table 3).

Format	Content	Name of the file
TECPLOT ASCII	x,y,z	grid_ONERA_TCF1.dat

Table 3: Mandatory grid.

4 Description of available reference data

- *Skin friction coefficient*

The skin friction constitutes a primary quantity of interest and its assessment deserves particular attention. Several data available in the literature including both DNS and experimental results have been gathered in Table 4 and plotted in Figure 6.

Reference	DNS/Exp	Name of the file
Schlatter & Örlü [2]	*DNS*	Cf_DNS_Schlatter_Orlu_2010.dat
DeGraaff & Eaton [3]	*Exp*	Cf_DEGRAAF_2000.dat
Österlund et al [4]	*Exp*	Cf_OSTERL1999.dat

Table 4: Summary of available experimental/DNS Cf data

Numerical results can also be compared with the widely acknowledged Coles-Fernholz correlation (see Ref [5]) given by

$$C_f^{CF} = 2\left(\frac{1}{0.384}\ln(\mathrm{Re}_\theta) + 4.127\right)^{-2}$$
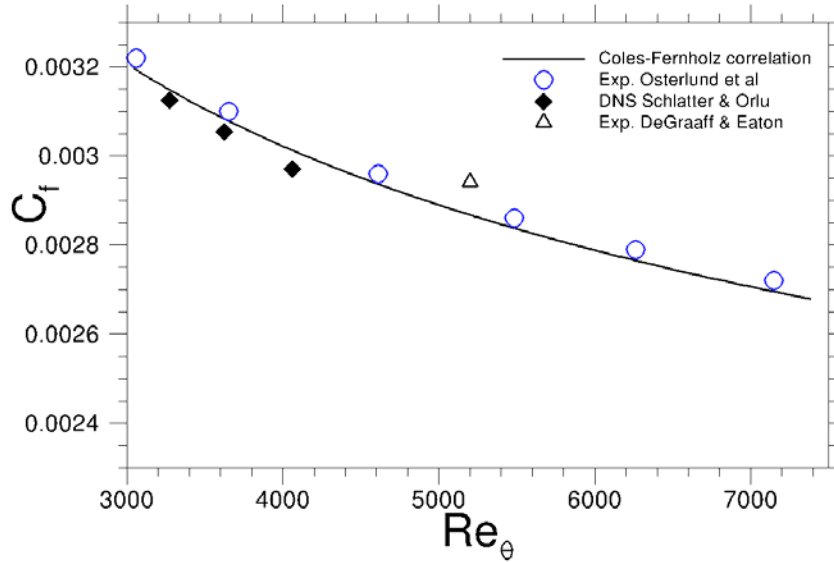
Figure 6: Streamwise evolution of the skin friction coefficient (C_f=[0.0023-0.0033]; Re_θ=[3000-7500])

Based on the Coles-Fernholz correlation, one can define the error on the skin friction as follows

$$Err = \frac{\left|C_f^{CF} - C_f\right|}{C_f^{CF}}$$

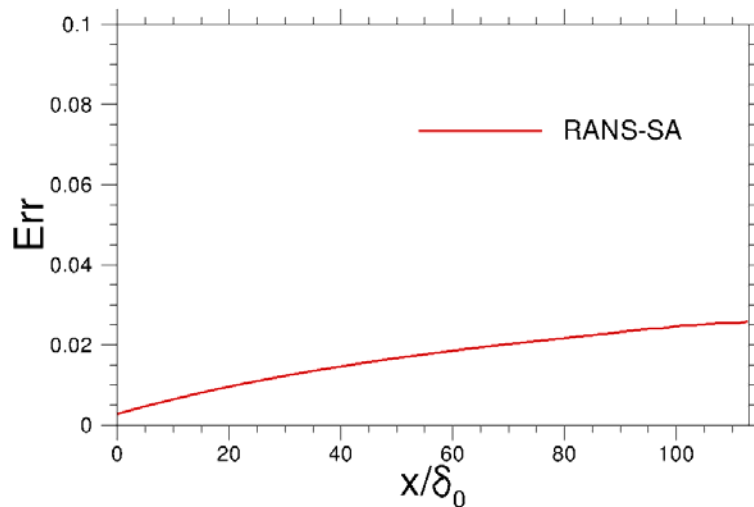and plot this quantity as a function of the streamwise distance from the inlet.

Figure 7: Streamwise evolution of the skin friction coefficient (Err=[0.0-0.1]; x/δ_0=[0-113])

- *__Velocity profile and Reynolds stresses__*

Several velocity and Reynolds stresses data available in the literature including both DNS and experimental results have been gathered in Table 5 and Figure 8 displays for instance the normal Reynolds stresses Re_θ=4060, 5200.

Reference	DNS/Exp	Re_θ	Name of the file
Schlatter & Örlü [2]	*DNS*	*4060*	Vel_DNS_Schlatter_Orlu_2010_Req4060.dat
DeGraaff & Eaton [3]	*Exp*	*5200*	Vel_EXP_DEGRAAF_2000_Req5200.dat
			up2_EXP_DEGRAAF_2000_Req5200.dat
			vp2_EXP_DEGRAAF_2000_Req5200.dat
			uv_EXP_DEGRAAF_2000_Req5200.dat

Table 5: Summary of available experimental/DNS velocity data
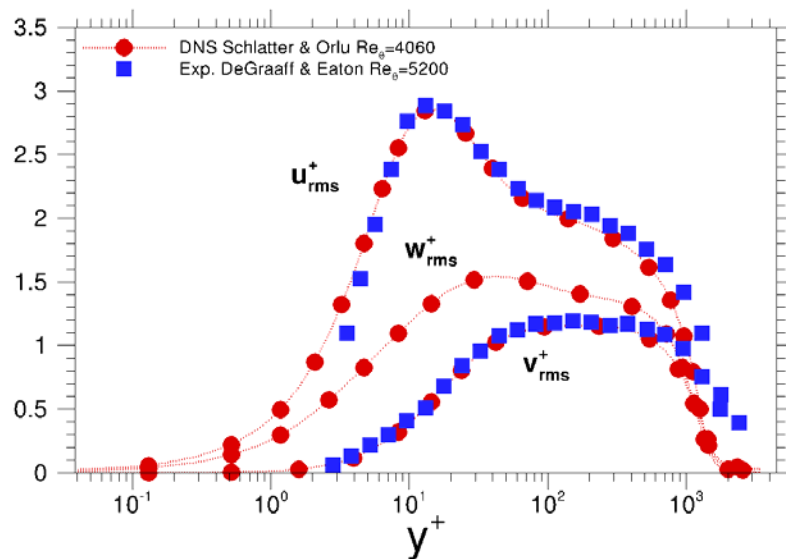

Figure 8: Normal Reynolds stresses at Re_θ=4060 and 5200

5   Mandatory and optional results

This section provides a description of the data expected from each partner contributing to the test case. Each data have to be sent in *Tecplot ASCII Point* format using the nomenclature described hereafter:

- ***Cf results***

Nomenclature:

data_Cf_grid_organisation_model_option.dat

grid	=	mandatory, etc
organisation	=	DLR,FOI,NLR,NTS,ONERA,UNIMAN
model	=	IDDES, XLES, ZDES, etc
option	=	relevant option of the model like the location of a prescribed interface, the value of a constant of the model, etc

Example :   data_Cf_mandatory_ONERA_RANSSA.dat

Each file contains the **4** quantities:

Re_θ Reynolds number based on momentum thickness: $Re_\theta = \dfrac{U_0 \theta}{\upsilon}$

Re_τ Reynolds number based on friction velocity $Re_\tau = \dfrac{u_\tau \delta}{\upsilon}$

Err   Error on Cf compared with C_f^{CF} $Err = \dfrac{\left| C_f^{CF} - C_f \right|}{C_f^{CF}}$

x/δ_0 Normalized distance (at the inlet x/δ_0)

The head of the file (Tecplot ASCII POINT) should read as follows:

```
TITLE    = "RANS SA (ONERA)"
VARIABLES = "Re<SUB><GREEK>q</GREEK></SUB>"
"Re<SUB><GREEK>t</GREEK></SUB>"
"Err"
"x/<greek>d</greek><sub>0</sub>"
ZONE T="XXXX"
 STRANDID=0, SOLUTIONTIME=0
 I=587, J=1, K=1, ZONETYPE=Ordered
 DATAPACKING=POINT
 DT=(SINGLE SINGLE SINGLE SINGLE )
3.039205322E+03 1.065962402E+03 2.819159301E-03 0.000000000E+00
```
Figure 9 Example of head of the file data_Cf_X200Z100mandatory_ONERA_RANSSA.dat

- ***Velocity and Reynolds stresses***

Nomenclature:

data_Vel_grid_Retheta_organisation_model_option.dat

grid	=	mandatory, etc
organisation	=	DLR,FOI,NLR,NTS,ONERA,UNIMAN
Retheta	=	station at specified Re_θ : 4060 and 5200
model	=	IDDES, XLES, ZDES, etc
option	=	relevant option of the model like the location of a prescribed interface, the value of a constant of the model, etc

Example :   data_Vel_mandatory_4060_ONERA_RANSSA.dat

Each file contains the **10** quantities:

|		
y^+	normalized distance to the wall:	$y^+ = \dfrac{y u_\tau}{\upsilon}$
y/δ	normalized distance to the wall	$\dfrac{y}{\delta}$
u^+	normalized streamwise velocity	$u^+ = \dfrac{\langle u \rangle}{u_\tau}$
u/U_0	normalized streamwise velocity	$\dfrac{\langle u \rangle}{U_0}$
u_{rms}^+	normalized streamwise velocity fluctuations	$u_{rms}^+ = \dfrac{u_{rms}}{u_\tau}$
v_{rms}^+	normalized wall-normal velocity fluctuations	$v_{rms}^+ = \dfrac{v_{rms}}{u_\tau}$
w_{rms}^+	normalized spanwise velocity fluctuations	$w_{rms}^+ = \dfrac{w_{rms}}{u_\tau}$
$-u'v'^+_{res}$	normalized resolved Reynolds shear stress	$-u'v'^+_{res} = \dfrac{-\langle u'v' \rangle}{u_\tau^2}$
$-u'v'^+_{mod\,el}$	normalized modelled Reynolds shear stress	$-u'v'^+_{mod\,el} = \upsilon_t \left(\dfrac{\partial \langle u \rangle}{\partial y} + \dfrac{\partial \langle v \rangle}{\partial x} \right) / u_\tau^2$
$-u'v'^+_{tot}$	normalized total shear stress	$-u'v'^+_{tot} = -u'v'^+_{res} - u'v'^+_{mod\,el}$

The head of the file (Tecplot ASCII POINT) should read as follows:

TITLE   = "RANS-SA – Rtheta=4060 (ONERA)"
VARIABLES = "y⁺"
"u⁺"
"u⁺_{rms}"
"v⁺_{rms}"
"w⁺_{rms}"
"y/<GREEK>d</GREEK>"
"-u'v'tot+"
"-u'v'res+"
"-u'v'model+"
"U/U0"
ZONE T="SubZone"
 STRANDID=0, SOLUTIONTIME=0
 I=1, J=127, K=1, ZONETYPE=Ordered
 DATAPACKING=POINT
 DT=(SINGLE SINGLE SINGLE SINGLE SINGLE SINGLE SINGLE SINGLE SINGLE SINGLE)
 0.000000000E+00   0.000000000E+00   0.000000000E+00   9.769767788E-24   0.000000000E+00
0.000000000E+00 5.827382000E+06 0.000000000E+00 5.827382000E+06 0.000000000E+00
 1.979449272E+00   2.010954618E+00   4.148509561E-06   2.203833560E-07   6.437776978E-09
1.522622188E-03 3.412874416E-03 -8.099204358E-13 3.412874416E-03 7.783416659E-02

Figure 10: Example of head of the file data_Vel_mandatory_4060_ONERA_RANSSA.dat

In addition, several profiles of resolved Reynolds stresses -u'v'$_{res}$+ at several streamwise locations ranging from $x/\delta_0 = 0$ to 10 may be useful.

Figure 11 presents for example a comparison of the mean velocity profile with the available experimental data.
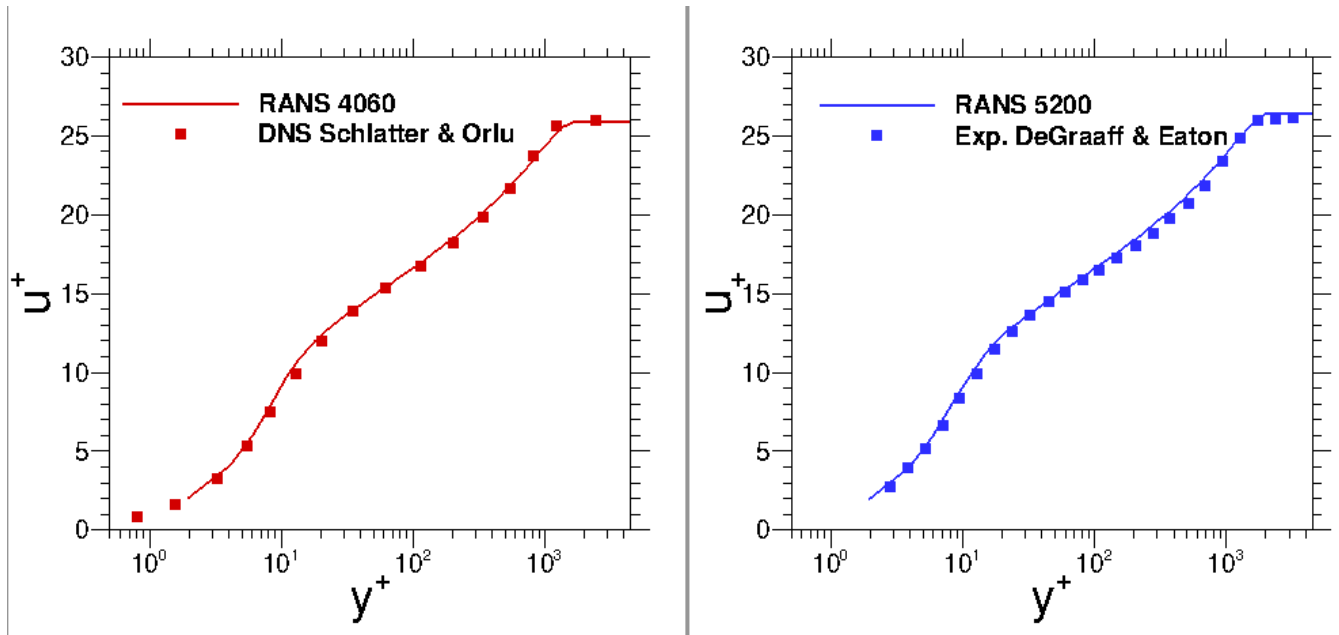
Figure 11: Velocity profiles at Re$_\theta$=4060,5200

- *Visualizations (optional)*

a) The turbulent structures can be educed by plotting a surface of the normalized Q criterion
$Q * \left(\dfrac{\delta_0}{U_0}\right)^2 = 0.15$, eventually coloured by the normalized streamwise velocity u/U$_0$.

b) Normalized vorticity magnitude $\dfrac{\|\vec{\omega}\|\delta_0}{U_0}$ snapshots in several XZ plane at several different distances to the wall (y/δ_0=0, 0.02, 0.05, 0.25, 0.5, 1.) can also be plotted.

Besides, it is asked to the partners participating in this test case to provide the information gathered in Table 6.

Partner	Solver	Model	Spatial scheme	Grid	Time step, Δt	Comments
Name of the partner	*Name of the code*	*IDDES, ZDES, etc*	*Jameson, AUSM, etc*	Mandatory, etc	*Time step in μs*	*Variant of a model, etc*

Table 6 :Summary of calculations concerning TC F1

6 References

[1] Laraufie, R. and Deck, S. (2013). Assessment of Reynolds stresses tensor reconstruction methods for synthetic turbulent inflow conditions. Application to hybrid RANS/LES methods. International Journal of Heat and Fluid Flow, vol 42, pp 68-78.

[2] Schlatter, P. and Örlü, R. (2010). Assessment of direct simulation data of turbulent boundary layers. Journal of Fluid Mechanics, vol 659, pp 116-126.

[3] DeGraaff, D.B. and Eaton, J.K. (2000). Reynolds number scaling of the flat-plate turbulent boundary layer. Journal of Fluid Mechanics, vol 422, pp 319-346.

[4] Österlund, J.M., Johansson, A.V.; Nagib, A.V. and Hites, M. (2000). A note on the overlap region in turbulent boundary layers. Physics of Fluids, vol 12, 1-4

[5] Nagib, H.M., Chauhan, K.A.; Monkewitz, P.A. (2007). Approach to an asymptotic state for zero pressure gradient turbulent boundary layers. Philosophical Transactions of the Royal Society A, vol 365, 755-770.