WALLTURB : A EUROPEAN SYNERGY FOR THE ASSESSMENT OF WALL TURBULENCE.

EC PROJECT N°: AST4-CT-2005-516008

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1. Introduction

The WALLTURB consortium is composed of 16 partners (Table 1). This consortium includes high level industrials from Aeronautics, large public research organizations and well known Universities from the Mechanical Engineering and Aeronautical field. All partners are strongly involved in the research on turbulence at European and International level. They have proven their efficiency and ability to cooperate in the frame of previous European programs.

LML UMR CNRS 8107	F
ONERA	F
LEA UMR CNRS 6609	F
LIMSI UPR CNRS 3251	F
Chalmers University of Technology	SE
ENSTA/ARMINES	F
CNRS SPEC/CEA Saclay	F
University of Cyprus	CY
University of Rome la Sapienza	IT
University of Surrey	UK
Polytechnic University of Madrid	SP
Technische Universität München	G
Technical University of Czestochowa	PL
Norwegian Defence Research Establishment	NO
AIRBUS	UK
DASSAULT AVIATION	F

Table 1 : List of WALLTURB partners

The global aim of WALLTURB was to bring in four years a significant progress in the understanding and modelling of near wall turbulence in Boundary Layers. This goes through:

- generating and analyzing new data on near wall turbulence,
- extracting physical understanding from these data,
- putting more physics in the near wall RANS models,
- developing better LES models near the wall,
- investigating alternative models based on Low Order Dynamical Systems (LODS).

To reach the above objectives, the WALLTURB Consortium took advantage of recent progress in the experimental and numerical approaches of turbulence and complementary skills of leading teams in Europe working on turbulence.

It has generated a large and original database, with recent and relevant data about near wall turbulence (from both experiments and DNS already available at the partners). This database is shared by the partners to extract relevant physical data.

The consortium has also generated new experimental and DNS data, allowing to assess Adverse Pressure Gradient Turbulent Boundary Layer physics, with and without separation, to go in the common database.

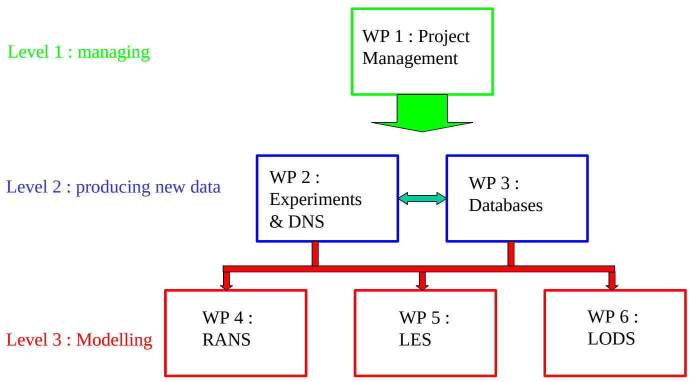


Table 2 : Work program Structure

This database was extensively used by all the partners to improve RANS, and LES near wall turbulence models and to develop a LODS/LES coupling near the wall.

The work performed aims at making available new turbulence models based on a detailed physical characterisation and to assess the relative merits and drawbacks of these models. These models are assessed by two leading industrial in the field of aeronautics : AIRBUS and DASSAULT AVIATION.The WALLTURB project was organized in 6 work packages, as summarized in table 2.

2. Experiments and DNS

The overall objective of the experiments and DNS performed is to complement the previously existing databases with time and space resolved data at high Reynolds numbers for ZPG and APG attached flows and to provide well documented test cases for the RANS modelling of separated flows. The unsteady data are suitable for LES initial and boundary conditions, as well as of value to the POD and LODS evaluations. Experiments were carried out at LML, Surrey and Czestochowa, in both ZPG and APG boundary layers, with and without wall curvature and separation.

The 'WALLTURB joint experiment' at LML BL wind tunnel.

This experiment was performed jointly by LML, LEA and Chalmers University in June and September 2006. Figure 1 gives a sketch of one of the set-ups used. This set-up was designed to assess the very large scales in the flat plate turbulent boundary layer.

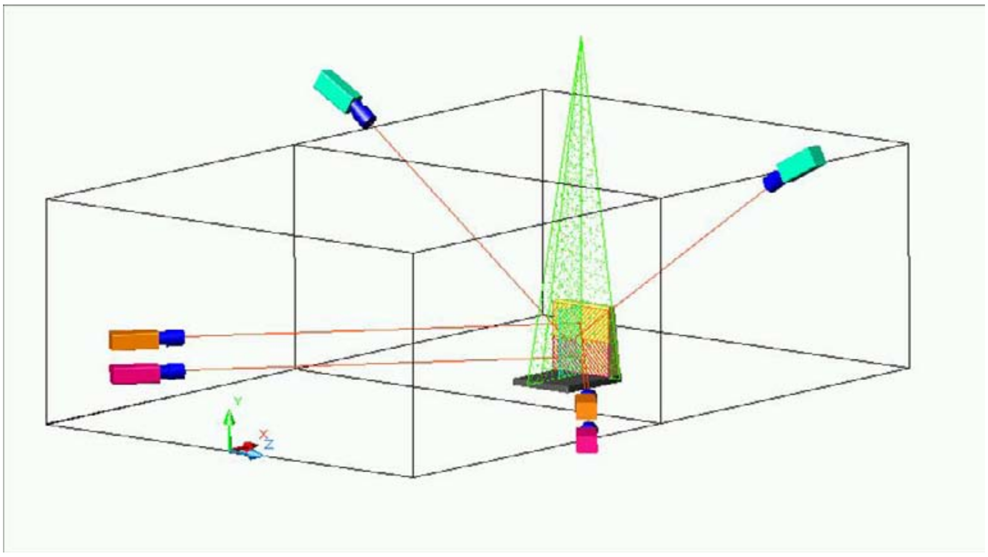


Figure 1. Experimental set-up for the assessment of the very large scale structures in the flat plate turbulent boundary layer. The flow is along the x axis, y is the wall normal. The vertical square block behind the green light sheets is the hot wire rake with 143 single hot wires. Three stereo PIV systems are synchronized with the hot wire data acquisition system in order to assess the full space time velocity correlations on times corresponding to about 100 BL thicknesses.

Two Reynolds numbers were tested (R = 10,000 and 20,000) with three different set-ups: the set-up of figure 1, a set-up with the hot wire rake and a high repetition rate Stereo PIV system in a plane parallel to the wall and finally the hot wire rake alone to enhance the statistical convergence. A total of about 2300 blocks of 6s of data were recorded for each Reynolds number with the rake (6s corresponding to more than 100 BL thicknesses). The Stereo PIV systems were fully synchronized with the hot wire rake acquisition system. The number of records was high enough (9600) to ensure good statistical convergence.

Figure 2 gives a photogaph of the rake in the wind tunnel. Although it is made with thin electronic boards, it is a significant obstacle to the developing boundary layer.

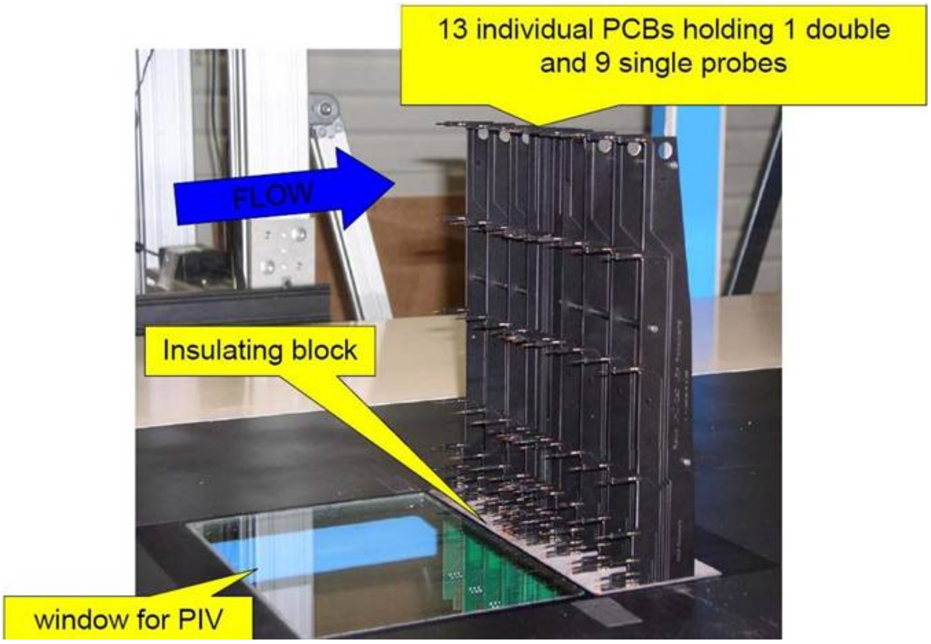
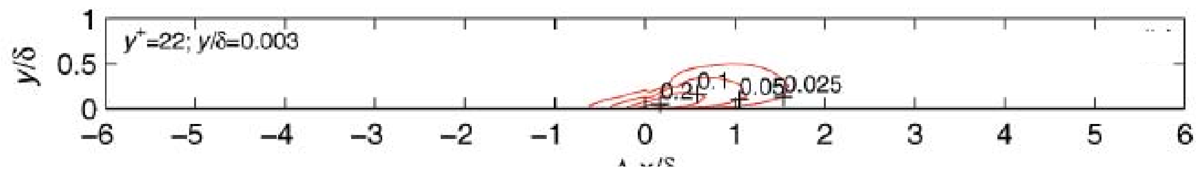
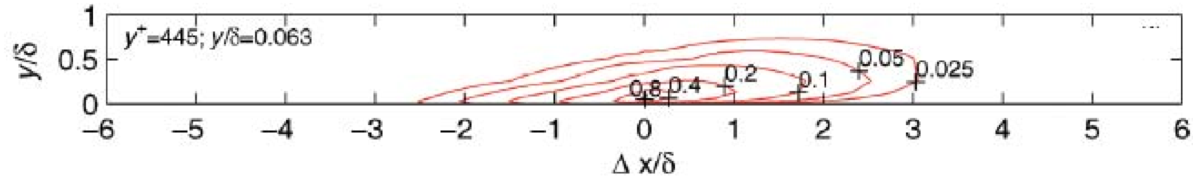


Figure 2. Hot wire rake equipped with 143 single hot wires mounted in the wind tunnel for the flat plate experiment. The glass window is used for the stereo PIV measurements.

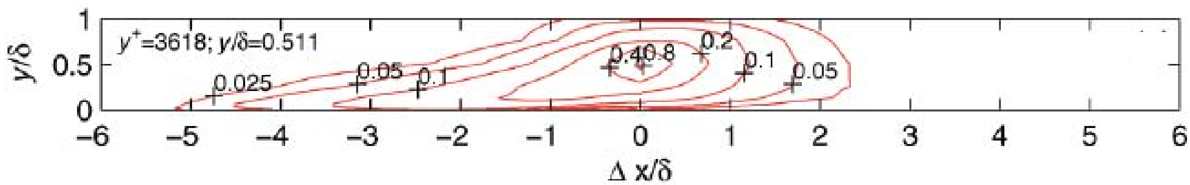
This point has been addressed using a simple potential flow model in planes parallel to the wall. The comparison of the RMS of the streamwize velocity fluctuations with and without rake confirms that the blockage is potential.



(a)



(b)



(c)

Figure 3. Space-time correlation of the streamwise velocity component deduced from the hot wire rake measurements at different wall distances for the fixed point : (a) y+ = 22, (b) y+ = 445, (c) y/ = 0.511 at R = 20 000. The streamwise extend of the large scale structures is evidenced together with the asymmetry at all wall distances.

Figure 3 gives an example of result obtained from the hot wire rake signals. The space-time correlation of the streamwise velocity component in a streamwise/wall normal plane has been computed at each probe locations. Samples are given of three of them at wall distances representative of the buffer layer, the log layer (which is well developed at this Reynolds number) and the wake region. The extend of the correlation gives an idea of the extend of the large scale motions (called sometime 'inactive motions' as they contribute little to the turbulent shear stress) which are suspected in WP4 to play a significant role in the discrepancy between the RANS model predictions and the experiments when the turbulent kinetic energy is looked at.

The Surrey bump experiment.

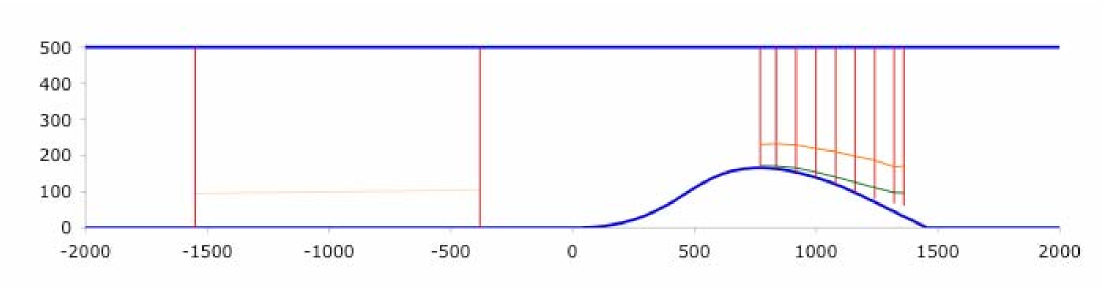


Figure 4. Geometry of the bump experiment at Surrey showing the two inlet boundary conditions measurement stations and the APG flow measurement stations. The free stream velocity is 10 m/s.

This experiment was designed as an a posteriori validation experiment for the RANS and LES models. The LML AEROMEMS bump was used as a starting reference. It was scaled at ½ in order to fit the scale of the Surrey wind tunnel and the rear part was slightly modified in order to generate a small separation bubble. This was in fact a small modification as the LML bump is already bringing the BL near to separation. The aim of making a small separation bubble was to have a flow with the BL going down to separation but without significant 3D effects, to allow 2D computations which are more suited to test models.

Figure 4 gives the flow geometry, together with the different measurement stations. Coordinates are in mm. The boundary layer develops on the lower flat wall, from the inlet of the test section which is at - 7650 mm from the bump origin. Extensive measurements of static pressure distribution, skin friction and hot wire measurements of the three mean velocity components and full Reynolds stress tensor where performed over the diverging part of the bump (stations in red). Also, the inlet (at two stations) and upper wall boundary conditions have been characterized in detail. Figure 5 gives the evolution of the mean velocity on the decelerating part of the bump, measured by traversing a single hot wire anemometer and figure 6 the profiles of streamwise turbulence intensity at different stations, showing clearly that the turbulence peak ismoving rapidly away from the wall.

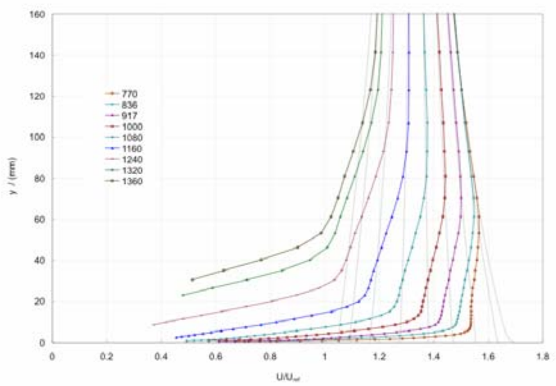


Figure 5. Mean velocity profiles at different stations on the APG side of the bump. The effect of the deceleration is clearly evidenced. The separation point is at x = 1327mm.

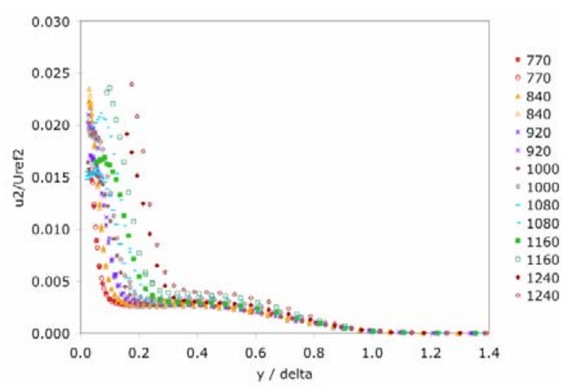


Figure 6. Streamwise turbulence intensity profiles on the APG side of the bump, showing that the turbulence peak is moving away from the wall.

The Czestochowa APG BL experiment.

The experiment performed at Czestochowa Technical University has been designed to generate an adverse pressure gradient boundary layer representative of turbomachinery conditions. Figure 7 presents the experimental set up. The boundary layer develops on the lower flat wall (2.8 m in length), first without pressure gradient to increase the Reynolds number. Then a converging diverging upper wall is used to bring the BL into an adverse pressure gradient flow. No separation occurs, even on the upper wall, so the pressure gradient is mild on the lower wall. Extensive hot wire measurements have been performed, first to check the inlet boundary conditions at two stations (1.74 and 1.94 m from leading edge) and then to characterize the flow in the APG region of the flow. The Reynolds number at the first station is R = 2500.

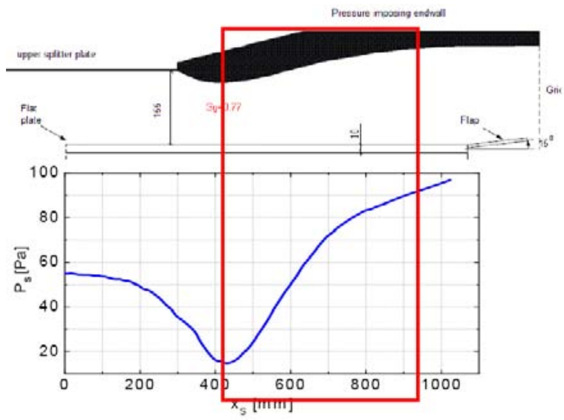
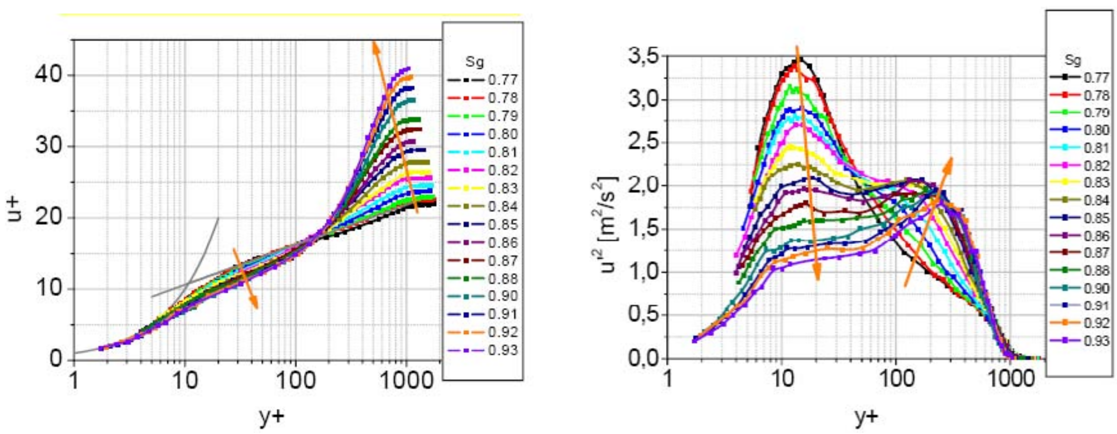


Figure 7. Sketch of the converging diverging part of the wind tunnel, showing the pressure distribution (blue line) and the region of hot wire investigation (red rectangle).

Figure 8 gives as an example the mean velocity measured with a single hot wire, together with the streamwise component of the diagonal Reynolds stresses. Results are plotted as profiles along y at different streamwise positions. The results clearly show the effect of the adverse pressure gradient. The interest of this test case is that

it is performed at Reynolds number which is low and representative of turbine blade conditions. An other interest is that the flow is free of curvature effect, which is not the case of the other experiments of WP2 (LML and Surrey bumps). This test case will be used as a "blind test case", for a posteriori validation of RANS models.



(a) (b)

Figure 8. (a) Mean velocity and (b) streamwise diagonal Reynolds stress profiles as a function of streamwise position. Showing the strong evolution of the mean velocity on both the log layer and the outer region and the disappearance of the near wall turbulence peak in benefit of a smaller one further away from the wall.

DNS of plane channel flow at Madrid and Rome Universities .

DNS results for the plane channel flow are made available for a wide range of Reynolds number by Madrid (J. Jimenez) and Rome (P. Orlandi) Universities. These DNS serve to build and check the near wall turbulence models in WP4, 5 & 6. All turbulence statistics are available, including the full Reynolds stress budget. Also, Rome University has computed the turbulence structure tensor which is of strong interest for the structure based RANS models.

In Figure 9, Rome University has plotted two components of the circulicity tensor as a function of wall distance and for varying Reynolds number. These data are of direct use for Structure Based models (ASBM) developed in WP4.

Also, Madrid University has computed the energy and Reynolds stress budget from the DNS at the highest Reynolds number available. The redistribution role of the pressure terms is clearly evidenced, together with the complex role of the turbulent transport as a function of wall distance.

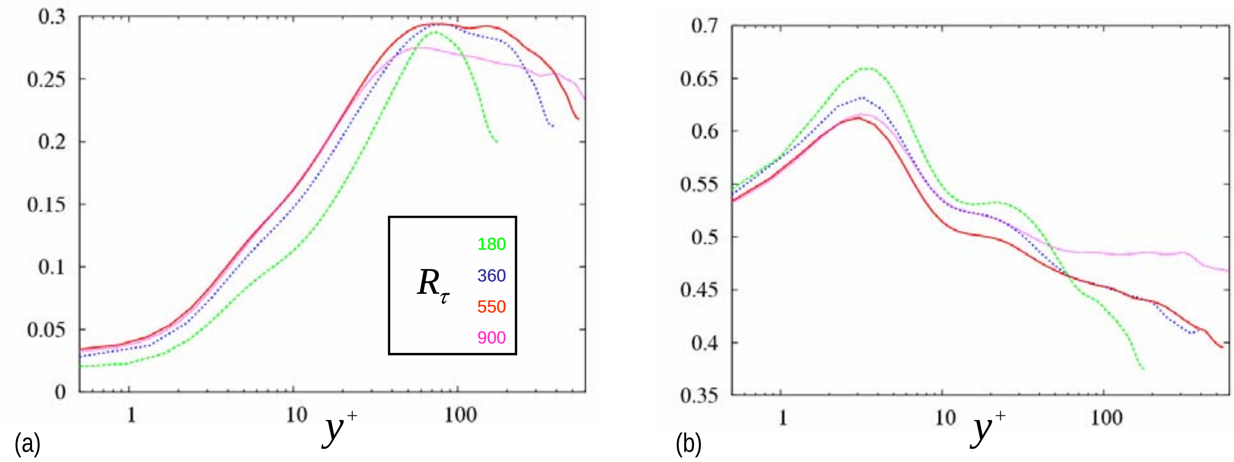


Figure 9. Profiles of two components of the circulicity tensor (a) F11 and (b) F22 as a function of wall distance and for different values of the Reynolds number in a plane channel flow, computed by Rome University.

DNS of Couette-Poiseuille flow at Rome University .

The flow in a plane channel with one wall moving at a constant velocity is of strong interest for near wall turbulence modelling as it is an elegant way to vary the wall shear stress. The DNS of such a flow has been performed by Rome University (P. Orlandi) for different wall velocities and Reynolds numbers (Figure 10). Here again, the full set of statistics, Reynolds stress budget and turbulence structure tensor is available to modellers of WP 4 &5.

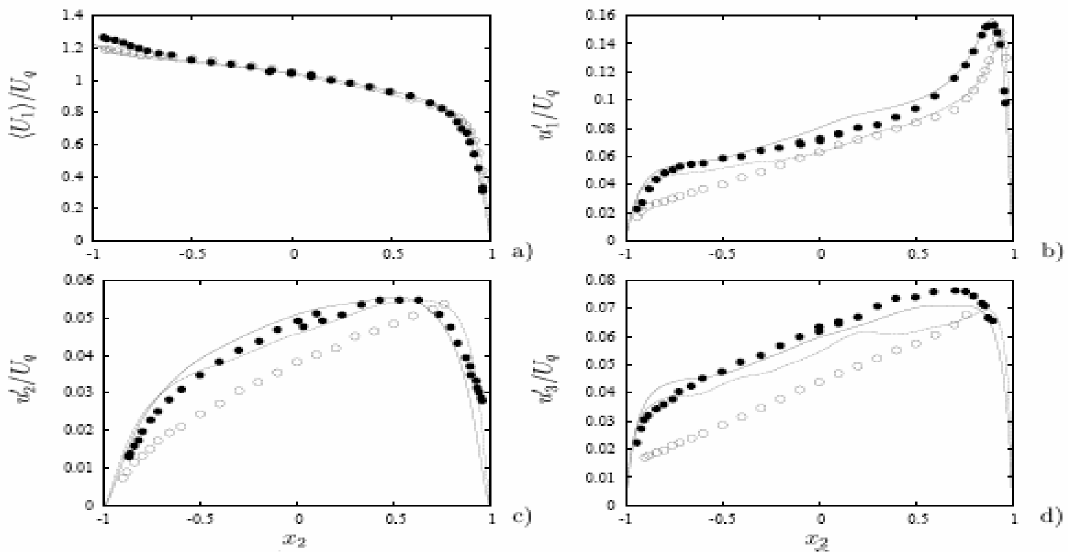


Figure 10. Mean velocity and turbulent intensity profiles for an intermediate type Couette-Poiseuille flow DNS computed by Rome University (solid lines), compared to experiments by Gilliot (full symbols) at comparable Reynolds number.

DNS of converging diverging channel at LML.

In order to investigate adverse pressure gradient near wall flows, LML has performed two DNS of a converging diverging channel at Re = 400 and 600. The channel geometry was chosen identical to the bump used in the LML wind tunnel (AEROMEMS bump). Only the inlet conditions are different: a fully developed channel flow DNS is used as inlet condition for the converging channel DNS. The smallest Reynolds number simulation was performed at CRIHAN and IDRIS. The second one benefited from a DEISA allocation of computer time.

Figure 11 shows the strong vortical structure generation occurring just after the bump submit and developing rapidly downstream.

In Figure 12, the main components of the Reynolds stress tensor are plotted as a function of wall distance at different stations near the lower and the upper wall. The strong effect of the pressure gradient on the Reynolds stress balance is clearly visible.

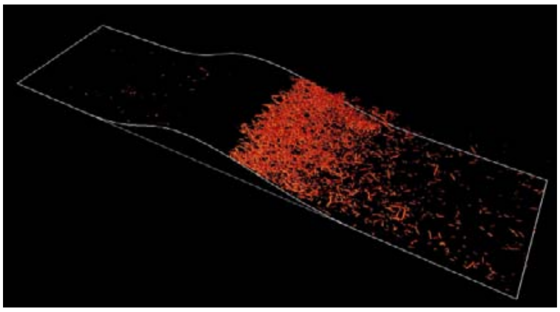


Figure 11. Isovalues of the Q criterion to evidence vortical structures near the curved wall in the DNS of converging diverging channel flow at Re = 600.

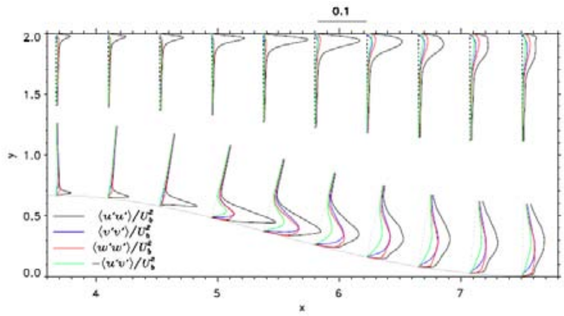


Figure 12. Reynolds stress tensor components in the APG part of the DNS of converging diverging channel flow at Re = 400. Profiles are plotted near the lower and the upper wall.

DNS of turbulent boundary layer at UPM.

The University of Madrid is running DNS of boundary layers under zero and adverse pressure gradient (Figure 13). These DNS complement the existing database of DNS of plane channel flow at different Reynolds numbers.

N_x	N_y	N_z	L_x/θ_e	L_y/θ_e	L_z/θ_e	Re_θ	$\delta^* \partial_x P^+$		points
1536	301	768	43	9	20	800-2000	20-1000	Dec-08	350M

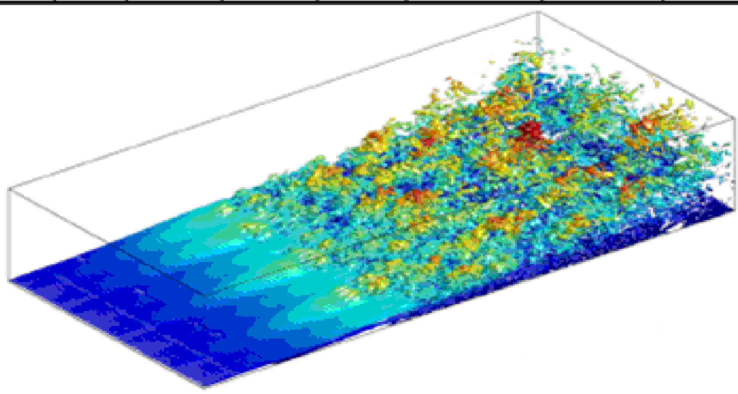


Figure 13. Direct numerical simulation of adverse pressure gradient boundary layer performed at Madrid Polytechnic University. Visualization of coherent structures.

3. WP3 : Databases

This workpackage is devoted to the management of the databases generated in the project and to the post processing of these data for modelling purposes. The databases generated are accessible through the WALLTURB web site : http://wallturb.univ-lille1.fr

Analysis of wall turbulence through the entropic skin theory at ENSTA.

Ecole Nationale Supérieure des Techniques Avancées (D. Queiros Condé) is developping the Entropic skin theory for the characterisation of turbulence intermittency (Figure 14). This theory is applied to wall turbulence with the help of the WALLTURB database.

4. WP4 : RANS modelling

In the WALLTURB project, the goal of the RANS model work package is to improve Explicit Algebraic Reynolds Stress Models (EARSM), which are considered as the next industry workhorse. In these explicit algebraic models, the constitutive relation, which relates the Reynolds stress tensor to the mean flow and turbulence properties, is deduced from an equilibrium relation in the Reynolds stress budget. The derivation is performed for homogeneous turbulence, or under assumptions which lead to the same behaviour, but these assumptions are known to fail close to the wall. The goal is thus to account for the wall influence in the constitutive relation. Various approaches have been considered to extend EARSM models to the wall region.

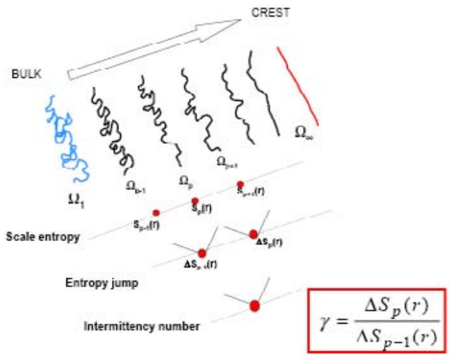


Figure 14. Study of the turbulence structure geometry by the Entropic skin. A multiple threshold procedure allows to define the intermittency number From theory, for isotropic turbulence = 0.68, for wall turbulence = 0.36.

A first route is to use the information about the wall normal diagonal stress, which can be derived from a v^2-*f* approach, to alter the constitutive relation near the wall and reproduce the correct near-wall behaviour. This is the route followed by FFI.

The model has presently been validated on various test cases issued from the project, among which the LML bump data, using as well the experimental as the DNS data, and on Couette-Poiseuille flows, using LML experimental data and Roma University DNS. Agreement is very nice on all Couette-Poiseuille flows, as shown in figure 15.

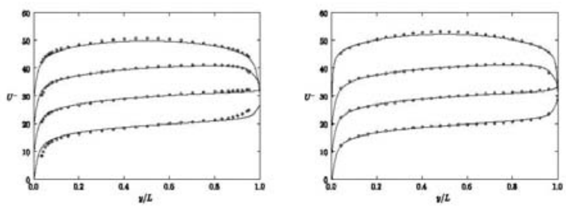


Figure 15. Comparison of experimental and predicted mean velocity profiles for Couette-Poiseuille flows. Left: LML experiments – Right: Roma University DNS. From top to bottom: Pure Poiseuille, Poiseuille type, intermediate and Couette flows

The bump test cases evidenced that some improvement are needed to sensitize the model to pressure gradients.

LEA considered that the major wall effect is through the pressure terms in the Reynolds stress budgets. Therefore, they derived their EARSM model from the elliptic blending second moment closure. This approach allows introducing a new tensor, linked to the "wall normal" direction, in the EARSM formulation, which is directly given by the elliptic blending approach. Different formulations, of various degrees of complexity, were derived and compared. Linear models are favoured for numerical stability reasons. Introducing information about the wall normal allows to selectively damp the turbulence near the wall. As a linear model cannot fully represent the turbulence anisotropy, other slightly more complex formulations were investigated. The various models were validated with respect to UMP channel flow and Roma's Couette-Poiseuille flow DNS (figure 16).

Looking for a strategy to derive a universal wall damping, ONERA first completed the analysis of Couette, channel and boundary layer DNS data. No universal behaviour of the turbulent quantities can be evidenced all over the wall region whatever the flow conditions. For moderate pressure gradients, nearly universal behaviours can be obtained e.g. using together Kolmogorov's and mixed scalings. Then, from channel DNS budgets, ONERA pointed out that, in the wall region, budgets for the anisotropy tensor which are the building stone of EARSM models, are simpler if the pressure terms as well as the viscous terms are grouped. The unexpected result is that, in the wall region, turbulent diffusion plays a major role in the anisotropy balance.

UCY developed the Structure Based Model, which accounts for the different turbulent structures in the flow. The Algebraic Structure-Based Model (ASBM) was improved, mainly to account for the length scale blocking close to the wall and consistency of the length scale equation with the logarithmic region and edge region constraints. The present model is still under qualification but was already checked with respect to channel DNS flows and zero pressure gradient boundary layer experiments. Airbus UK has tested the ASBM on transonic aerofoil, Cp and shock location are similar to kω and SST, which means that the model could be integrated into current design methods.

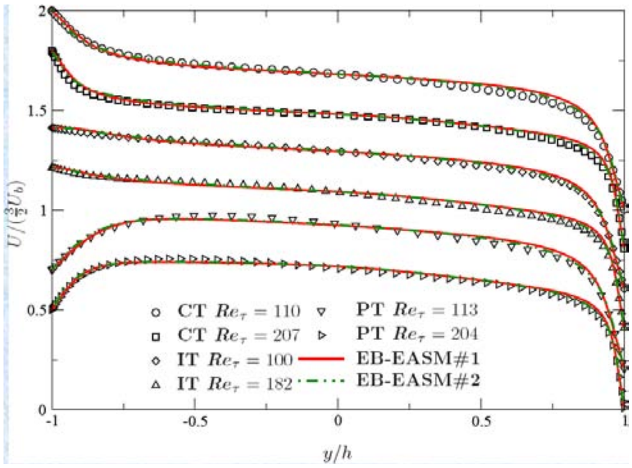


Figure 16. Prediction of mean velocity for Couette type, intermediate type and Poiseuille type flows by the elliptic blending Differential Reynolds stress model and the derived EARSM models

5. WP5 : LES modelling

WP5 is devoted to the improvement of LES modelling near the wall, and especially the investigation of new models for this region. The first objective of the current work package is the development of wall modelling approaches in the framework of existing and emerging LES techniques for industrial applications. The validity and performances of several LES models for wall bounded flows with and without APG are studied.

The performance of LES models are evaluated by comparison to real solutions at high Reynolds number from measurements and Direct Numerical Simulation.

The second objective is to take advantage of the numerical and experimental database to improve the understanding of physical processes of turbulence in the vicinity of a wall and to test the ability of the LES models to reproduce such processes with a minimum of grid points. The third objective is to propose and to test some conceptually new models which have the ability to deal with complex flows.

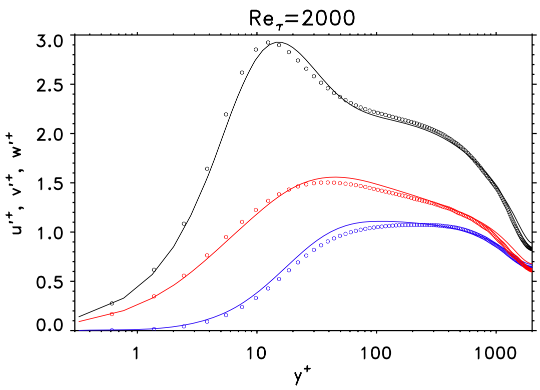


Figure 17. Comparison of the turbulent intensities from a LES using the WALE model with the DNS results (Jimenez & al) for a plane channel flow at R = 2000. Symbols correspond to the LES and lines to the DNS.

Coupling of implicit LES with TBLE model at TUM.

The Technical University of Munich is developing for some time implicit Large Eddy Simulation for turbulent flows. In the framework of WALLTURB, TUM is investigating the possibility of coupling the implicit LES with a one equation model near the wall in order to overcome the grid refinement problem at high Reynolds number. This coupling is successful for a plane boundary, showing a significant improvement in terms of grid size and computer time. Figure 18 shows representative results for the plane channel flow.

LES modelling at TUCz

The Technical University of Czestochowa is implementing and testing various LES models in a home made LES code named SAILOR. The aim is to perform computations of APG flows available in the WALLTURB database. Tests are performed in converging-diverging channels at low Reynolds number before computing the experiments available for comparison.

6. WP6 : LODS modelling

Low Order Dynamical Systems is a very promising modelling approach of turbulent flows which involves difficult theoretical developments. In particular, the coupling of a LODS near the wall with a LES in the field can be a good alternative to the present wall treatment in Large Eddy Simulation. The goal of WP6 is two-fold : First, to widen the experience with LODS and explore the relationship they hold with real flows. Second, the aim is to use low-order dynamical systems to simulate the flow both cheaply and efficiently, using a coupling between LODS and LES. LODS aims at representing the flow in the wall region, which is poorly resolved by LES. The idea is to advance both systems of equations in time, using each of them to provide adequate boundary conditions for the other. LEA and LIMSI are working on the construction of the POD database from both experimental and DNS data.

Figure 19 gives an example of POD modes derived from a DNS performed by UPM (Pr Jimenez). Besides, the derivation and stabilization of the LODS system is under way.

7. Conclusion

The WALLTURB project has run from April 2005 to June 2009 with a consortium of 16 partners. A unique database of both experimental and DNS data on high Reynolds number wall flow was gathered, analysed and used to develop and improve RANS, LES and LODS turbulence models. An international workshop was organized in Lille on April 21-23 2009, to present the main results of the project. The proceedings of this workshop will be published in the ERCOFTAC series at Springer Verlag and available in October 2009. All information on the project are available at http://wallturb.univ-lille1.fr.

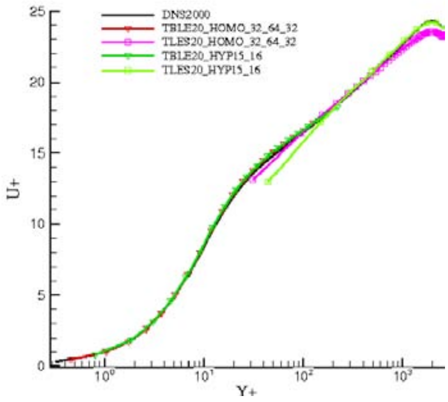


Figure 18. Comparison of implicit LES coupled with a TBLE model with DNS results (Jimenez et al) for the plane channel flow at R = 2000.

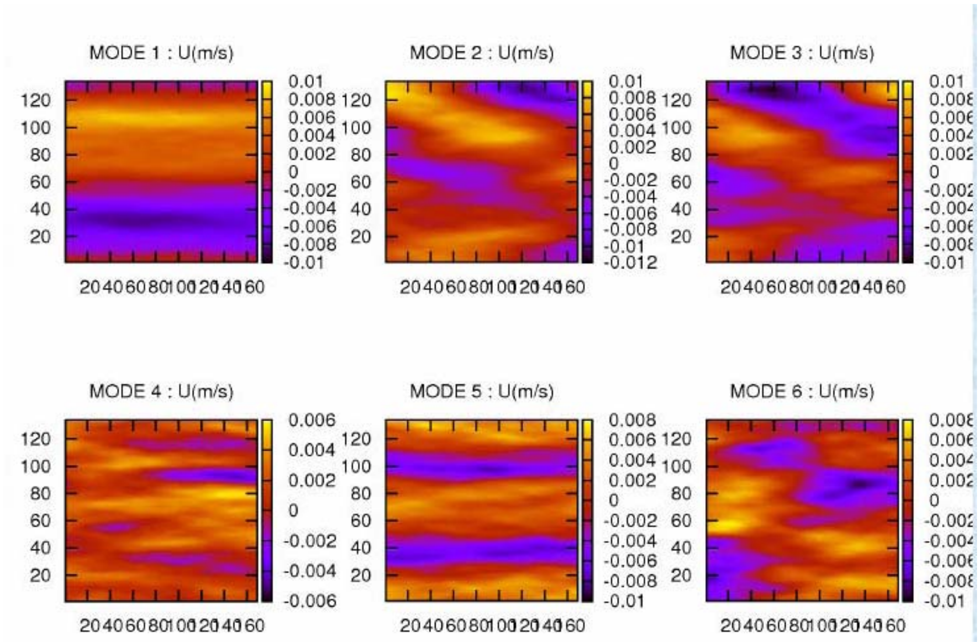


Figure 19. Spatial POD modes at y+ = 50, computed from a Direct Numerical Simulation at Re = 550.

This work has been performed under the WALLTURB project. WALLTURB (A European synergy for the assessment of wall turbulence) is a collaboration between LML UMR CNRS 8107, ONERA, LEA UMR CNRS 6609, LIMSI UPR CNRS 3251, Chalmers University of Technology, Ecole Nationale Supérieure de Techniques Avancées, CNRS groupe Instabilité et Turbulence Saclay, University of Cyprus, University of Rome la Sapienza, University of Surrey, Universidad Politécnica de Madrid, Technische Universität München, Czestochowa University of Technology, FFI, DASSAULT AVIATION, AIRBUS. The project is managed by LML UMR CNRS 8107 and is funded by the EC under the 6th framework program (CONTRACT N°: AST4-CT-2005-516008).