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PRIORITY 4 AERONAUTICS and SPACE

A European Synergy for the assessment of wall turbulence

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ONERA	F	University of Surrey	UK
LEA UMR CNRS 6609	F	Polytechnic University of Madrid	ES
LIMSI UPR CNRS 3251	F	Technische Universität München	D
Chalmers University	SE	Technical University of Czestochowa	PL
Ecole des Mines de Paris	F	FFI	NO
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Contents

1 Summary

The WALLTURB project was a challenging research program within the objectives of the FP6 in Aeronautics and of strong industrial interest at intermediate and long term.

The global aim of WALLTURB was to bring a significant progress in the understanding and modelling of near wall turbulence in Boundary Layers. This went 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 these objectives, the WALLTURB Consortium took advantage of the recent progress in the experimental and numerical approaches of turbulence and the 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. This database was shared by the partners to extract relevant physical data and will be used by the scientific community in the next years.

This database comprises new experimental and DNS data, giving new insights into both Zero and Adverse Pressure Gradient Turbulent Boundary Layer physics, with and without separation.

This database was used by the partners in the frame of WALLTURB to improve RANS, and LES near wall turbulence models and to investigate LODS/LES coupling near the wall.

The work performed has allowed development of new turbulence models and the assessment of the relative merits and drawbacks of these models. These models were also evaluated by AIRBUS in the industrial context.

It has also generated new physical insights, both with regard to classical scaling laws (on which most models to-date have been based) and turbulent structures (on which future models will most likely be based.)

2 Introduction

Europe seeks to reduce aircraft development and operating costs in the short and long terms. This must be accomplished both through improved aircraft performance and through reduction in maintenance and other direct operating costs.

To reach these objectives, the aeronautical industry needs improved models based on a deeper understanding of the physics, which in turn must be acquired using the most advanced experimental and modelling methods. While this is true for all the aspects of the design and operation of an aircraft, it is particularly true for aerodynamics. Although aerodynamics has made tremendous progress in the last century, it still lacks reliable turbulence models (which are crucial also for many other industrial design problems) and the understanding to develop them. The search for these models remains a very active domain for research and improvement. In fact, turbulence remains one of the great unsolved riddles of engineering and natural sciences, nowhere more so than for flow near surfaces.

The potential benefits from even modest gains in understanding and predictive ability can best be illustrated by a simple example. On an Airbus A340, approximately one-half of the drag at cruising speed is skin friction drag. Based on Airbus estimations, even a 10% reduction of this drag would result in a fuel saving of about 100,000 Euros per aircraft per year, or 1 billion Euro saving over the world every year. In practice, it is the inner part of the boundary layer nearest the wall that is crucial in determining the skin friction drag; and, in fact, it is in this region that the present turbulence models are the least reliable, most notably when the flow is close to separation or separated. Therefore, a better understanding and modelling of this region, which is fairly universal, is crucial: – first to have reliable estimations *a priori* of the drag of a new aircraft design if one wants to reduce significantly development costs; and – second to move toward intelligent control strategies of the near wall flow with the objective of reducing drag.

Beside the potential improvements in cruise flight drag, significant benefit can be expected from a better knowledge and modelling of boundary layer flow in transient phases of flight. A representative example is the landing phase. The high lift configurations needed result in boundary layers with regions of strong adverse pressure gradients close to separation, and sometimes even locally beyond separation. Improved models should lead to improved designs and simpler and lighter high lift devices. Better physical knowledge should also lead to efficient control strategies, again improving performance or obtaining the same performance from simpler and lighter geometries (e.g., single flap instead of double).

In this respect, the WALLTURB objectives were the following:

- to advance the knowledge about and the prediction of wall-bounded turbulent flows.
- to put in a common database, shared by the WALLTURB partners, the existing relevant data they have about near wall turbulence (from both experiments and DNS),
- to generate by experiment, and by complementary DNS, equivalent data for the

Adverse Pressure Gradient Turbulent Boundary Layer physics (including separated flow cases), and to put them in the common database,

- to use this database to improve near wall turbulence models such as RANS, LES and LODS, and especially to understand their relative strengths and weaknesses.

To reach these objectives, the work was organized in the following way:

a/ A shared database on near wall turbulence

Large amounts of recently generated data, already existing at some partners, on both low and high Reynolds number near wall turbulence (flat plate boundary layer or channel flow) was put in common, and with uniform access.

b/ Adding new data on APG TBL

Since very little was known at the start of the project about the turbulence physics in adverse pressure gradient boundary layers, either in the near wall region or further away from the wall, state-of-the-art experiments and DNS were performed to allow a better understanding of the flow physics for the APG TBL.

c/ Improving near wall turbulence models

RANS modeling

In spite of their limitations, many consider two-equation turbulence models as a good industrial compromise between complexity and generality. It is well-known that the main weakness of these models is the length scale equation, especially near the wall.

To improve such models, due to the anisotropy near the wall, it is necessary to have representative scales in different spatial directions. This information is provided by the double spatial correlation tensor, which can be extracted from DNS at low and moderate Reynolds number. It can also be obtained in detail by PIV at high Reynolds numbers. The project took advantage of the shared database to extract these scales. It also made extensive use of the Reynolds stresses budgets and of the structure tensor derived from the DNS. Classical two-equation and Reynolds stress models were examined, along with advanced models such as elliptic relaxation and Algebraic Structure-Based Models. Tests of these improved models were also performed by AIRBUS in their in house codes.

LES modeling

Large Eddy Simulation is a prediction method which offers an alternative in some situations of strong industrial interest, especially where the RANS approach fails due to its basic hypotheses. It has been demonstrated now that the standard LES models fail near the wall, unless they are turned locally into a DNS in order to represent correctly the near wall turbulence structure. This is very memory and time consuming, and limits presently the extensive use of this approach in industry. The objective of WALLTURB was here again to take advantage of the network database to quantify the accuracy of standard LES models near the wall. Effort was also made to develop improved near wall models; e.g., models based on recent advances using the Rapid Distortion Theory and implicit subgrid-scale models.

LODS/LES coupling

By introducing the Proper Orthogonal Decomposition and the Low Order Dynamical System approach, Lumley and his co-workers have opened an entirely different approach to near wall turbulence modelling. This is easily demonstrated by the number of teams working on this approach around the world. LODS is an elegant way to cope with the representation of the relevant coherent structures in turbulence, and it has already shown its ability to represent the very near wall structure and dynamics. Although not yet suited for a full industrial flow, this approach is a very good alternative, solidly grounded in physics, for adapting LES near the wall. The detailed DNS/PIV/HW data available was a unique opportunity to develop such models, and test them and their underlying hypotheses.

The work program was divided into 6 work packages which formed coherent groups of similar tasks. The following diagram (Figure 1) makes clear important links between them. As can be seen, the proposed program has been organized in three levels.

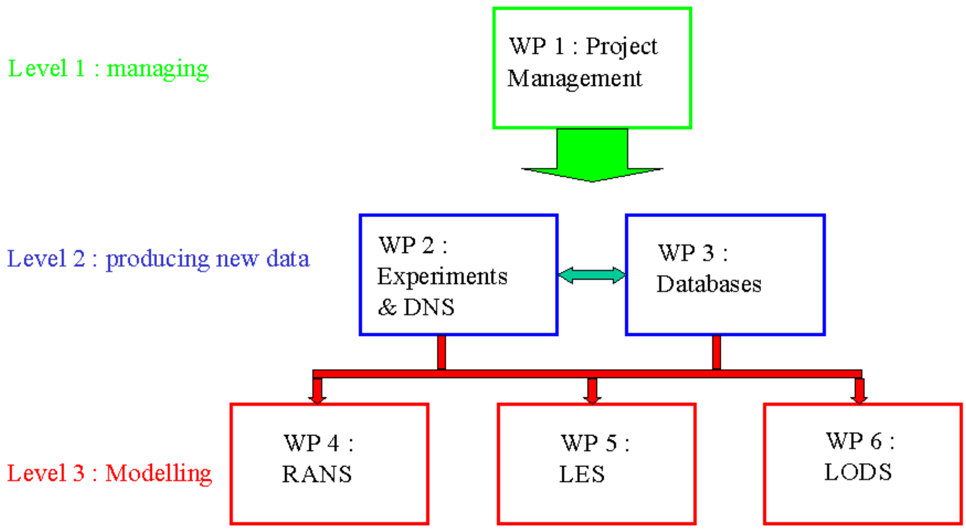


Figure 1: Program structure.

At **level 1**, WP1 covered all the management and exploitation activity needed for smooth operation of the project. The WALLTURB web site was an important tool of this work package.

At **level 2**, the objective of the consortium was to generate a full database of new results on wall turbulence. These data came from both experiments and DNS. The most advanced tools were used to generate them. This level has been structured in two work-packages:

- WP2 was focussed on the experiments and DNS performed during the project (Direct Numerical Simulation being considered here as an experiment). It was divided into 4 tasks in order to clearly identify the type of experiments performed.

- WP3 was the kernel of the project as it was responsible for the management and processing of the different databases (a total of 8) that were put in common by the partners. These databases were fed both by existing data at the start of the project and by the experiments performed in WP2. The workpackage was organized in three tasks which group the databases in a coherent manner with respect to the type of flow.

Level 3 was organized into three work packages which were devoted to the development, improvement and validation of three different kinds of modelling approaches:

- WP4 was concerned mostly with the classical and industrial RANS approach and had the aim of improving the physical content of the models. This was done extensively for plane channel, ZPG boundary layer and Couette flow. Adverse Pressure Gradient was also addressed.

- WP5 was devoted to the improvement of LES modelling near the wall, and especially the investigation of new models for this region.

- WP6 investigated the possibilities of the fairly recent Low Order Dynamical Systems approach, and of its coupling with LES in the near wall region.

3 Activity

3.1 WP 1: Management

Beside the day-to-day management of the project, an important action of the coordination was the dissemination of the project activity. This was done through the newsletters, published on the website ([NL1, NL3], through the organisation of workshops at midterm ([Rome Workshop]) and end ([Lille Workshop])of the project and also through the presentation of the project in broadband conferences ([1, 2]).

3.2 WP 2: Experiments & DNS

Work Package manager: TUCh

Objectives The overall objective of the experiments and DNS performed was to complement the previously existing databases with time and space-resolved data at high Reynolds numbers for ZPG (zero-pressure gradient) and APG (adverse pressure gradient) attached boundary layer 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 of WP6. In addition to the signature cooperative experiment at LML, additional and complementary experiments were performed at Surrey and Czestochowa in ZPG and APG boundary layers, both with and without wall curvature and separation. These were further augmented by DNS of wall-bounded flows at UPM (Madrid) and URS (Rome) and a DNS of the bump by LML.

3.2.1 Main results

The primary results from each part of WP2 are summarized in the following paragraphs.

Experiments

Wind tunnel tests at LML

Figure 2: The international team of the 'WALLTURB Joint experiment' at LML (From left, M. Tutkun (Chalmers/FFI), M. Stanislas (LML), J-M Foucaut (LML), J. Delville (LEA), W. George (Chalmers), J. Costas (LML/Australia), P. Johansson (Chalmers), S. Coudert (LML), F. Mehdi (Chalmers/USA). Chalmers and LEA were in charge of the hotwire anemometry, LML did set up the optical measurements. ONERA and LML took in charge the skin friction measurements

This was the challenging experiment of WALLTURB, and was performed jointly by LML, LEA,Chalmers University and ONERA in June and September of 2006. The purpose was to exploit the unique experimental facility at LML to carry out high Reynolds number turbulent boundary layer measurements on a scale allowing detailed characterization of the near wall region. This was a truly international cooperative effort that would have been nearly impossible outside of an EU framework, since the manpower and equipment required was well-beyond the capabilities of any single existing institution.

The LML facility uses a 20m long test section to develop a smooth wall boundary layer of approximately 0.3m in height corresponding to a turbulent Reynolds number $\Re_\theta$ of approximately 20,000, which is at the lower limit of Reynolds numbers representative of industrial flows around airplanes. Even more important than the Reynolds number and boundary layer height, the size of the viscous length scale was large enough to be resolved by modern optical methods (approximately 40 microns). This meant that the important wall region of a ZPG could be interrogated in a boundary layer truly representative of flows interesting to industry. A second experiment using the same methodology and team was carried out using the LML 'bump' which was constructed in a previous EU project (AEROMEMS). The bump was designed by Dassault to be representative of the combination of flows encountered in aerodynamics with both favorable and adverse pressure gradients.

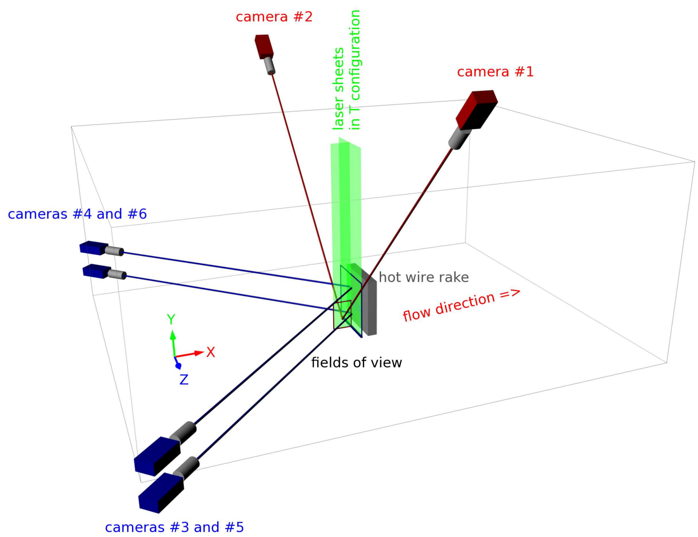


Figure 3: Experimental setup for the assessment of the very large scale structures in the flat plate turbulent boundary layer. The flow is along the x axis, y is the wall normal. The vertical square block behind the green light sheets represents the hot wire rake with 143 single hot wires. Three stereo PIV systems were synchronized with the hotwire data acquisition system in order to assess the full space-time velocity correlations over a cross-sectional area of approximately one boundary layer thickness squared for times corresponding to about 100 BL thicknesses convected in the streamwise direction. The simultaneous use of hotwires and PIV together was unique, especially by the scale at which they were employed (3 stereo PIV systems, one time-resolved, and 143 hotwires).

Figure 2 gives a photograph of the team involved in the test campaign and Figure 3 provides a sketch of one of the setups used. This setup was designed to assess the very large scales and the very small scales simultaneously in the flat plate turbulent boundary layer. Figure 4 gives a photograph of the 143-hotwire rake in the wind tunnel. Two Reynolds numbers were tested ($\Re_\theta$ = 10,000 and 20,000) with two different setups: the setup of figure 1 and a setup with the hotwire rake and a high repetition rate Stereo PIV system in a plane parallel to the wall in the near wall region, to provide data for WP6.

Figure 5 gives an example of Stereo PIV result obtained simultaneously in the two orthogonal planes of figure 3. The effect of the Reynolds number is clearly evidenced. The data have been used so far to extract the full spatial correlation tensor, from which relevant scales for turbulence modelling have been (and will continue to be) extracted.

There has already been much new insight gained from the large database that has been assembled, some of which has already been reported in journals and the WALLTURB final workshop proceedings ([Lille Workshop]). Here we select only the three things that are completely new and most significant: The first was the recognition of the role of the Kolmogorov microscale, not only in determining the nature of the vortices which comprise most of the motion, but also even as a scaling for the mean velocity profile. The basic character and complexity of these vortex motions is illustrated by the following movie: **HRSPIV** which gives the three velocity components and the vorticity component normal to the plane, in a plane parallel to the wall, as recorded by time resolved Stereo PIV at 50 wall units from the wall. The second major contribution was that for the first time a complete

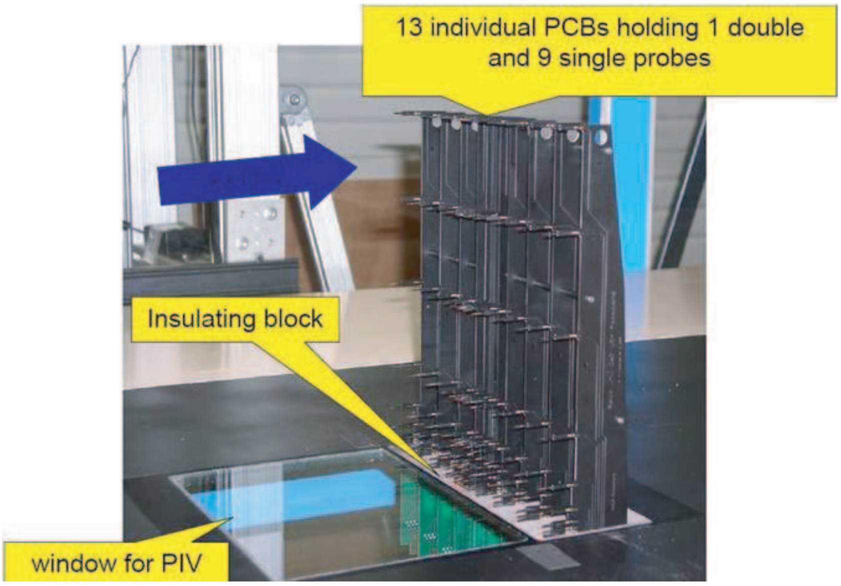


Figure 4: Hotwire rake equipped with 143 single hot wires mounted in the wind tunnel for the flat plate experiment. The glass window is used for the stereo PIV measurements.

three-dimensional picture of a moderately high Reynolds number turbulent boundary layer is available. Figure 6 shows the space-time correlation of the streamwise velocity component in a streamwise/wall normal plane obtained from the hotwire rake data. Samples are given at three wall distances: the first representative of the outer limit of the viscous sublayer; the second of the log layer (which is well developed at this Reynolds number); and the third, of the outer boundary layer region. The correlations show the extent of the large scale motions (sometimes referred to as 'inactive motions' since they contribute little locally 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 of the turbulence kinetic energy.
The same data set was used together with classical POD (proper orthogonal decompo-

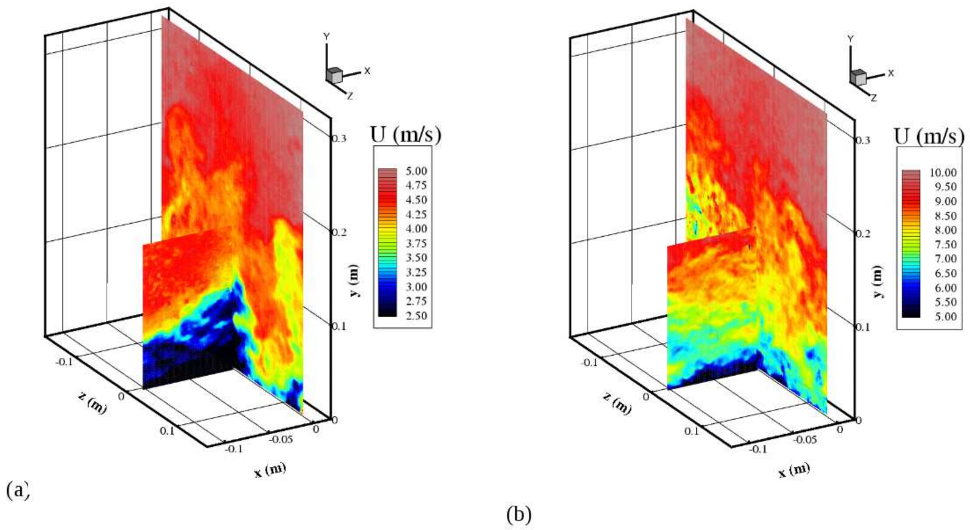


Figure 5: Simultaneous instantaneous velocity maps in streamwise/wall normal and spanwise/wall normal planes measured with three synchronized Stereo PIV systems at (a) R = 10 000 and (b) R = 20 000. The field of view in the spanwise/wall normal plane is 30 x 30 cm^2, with a spatial resolution of about 5 mm.

sition) techniques to decompose the boundary layer into orthogonal modes, which were then used to re-construct the instantaneous spatial fields. This had never before been attempted in a boundary layer at any Reynolds number due to insufficient data. The results of the partial reconstructions are illustrated in the following movies: **movie-k1**, **movie-k2**, **movie-k3**, **movie-k4**, which show the reconstructed velocity fluctuations on a plane perpendicular to freestream direction. The reconstruction is done using the most important POD and Fourier modes in terms of turbulence kinetic energy; Reconstruction using first four POD modes, frequencies up to 100 Hz together with spanwise Fourier modes of (i) first, (ii) second, (iii) third, and (iv) fourth. These illustrate clearly that the lowest order modes are strongly coupled from top to bottom of the boundary layer. This represents a major shift in our thinking, which has traditionally viewed the different levels of the boundary layer as uncoupled; and it has already had important consequences for the attempts to construct dynamical models in WP6.
After the successful flat plate experiment, the same test campaign was repeated in September 2006 on the AEROMEMS bump which mimics the APG flow encountered on the suction surface of an airfoil [3]. Figure 7 shows the hotwire rake mounted on the bump and a sample of Stereo PIV results in the two orthogonal planes. The data have been processed and added to the data base. Detailed analysis will continue, hopefully with EU support.
There have two Ph.D. students who completed their work as part of WP2, Tutkun [4] and Herpin [5].

The deliverables have been reported as [D2.6], [D2.11], [D2.29.1] and [D2.29.2]. In addition there were many publications in technical proceeding and in archival journals: [6], [7], [8], [9], [10], [11], [12], [13], [14], [15],[16], [17], [18], [19],[20], [21], [22], [23], [24], [2], [25], [26], [27], [28], [29], [30], [31], [32], [33], [34].

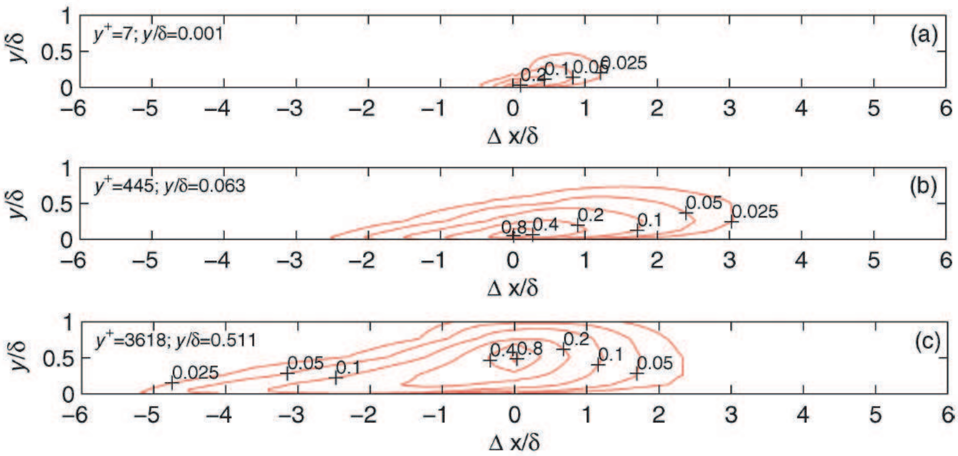


Figure 6: Space-time correlation of the streamwise velocity component deduced from the hot wire rake measurements at different wall distances for the fixed point: (a) $y^+ = 7$, (b) $y^+ = 445$, (c) $y/\delta = 0.5$ at R = 20 000. The streamwise extend of the large scale structures is evidenced together with the asymmetry at all wall distances.

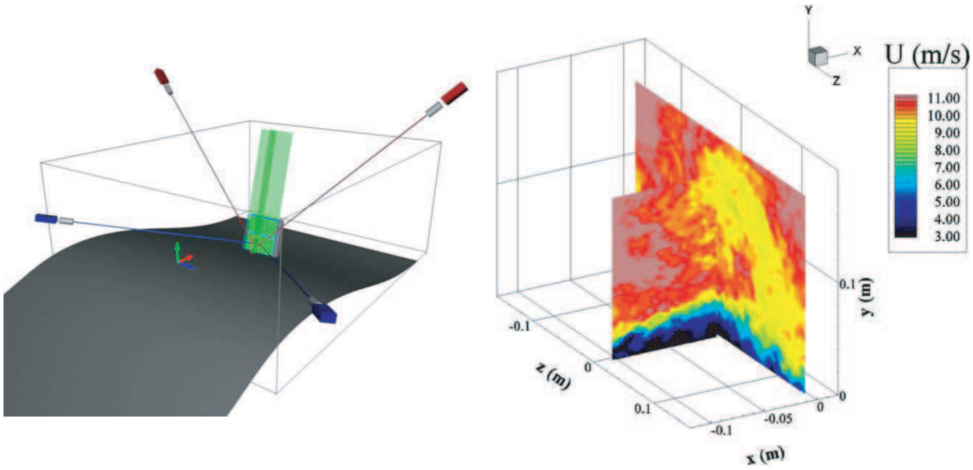


Figure 7: 'WALLTURB joint experiment' on the AEROMEMS bump. (a) Experimental setup with the hot wire rake mounted at the wall in the diverging part of the bump and the two synchronized SPIV planes upstream of it. (b) Sample of instantaneous velocity maps in two orthogonal planes showing very large scale structures.

Oil film skin friction

Beside the velocity field characterization and in order to allow proper modelling and validation, measurements of the wall friction using oil dropplet interferometry took place successfully for both ZPG and APG configurations in May and July 2006. These were performed jointly by ONERA and LML. Details of the oil film experiments are documented in [35], [36].

Experiments at Surrey

Adverse pressure gradient boundary layers, especially near separation and beyond, have been particularly problematical for turbulence modellers. Therefore this experiment was designed to complement the LML bump experiments, both as an *a posteriori* validation experiment for the RANS and LES models, and to provide sufficient detail on the turbulence moments to facilitate further development of the closure models for them. The LML AEROMEMS bump was used as a starting reference. It was scaled to on half in order to fit 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 since the LML bump is already close to separation.) The goal of making a small separation bubble was to have a flow which separated, but without significant 3D effects, thus simplifying 2D computations which are more suited to test models. Detailed flow measurements were performed using a variety of experimental techniques, including laser Doppler anemometry (LDA), hotwire and pulsed-wire anemometry, as well as oil film techniques for direct measurement of skin friction.

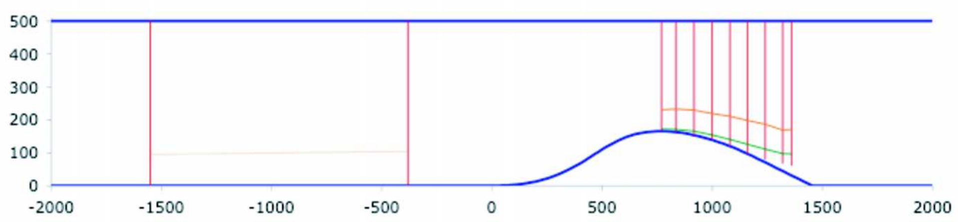


Figure 8: Geometry of the bump experiment at Surrey showing the two inlet boundary conditions measurement stations and the APG flow measurement stations. The free stream velocity is 10 m/s.

Figure 8 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 hotwire measurements of the three mean velocity components and full Reynolds stress tensor were performed over the diverging part of the bump. Also, the inlet (at two stations) and upper wall boundary conditions have been characterized in detail. A clear Reynolds number effect is evident in the outer part of the boundary layer. This result is consistent with the results obtained in the LML wind tunnel for the flat plate at various Reynolds number. Figures 9 and 10 give samples of results on the decelerating part of the bump.
The results are reported in : [D2.17],[D2.20.1],[D2.20.2],[D2.34],[37],[38],[39]

Experiments at Czestochowa

The experiment performed at Czestochowa Technical University was designed to generate an adverse pressure gradient boundary layer representative of turbomachinery conditions. The main interest of this test case is that it is performed at Reynolds number which is relatively low and yet representative of turbine blade conditions. Another interest is that the flow is free of curvature effects, which is not the case of the other experiments of WP2 (LML and Surrey bumps). This test case was used as a "blind test case" for a posteriori validation of RANS models.

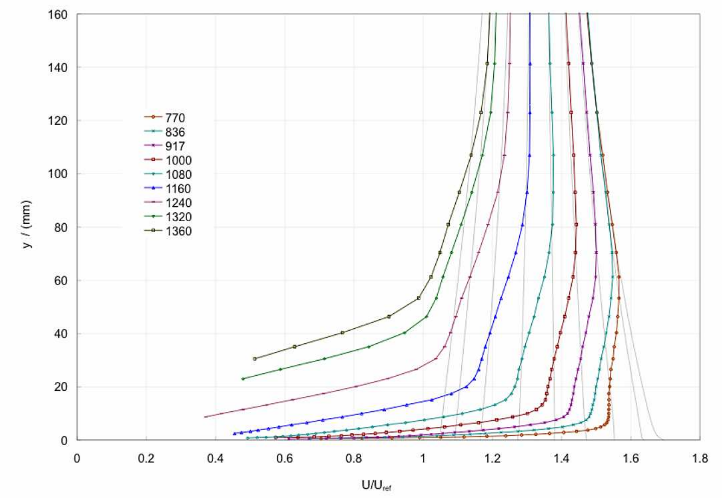


Figure 9: Mean velocity profiles at different stations on the APG side of the Surrey bump. The effect of the deceleration is clearly evidenced. The separation point is at x = 1327mm.

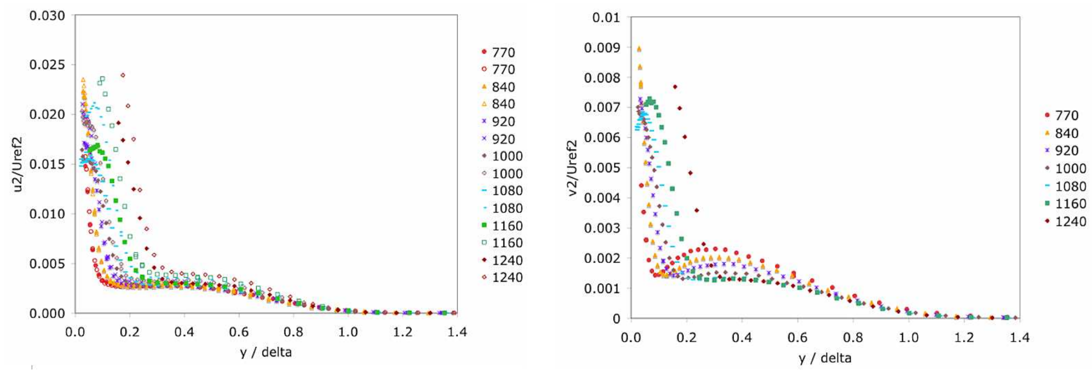


Figure 10: Two components of the diagonal of the Reynolds stress tensor (u'2 and v'2) at different stations on the APG side of the Surrey bump, showing how the peak in turbulence kinetic energy moves rapidly away from the wall as the APG boundary layer develops.

The boundary layer develops on the lower flat wall (2.8 m in length), first without pressure gradient to increase the Reynolds number, then with a converging diverging upper wall to bring the BL into an adverse pressure gradient flow. Figure 11 shows an enlarged sketch of the converging diverging part of the wind tunnel with the region of investigation in the red rectangle. No separation occurs, even on the upper wall, so the pressure gradient is mild on the lower wall. Extensive hot wire measurements were 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 $\Re_\theta = 2500$.

Figure 12 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.

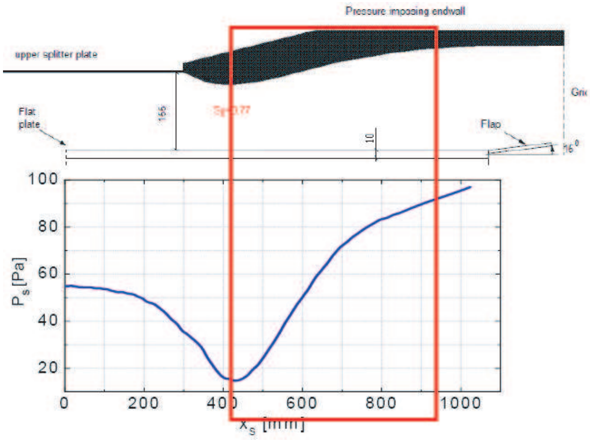


Figure 11: Sketch of the converging diverging part of the wind tunnel, showing the pressure distribution (blue line) and the region of hot wire investigation (red rectangle).

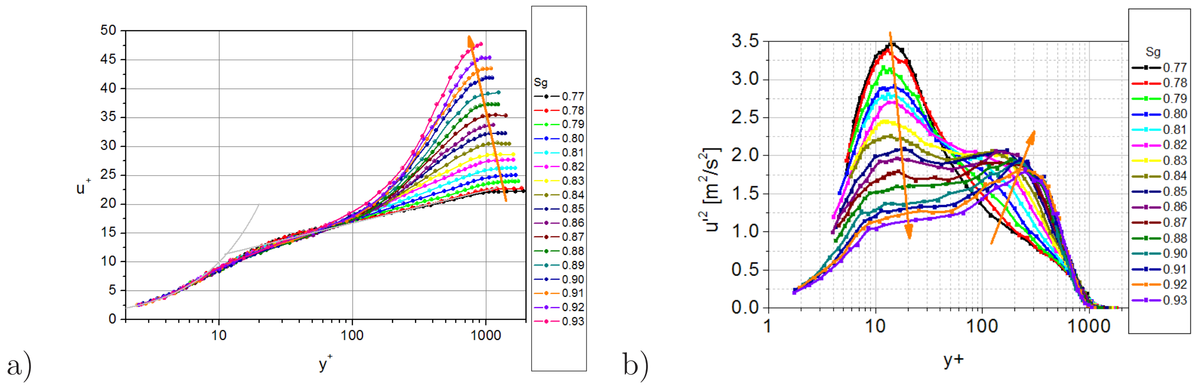


Figure 12: (a) Mean velocity and (b) streamwise diagonal Reynolds stress profiles as a function of streamwise position. Note the strong evolution of the mean velocity in both the log layer and the outer region and the disappearance of the near wall turbulence peak and the development of a smaller one further away from the wall.

The results of this experiment are reported in : [D2.10],[D2.21],[D2.30],[D2.33],[D2.35], [D2.41],[40],[41],[42], [43],[44]

Direct numerical simulations

DNS at UPM

The University of Madrid has produced DNS of boundary layers under both zero and adverse pressure gradient ([45],[46],[47]). The range of parameters characterizing the APG simulations is summarized in table 1. Figure 13 shows the coherent structures at an instant in time, but only the movies show the real spatial and temporal character of this relatively high (for DNS) Reynolds number boundary layer. They show both **side**, and **top** views.

	n_x	n_y	n_z	L_x/θ	L_y/θ	L_z/θ	Re_θ	$\beta = \delta^* \partial_x P^+$
ZPG1	1282	256	127	176	35	35	$600 - 950$	-2×10^{-3}
ZPG2	6145	360	512	360	20	60	$600 - 2200$	2×10^{-4}
APG	1536	301	768	43	9	20	$800 - 2000$	$20 - 1000$

Table 1: Parameters for the boundary layer simulations at UPM. The domain lengths are normalized with the momentum thickness at the exit section. The Reynolds numbers for APG refer only to the reattached turbulent section.

The unique character of APG boundary layers can be seen by comparing the APG and ZPG movies which are also included. The DNS data have been used to generate energy and Reynolds stress balance data which has been added to the WALLTURB database.

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

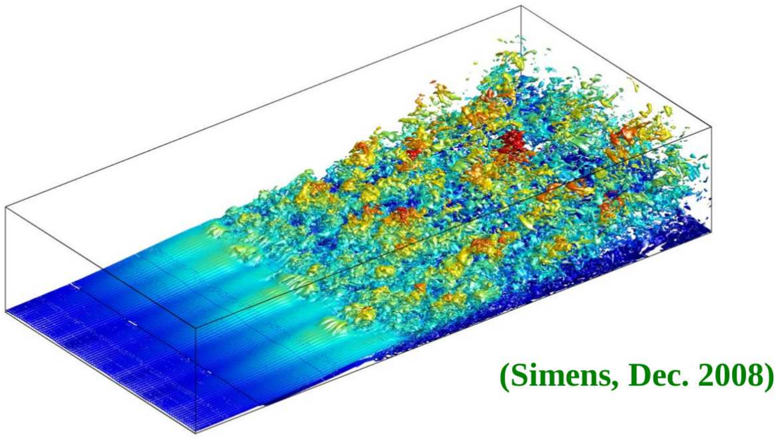


Figure 13: Direct numerical simulation of adverse pressure gradient boundary layer performed at Madrid Polytechnic University. Visualization of coherent structures. The relevant parameters of the simulation are summarized in the table above it.

DNS at URS

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 for different wall velocities and Reynolds numbers ([D2.12.1],[D2.13],[48]). Here again, the full set of statistics, Reynolds stress budget was provided and, for the first time in this type of flow, the full turbulence structure tensor was made available to the modellers of WP 4 & 5. Figure 14 shows the mean velocity and turbulence intensity profiles.
DNS results for the plane channel flow were also made available for a wide range of Reynolds number by Madrid (J. Jimenez) and Rome (P. Orlandi) Universities. These DNS have been already of great value for constructing and verifying the near wall turbulence models in WP4, 5 & 6. All turbulence statistics are available, including the full

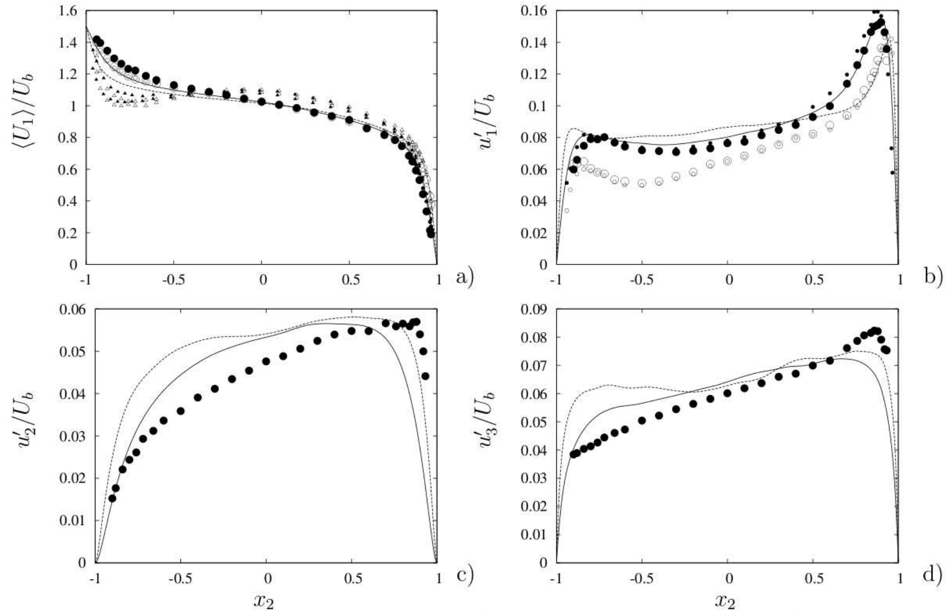


Figure 14: Mean velocity and turbulent intensity profiles for an intermediate type Couette-Poiseuille flow DNS computed by Rome University (solid lines), compared to experiments by Gilliot (full symbols) at comparable Reynolds number.

Reynolds stress budget. Also, Rome University has computed extensively the turbulence structure tensors which are a new information of strong interest for the structure based RANS models.

DNS 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 ([49],[50],[51]). 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.

The **movie** illustrates best the primary features of this flow. Snapshots are provided below. Figure 15 shows a snapshot of the strong vortical structure generation occurring just after the bump submit and developing rapidly downstream.
In figure 16, the near wall streaks can be seen all along the channel walls. On the upper wall, the effect of the adverse pressure gradient is clearly visible on the downstream part of the channel where it induces smaller scale structures and more waviness. On the lower wall, the small separation of the flow completely disorganizes the streaks which form back fairly rapidly in the rear part of the channel. In Figure 17, 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.
Reynolds stress tensor components in the APG part of the DNS of converging diverging

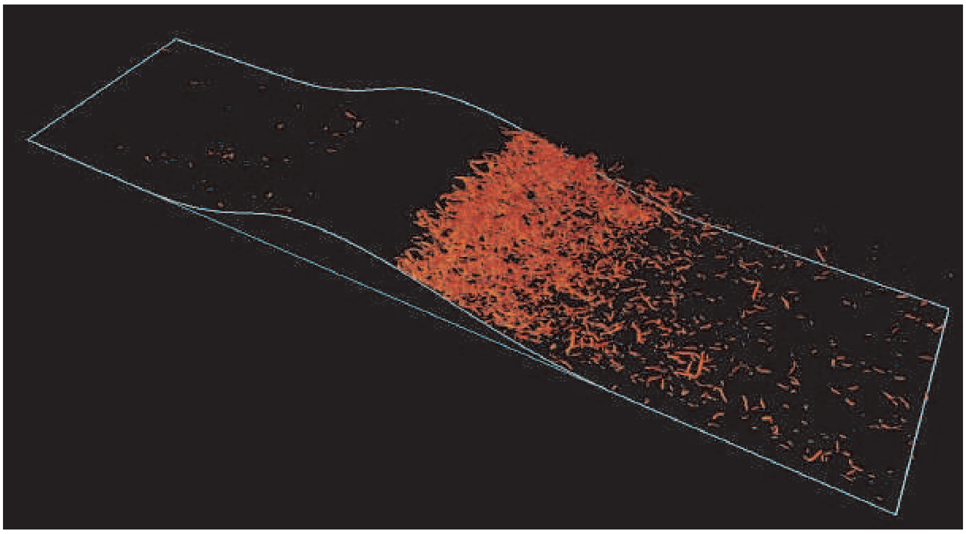


Figure 15: Isovalues of the Q-criterion elucidate vortical structures near the curved wall in DNS of converging diverging channel flow at $Re = 600$.

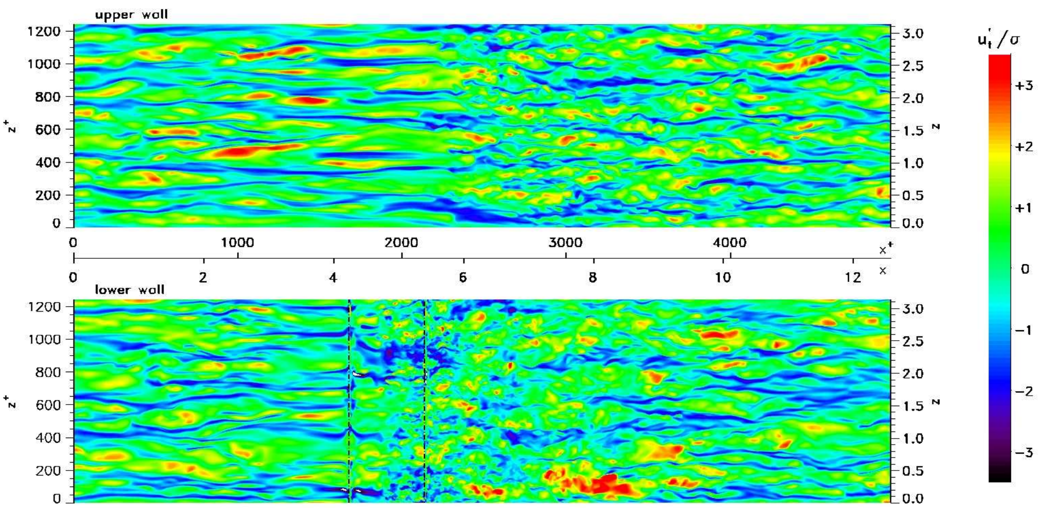


Figure 16: Visualisation of the streaks at $y^+ = 10$ near the upper and lower walls in the DNS of converging diverging channel flow at $Re = 400$. The dashed lines on the lower wall plot indicate the limits of the separation bubble. The submit of the bump is at $x = 2.35$ m.

channel flow at Re = 400 are shown in Figure 17. Profiles are plotted near the lower and the upper wall.

3.2.2 Conclusion

A number of carefully coordinated and complementary experiments and DNS have been carried out in turbulent boundary layers and channels. The original goal of WP2 in WALLTURB was to obtain detailed experimental data at high Reynolds number in both ZPG and APG boundary layers, and to complement this data with carefully selected

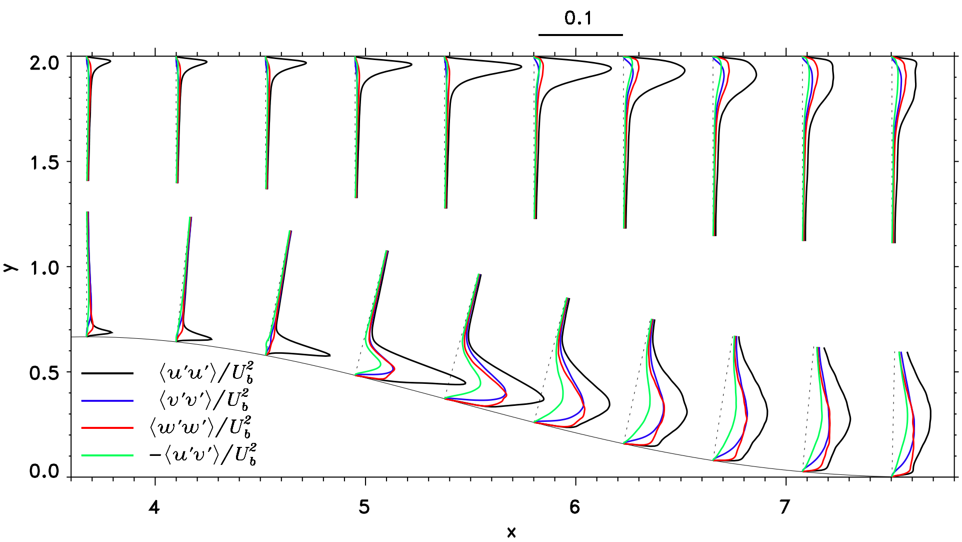


Figure 17: Reynolds stress tensor components in the APG part of the DNS of converging diverging channel flow at $Re = 400$. Profiles are plotted near the lower and the upper wall.

DNS. These goals were exceeded. By coupling PIV with many hot-wires in collaborative experiments at LML, full space-time information about high Reynolds number turbulent boundary layers was accessible for the very first time. These experiments were complemented by experiments at Czestochowa and Surrey which bridged the Reynolds number gap with DNS and extended the results to include separation. The DNS of several flows, both within WALLTURB and in parallel studies, including adverse pressure gradient boundary layers provided both a unique insight data bases for turbulence modellers, and insights into the role of boundary conditions and Reynolds number of such flows.

The details of the data produced are discussed in WP3 below. Also, as will be clear below, they have been used extensively in WP4-WP6. In addition these experimental and DNS studies have already contributed substantially to our theoretical picture of turbulence, both by calling into question old ideas and provoking new ones. The traditional view that the inner and outer parts of turbulent boundary layers can be viewed separately has very much been called into question, not only by the strong top-to-bottom correlations and POD eigenfunctions (joint experiment), but also by failure of turbulence models to predict them (see WP4). The strong correlations observed between fluctuating wall shear stress and the velocity away from the wall (USur) was also unexpected. Also the success ability to collapse the mean velocity profile with free stream velocity and Kolmogorov microscale alone is quite astonishing, and clearly demands new thinking.

3.3 WP 3: Databases management and processing

Work Package manager: LML

Objectives

The aim of this work package was to set-up the different databases at the different sites to give access to the different partners, to keep the databases accessible and operational during the course of the project, and to process these databases in order to extract physical understanding.

3.3.1 Main results

In the framework of the project, a unique set of databases on different types of wall bounded turbulent flows has been built. These databases consist of the following:

- DB1 Experimental database on ZPG Boundary Layer

  This database consists mostly of measurements performed in the LML boundary layer wind tunnel for Reynolds numbers R_θ ranging from 8,000 to 20,000 [D3.2]. It includes detailed hot-wire profiles of the mean velocity, the full Reynolds stress tensor, and a large set of stereo PIV data in different coordinate planes which can be used to assess the spatial correlation tensors and coherent structures. It is suited for advanced post-processing for both flow physics assessment and *a priori* model tests.

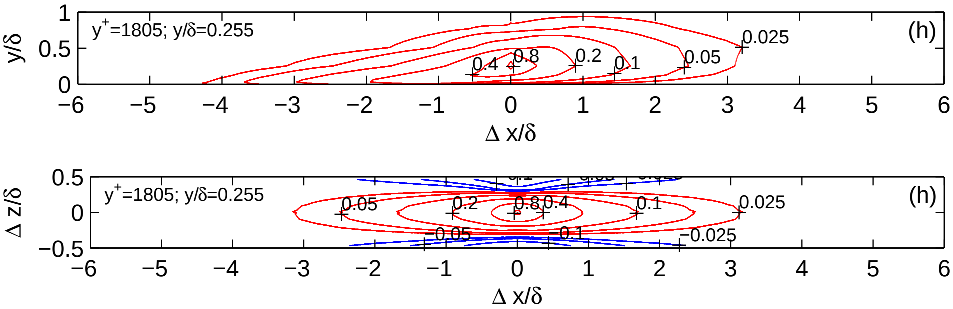
- DB2 DNS Database of plane Channel Flow

  An important DNS database has been provided by UPM for the turbulent channel flows at four Reynolds numbers up to $Re_\tau = 2,000$ [D3.3], [52, 53, 54]. The database contains mean and fluctuating profiles, spectra and correlation data, as well as full Reynolds stress budgets [D3.14.1]. A sufficient number of instantaneous flow data for extracting statistical information on the flow structures are also available. A second DNS database of the same flow (computed in WALLTURB) has been provided by URS at three lower Re_τ (up to 950), obtained by a different numerical method from UPM, but with the full turbulence structure tensor and Reynolds stress budget needed by RANS models.

  The same information has been provided for a Couette-Poiseuille flow by URS [D3.14.2]. These were computed in WALLTURB, as a DNS of plane channel flow with one moving wall, using different wall velocities so that the wall shear stress could be varied significantly for the same bulk velocity [48]. The DNS database is complemented by hot-wire data (full Reynolds stress tensor) provided by LML at a comparable Reynolds number (http://lmlm6-62.univ-lille1.fr/db/). Both these databases are suitable for advanced post-processing and *a priori* model testing.

- DB3 WALLTURB experiment database of ZPG Boundary Layer

  This database contains the results of the experiment performed jointly by LML, Chalmers University and LEA in June 2006 in the LML wind tunnel [D3.10]. The flat plate boundary layer has been characterized at Re_θ= 10,000 and 20,000, with two coordinate planes of stereo PIV synchronized with a rake of 143 hot-wires (which is a world record) [10, 27, 8, 9, 55, 11, 12, 14, 24, 25, 26, 31]. Also, the skin friction has been carefully assessed by ONERA and LML using the oil film interferometric technique [D2.29.1], [35, 36]. This unique data set will permit studying in detail the very large scales of the boundary layer (each record corresponds to about 200 boundary layer thicknesses in length). It will be post-processed using POD (Proper Orthogonal Decomposition) and LSE (Linear Stochastic Estimation) to reconstruct the large scales of turbulence, in addition to other advanced signal processing techniques.



Two points cross-correlation of the streamwise velocity component at $y/\delta = 0.2$, deduced from the hot wire rake measurements from the "WALLTURB joint experiment". These measurements evidence Large Scale Motions extending over several BL thicknesses.

- DB4 Experimental database on APG Boundary Layer

  This database corresponds to an experiment in the LML wind tunnel on the AEROMEMS (converging diverging) bump ([D3.5]). The interest of this database is that high quality stereoscopic PIV data is available at high Reynolds number on an adverse pressure gradient boundary layer (R_θ between 5,000 and 30,000) which is suitable for studies of the turbulence structures. The PIV data are complemented by hot-wire profiles at 5 stations along the diverging part of the bump. They will serve both for post-processing to assess the turbulence physics in this configuration and as a validation test case for RANS and LES.

- DB5 DNS database of APG BL and Channel Flow

  This database consists of three different DNS at fairly high Reynolds number:

  - A DNS of a boundary layer in a strong adverse pressure gradient performed at UPM [46, 47]. The initially laminar flow separates, transitions, and reattaches. In the reattached part, which continues to be subjected to a strong APG, the Reynolds number varies between $R_\theta \approx 700 - 2000$ and the dimensionless pressure gradient varies from $(\delta^* dP/dx)/\tau_w \approx 20$ to about 1000 as the turbulent layer proceeds towards a second separation just beyond the exit section. The database contains mean and fluctuating profiles, spectra and correlation data, as well as energy balances. A sufficient number of instantaneous flow data to extract statistical information on the flow structures are also included.
  - A DNS in a converging diverging channel flow with the same wall geometry as the experiment of DB4, at $Re_\theta = 400$, which was computed during WALLTURB [49]. This database contains the same type of data as the previous one. The APG wall turbulence can be studied with and without curvature by looking at the lower and upper walls.

- The same converging diverging channel flow DNS as above, at $Re_\theta = 600$, was computed also during WALLTURB with the help of a DEISA allocation, with the same type of data as above and a large number of instantaneous fields allowing advanced post-processing [50].

This set of DNS is a key element for the assessment of APG near wall flows. It provides the most advanced data in the world on APG flows. It can be used mostly for advanced post-processing and *a priori* tests on RANS and LES models. It can also serve as validation test for these models.

- DB6 WALLTURB experiment database of APG Boundary Layer

  This database is for the LML bump APG BL flow [D3.11]. It is similar to that of DB3 in what it contains. It is the result of an experiment performed jointly by LML, Chalmers University, LEA and ONERA in the LML wind tunnel [20, 35, 36]. The decelerating boundary layer has been characterized with two coordinate planes of StereoPIV synchronized with a rake of 143 hot-wires. This unique data set permits studying in detail the very large scales of the boundary layer (each record corresponds to about 200 boundary layer thicknesses). It can be post-processed using advanced tools such as POD (Proper Orthogonal Decomposition) and LSE (Linear Stochastic Estimation) to reconstruct the large scales of turbulence and the results can be compared to the flat plate case of DB3.

- DB7 APG+SEP experimental database from USur

  The University of Surrey has provided in WALLTURB a database of hot-wire data recorded in an APG boundary layer with separation [D3.21]. The configuration is similar at one-half scale to the LML bump configuration and is representative of aeronautical applications. Only the rear part of the bump has been modified to obtain a separation of limited extension [37, 38, 39]. The database contains the boundary condition data necessary to set up computational prediction using RANS and LES modeling, pressure distribution, wall friction distribution and extensive hot-wire measurements along the curved surface [D3.13]. It will serve as a validation test case for the RANS and LES models developed in the project.

- DB8 APG experimental database from TUCz

  University of Czestochowa has set up in WALLTURB a database of detailed hot-wire, pressure and skin friction data recorded on a flat plate under adverse pressure gradient [D3.26], [40, 41, 42, 43, 44]. The inlet boundary conditions were also characterized in detail [D3.16.1], [D3.16.2]. The flow conditions are representative of turbomachinary configurations and can serve as validation test case for the RANS and LES models.

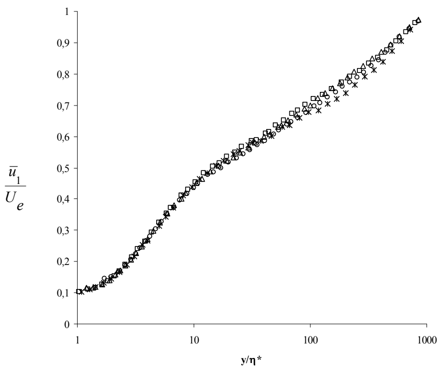
- DB9 DNS database of ZPG Boundary Layer

  This database contains the results of a direct numerical simulation of a ZPG boundary layer, performed by the UPM during WALLTURB, The Reynolds number varies over $R_\theta = 600 - 2200$, of which the range $R_\theta = 900 - 2050$ can be considered free of entry and exit effects. The computational box is $43 \times 7\,\delta_{99}$, based on the exit thickness of the layer, or about 3.3 times larger based on the inlet conditions.

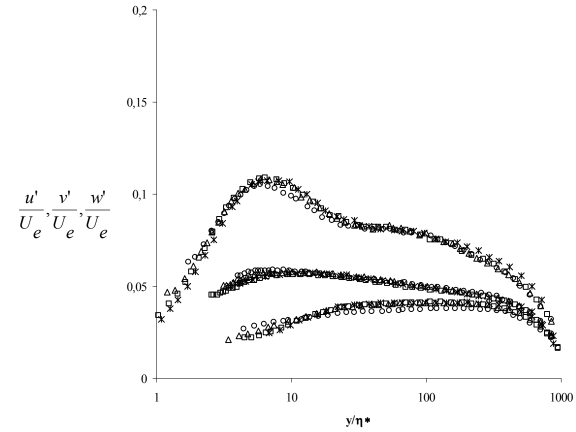
Beside the building of these databases, several partners of the project have performed some post-processing of the available data in order to extract relevant scales and physical understanding of near wall turbulence.

The full Reynolds stress budget has been provided both by UPM and LML for the DNS of plane and converging diverging channel flow respectively [45], [56], [57], [58]. Also, Rome University has provided the structure tensor in plane channel and Couette-Poiseuille flow in order to help establish the SBM models of WP4 [D2.13], [D3.14.1]. LML has also analysed the flat plate boundary layer database in order to provide Taylor integral and microscales in both the flat plate and adverse pressure gradient boundary layers [D4.3].

ENSMP has completed a detailed study on the use of entropic skins in the characterization of wall flows. The processing was performed on HWA as well as on PIV data from the ZPG boundary layer in DB1. In the context of entropic-skins geometry, a new model of intermittency based on geometrical multi-scale features has been developed which takes into account the distance to the wall. A general expression of scaling exponents ζ_p was obtained, characterizing the deviation from Kolmogorov theory and in excellent agreement with experimental measurements in a turbulent boundary layer. [D3.4], [D3.15], [D3.23], [59]



a)



b)

Figure 18: a) Mean velocity and b)Turbulence intensities as a function of wall distance scaled with the external velocity Ue and the clipped Kolmogorov length scale $\eta*$. Re_θ= 8 200 ($*$); Re_θ= 11 500 ($\square$); Re_θ= 14 500 ($\triangle$); Re_θ= 20 800 ($\circ$).

LML has also post-processed the PIV data from BD1. The aim was to characterize the vortical structures in the buffer and lower part of the log region. It was shown that these structure are of cane type and scale with the Kolmogorov scales [23], [5], [18], [19] [2]. Based on these results, a new scaling of the boundary layer, based on the external velocity and a clipped Kolmogorov scale was proposed. This scaling indicates that at high enough Reynolds number, the whole boundary layer should scale on Ue and the

Kolmogorov length scale [60]. Some analysis of the Adverse Pressure Gradient database was also performed [51]. Finally, Chalmers, FFI and LML did some analysis of the ZPG boundary layer from a theoretical point of view [61, 13, 14, 28, 4, 26, 32, 34].

3.3.2 Conclusions

The WALLTURB project was an opportunity to establish an up-to-date and very comprehensive set of databases on wall turbulence. These databases include both experimental and DNS data which are complementary. They give access to all scales of near wall turbulence, both in the ZPG and the APG cases. Even separation was addressed by USur. This set of databases has already proven to be helpful in support of the modelling work in workpackages WP4 to WP6, and as well to have contributed to the theoretical understanding of turbulence (as reported in the summary of WP2). It will certainly continue to be used to support both theoretical and numerical investigations in the near future.

3.4 WP 4: RANS modeling

Work Package manager: ONERA

Objectives

One aim of the project was to take advantage of the shared database, i.e. DNS data at low and moderate Reynolds number for channel, Couette-Poiseuille and boundary layer flows together with detailed PIV data for high Reynolds numbers boundary layer flows to extract the relevant information to develop and improve turbulence models. Another aim was the transfer of knowledge and models towards industry for further validation.

Mainly non-linear or algebraic models, which provide a fair description of the turbulence anisotropy, were considered. These models only require two transport equations and are thus considered as a good compromise between complexity and generality. Various approaches were used, the emphasis being put on different forms of the elliptic relaxation approach and the improvements brought by the Structure-Based Models.

3.4.1 Main results

It turns out that the performed activity can be classified in six different topics, which are briefly reviewed below.

Evaluation of existing models: In order to help partners select test cases in the WALLTURB database, ONERA performed computations of the project boundary layer experiments (Czestochowa, Lille and Surrey) using a boundary layer code and a large variety of standard turbulence models. The scatter between model predictions provides an estimate of how challenging a test case is. The Czestochowa experiment was shown to present significant pressure gradient effects, the influence of the small pressure gradient in the Lille experiment was also evidenced, as well as significant curvature effects in the Surrey experiment [D4.9].

As the expected model was not available in time, DASSAULT redefined its activity to compare standard and advanced models available from other studies: the Surrey bump experiment and a high-lift configuration. $k - kL$ and $k - kL$ EARSM approaches were shown to provide fair predictions, improving results compared to DASSAULT's in-house $k - \varepsilon$ SST model [62, 63].

Length scale analysis: Length scale analysis was initially motivated by the interest to investigate departures from the one-scale hypothesis in turbulence modelling as well as the wall induced anisotropy on the turbulence length scales. It turned out that extracting all the possible length scales from the DNS was too huge an effort so that this task was abandoned.

Nevertheless, LML analyzed its PIV data to extract some two-point correlations and the associated integral scales and Taylor macro-scales. Scale anisotropy as well as different behaviours with the wall distance i.e. either linear evolution or nearly constant values of the length scales, were so evidenced [D4.3].

DNS analysis: scalings: ONERA analysed a large set of DNS data, including channel flows, Couette-Poiseuille flows, attached boundary layer flows without pressure gradient, with various pressure gradient strengths and separated boundary layers, over a rather large range of Reynolds numbers. The goal was to identify relevant scalings or universal behaviours to be used in model development.

Only the mean velocity profile $u^+(y^+)$ was shown to really be universal. Reynolds number effects, linked to the presence of inactive motions, as well as pressure gradient effects were evidenced. Mixed scaling was shown to cope with Reynolds number effect but no satisfactory scaling dealt with the pressure gradient effect. Moreover, some modelling hypotheses were tested: e.g. Durbin's formulation for the eddy viscosity ($\propto k\overline{v'^2}/\varepsilon$) is supported by the analysis [D4.4].

Transport modelling: The analysis of near wall balances for the Reynolds stress transport equation was performed by ONERA. In the Reynolds stress transport equations, the viscous and pressure terms are usually split to evidence respectively a viscous diffusion of the Reynolds stresses and a pressure-strain or redistribution term. the inadequacy of this decomposition in the wall region was confirmed, as it leads to very complex behaviours of the various terms. The global pressure and viscous terms evidence a smoother behaviour and are more adequate for analysing the near-wall balance.

The EARSM model derivation is based upon an equilibrium assumption in the anisotropy budgets, assuming advection and diffusion effects are negligible. Analysis of the budgets from the DNS evidenced that turbulent diffusion effects cannot be neglected in the buffer region.

A model for the viscous term was derived from previous work by Jakirlić and Hanjalić. A model for the pressure term was adapted from LEA's work (see below). A model for the turbulent diffusion term was also developed. These models were then used to derive a new EARSM model which accounts for transport effects in the wall region [D4.23.1].

Elliptic approaches: A non-linear extension of the $v^2 - f$ model has been developed by FFI. From the analysis of the EARSM model derivation, they argued that the derivation is only valid for two-dimensional flows. They too used the two-dimensional model form as a model basis, and derived the model coefficients, not from a EARSM strategy, but by imposing realizability and internal consistency with the $v^2 - f$ model. This means that, on a flat surface, the wall normal diagonal stress $\overline{v'^2}$ provided by the model equals v^2 given by the $v^2 - f$ model. When only the linear terms are kept in the constitutive relation, the original $v^2 - f$ model is retrieved. The non linear model has been shown to give fair predictions in various flows such as Couette-Poiseuille flows, the Czestochowa experiment and the LML bump [D4.11, D4.16, D4.18.1].

An EARSM model has been derived at LEA from the elliptic blending approach developed by Manceau and Hanjalić. In the Reynolds stress transport equation, the velocity/pressure gradient and dissipation terms are blended between a near-wall model and a homogeneous model, with the help of an elliptic relaxation equation for the blending coefficient. Since the near-wall model involves the wall normal, a second rank tensor M linked to the wall normal vector has to be introduced in the EARSM projection basis. This arose from the simple test case of flow along a plate without velocity gradient, which evidenced the need of the M tensor related to the wall normal to reproduce the anisotropy induced by the presence of the wall. To keep a tractable model, only truncated projection bases have been retained. A variety of models, using several projection bases, has been considered.

An amazing result is that, on some test cases, the so-derived EARSM models perform better than the full Reynolds stress model they are derived from. The so-derived models have mainly been validated with respect to channel and Couette-Poiseuille DNS [D4.5, D4.10, D4.13]. Figure 19 compares the predictions of the components of the Reynolds stress tensor given by two variants of the EARSM model to the full Reynolds stress model and the DNS by URS for a Couette–Poiseuille flow.

Structure Based Models: Structure based models were developed as a further step beyond Reynolds stress models to circumvent some of their failures. In particular, there has been increasing evidence that all the important information is not only in the scales and in the anisotropy, but that information about the underlying turbulence structures (or at least their dimensionality) is needed. The Algebraic Structure Based model (ASBM) is a simplified version, in which turbulence is envisioned as a combination of simplified structures.

This approach leads to a constitutive relation which expresses the Reynolds stress tensor in terms of the respective importance of the various types of structures and of the eddy axis tensor, which is linked to the energy weighted direction of the structures. The complete constitutive relation is deduced as a simplification of the original SBM model.

This formulation is very convenient to represent wall effects, which are mainly accounted for via a rotation of the eddy axis to lean towards the wall. The projection of the eddy axis tensor is performed with the help of a scalar field given by an elliptic relaxation equation [64].

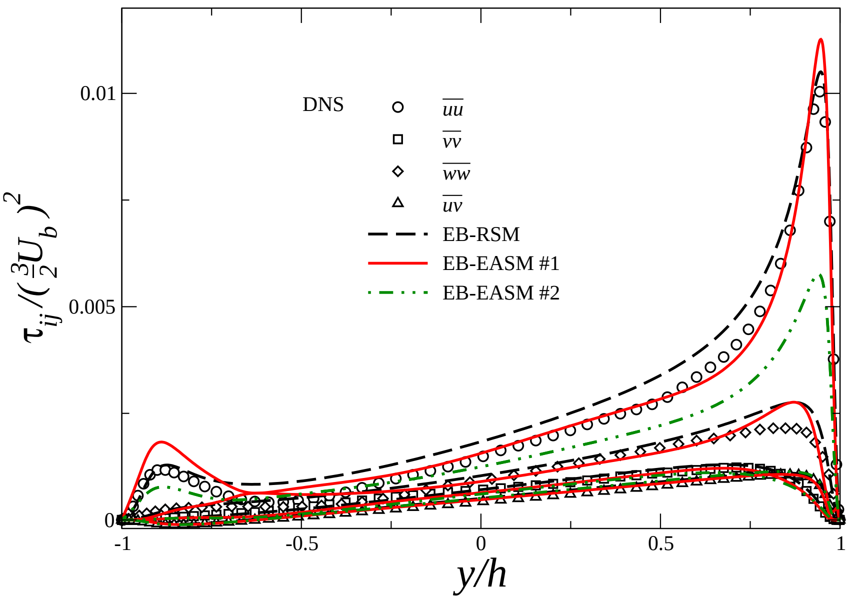


Figure 19: Predictions of the Reynolds stress tensor for the Couette-Poiseuille DNS using Reynolds stress and algebraic models based on the elliptic blending approach

The associated length scale equation is not a standard ε or ω equation but one for the enstrophy of the energy bearing eddies. It is linked to the energy cascade process and sensitized to the turbulence structure, so that it can, for example, account for subtle rotation effects. As initial tests evidenced that the model underestimated the wake strength, significant effort at UCY was devoted to improve this length scale equation, partly taking advantage of a cooperation with ONERA. The model was validated on Couette-Poiseuille flows. The post-processing of the DNS data performed by URS provided the structure tensors to enable a finer comparison with the model foundations. The Czestochowa experiment was also nicely reproduced [D4.8, D4.14, D4.19]

Outside of WALLTURB, but thanks to it, a cooperation between UCY and ONERA led to the coupling of the ASBM model with a more standard length scale equation. The $k-\omega$ model was selected as it provides a fair response to pressure gradients. Since the ASBM requires reasonable predictions of the turbulent kinetic energy and dissipation profiles, which a $k-\omega$ model does not provide in the wall region, a wall correction function was introduced in the model. The derivation of this function took advantage of the scaling analysis presented above. The final model was validated on channel, Couette-Poiseuille and boundary layer flows, including cases with very strong adverse pressure gradient where it performs better than the SST model [64].

The ASBM model was also implemented in the FFI solver as a post-processing tool. In the computation, the Reynolds stress tensor is evaluated with the current model but the ASBM evaluation of the Reynolds stress tensor is also available at the end of the computation. This proved to better reproduce the Reynolds stress tensor, e.g. for the LML bump experiment. As already mentioned above, the ASBM was also implemented in an in-house Airbus solver and gave fair predictions.

AIRBUS implemented several variants of the $v^2 - f$ model in an in-house code to compare their predictions with other standard models. The models considered are the original $k - \varepsilon - v^2 - f$ model by [65] , the $k - \varepsilon - \varphi - f$ model by Laurence et al. (2004), the $k - \varepsilon - \varphi - \alpha$ model by Billard et al. (2008) and its revised 2009 version (a simplified version of the elliptic blending approach developped by LEA). The motivation for this study of $v^2 - f$ models was to find those best suited, based on accuracy and robustness, for evaluation of the above-mentioned non-linear $v^2 - f$ model developed by FFI, and to provide scale equations for evaluation of the ASBM. The 2009 and 2008 versions of the $k - \varepsilon - \varphi - f$ model were finally used,respectively, in these two roles. All these models were compared to standard $k - \omega$ BSL and SST models.

The Surrey bump, the channel flow, the boundary layer developing on a flat plate and the RAE2822 transonic airfoil, for case 9 (i.e. attached flow) as well as case 10 (i.e. separated flow) were considered. The flat plate test case led to rejection of the $k - \varepsilon - \varphi - f$ model and the 2008 version of the $k - \varepsilon - \varphi - \alpha$ model as an EVM since the logarithmic region was poorly predicted. Nevertheless, the 2008 version of the $k - \varepsilon - \varphi - \alpha$ model was adopted as a convenient scale equation for the ASBM. Stability issues were also faced with the original $v^2 - f$ model in transonic flows.

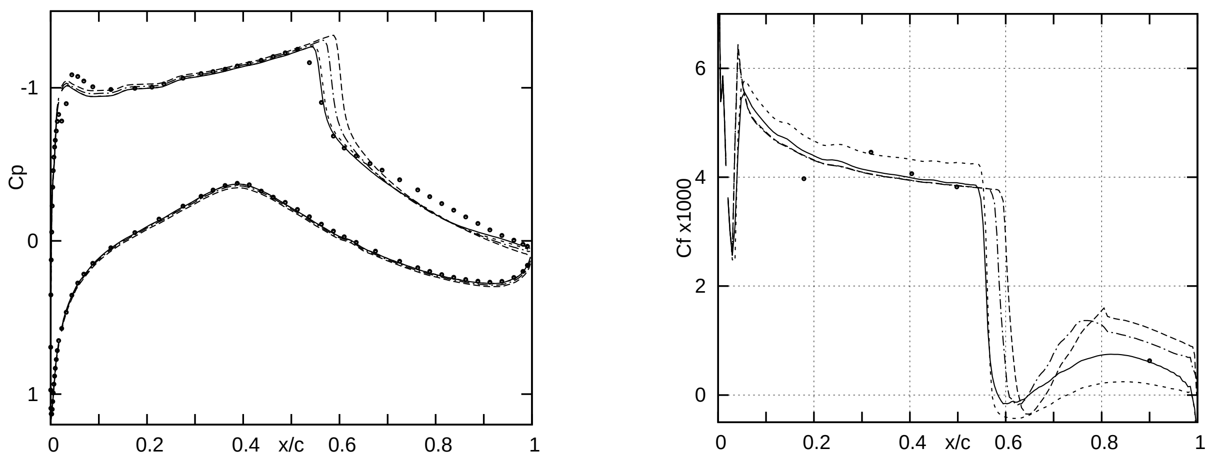


Figure 20: RAE2822 airfoil, case 10. Surface pressure C_p and friction C_f
Symbols: experiment; short dashed: SST; long dashed: linear $k - \varepsilon - \varphi - \alpha$ (2009); chained: non-linear $k - \varepsilon - \varphi - \alpha$ (2009); solid: ASBM + $k - \varepsilon - \varphi - \alpha$ (2008).

The main conclusion is that the 2008 version of the $k - \varepsilon - \varphi - \alpha$ model, coupled with the ASBM, performs as well and even better than the SST model, other models being less good on the transonic test cases. This is exemplified by the predictions of the RAE 2822 airfoil shown in figure 20 [D4.20.1],[62].

3.4.2 Conclusion

The main outcomes of this work package are:

- The evidence that the wall region has no universal character, which makes modelling challenging. This was attributed to the rôle of inactive motions, which are presently not captured by the models. Work is already underway to include them.

- The advances in the elliptic relaxation approaches, using it as a blocking tool in the non-linear extension of the $v^2 - f$ model and as an information about the direction and magnitude of wall effects in the EARSM and ASBM models.
- The development of the structure based model, which represents turbulence in a non-conventional but physical way and shows promising results
- The strong cooperation between the various partners. At the beginning of the project, the WP4 group was able to issue reasonable and detailed requirements towards data base providers, asking for Reynolds budgets and information about the structure based tensors, which highly supported model development and validation. FFI and ONERA cooperated with UCY in the development of the ASBM model, AIRBUS later joined that group to implement and test the model so that transfer from academic to industry was successful. ONERA took advantage of the LEA work in its own EARSM model development.

The project was mainly focused on non-linear or algebraic models, as they represent the next step after the one and two-equation eddy viscosity models which are the current industry work horses. Nevertheless, the expertise gained and the ideas developed could also be used to improve higher level models such as full Reynolds stress models or complete SBM models.

3.5 WP 5: LES modeling

Work Package manager: TUM

3.5.1 Objectives

The goal of the work undertaken in WP5 LES modeling was twofold. The experimental results and DNS results from WP2 and WP3 enabled the development of the sub-grid scale methods in the different groups as well as the application of wall-modelling approaches to LES. The databases made available improved the outcome considerably through the accuracy and fine resolution of the given results in zero-pressure gradient (ZPG) and adverse-pressure gradient (APG) environments.

3.5.2 Results

The comparison of the developed methods against the WP2 and WP3 results proved to be an excellent case for the effective application of the work delivered in WALLTURB. The improvement in the methods employed makes possible less-resolved simulations (and therewith lower computational times for large scale computations to an acceptable and reproducible margin of accuracy) to more complex flows with uneven surfaces and pressure gradients which are more typical for industrial applications.

3.5.3 LML – LES of turbulent bump flow

Large-Eddy Simulations with two subgrid scale (SGS) models based on turbulent viscosity (Wall Adaptive Eddy viscosity model (WALE) and Dynamic Smagorinsky Model (DSM)) have been compared to DNS of flat channel flow and converging-diverging channel flow at several Reynolds number. The LES were performed using the same numerical code and with several levels of mesh refinement for each case.

The SGS models were first implemented into the LML code and validated with DNS of flat channel flows at $Re_\tau = 395$ and $Re_\tau = 2000$ ([D5.2] and [D5.5]). The converging diverging channel flow is a challenging configuration for LES as it includes strong favorable and adverse pressure gradient with a very thin separation at the lower wall and no separation at the flat upper wall. The performances of the WALE and DSM models have been evaluated on this configuration for two Reynolds numbers ($Re_\tau = 395$ and $Re_\tau = 617$ at the inlet) ([D5.3] and [D5.9]). Three mesh refinements were used and the influence of the constant of the WALE model was also investigated. The characteristics of the two LES models are similar at the two walls, but the discrepancy with respect to the DNS is always amplified at the lower wall due to the flow separation. Surprisingly, the two LES models demonstrate very similar behavior for the three tested grids. The WALE model with the optimum constant from the three tested constants seems to give an overall better prediction than the Dynamic Smagorinsky Model. The results of the LML were compared to results of TuCz for the lowest Reynolds number on exactly the same configuration. As the WALE model was implemented in both codes, the effect of the numerical schemes as well as the normal discretization have been addressed ([66]). The general conclusion is that the streamwise discretization is a crucial parameter in order to predict accurately enough the flow under adverse pressure gradient, especially in the vicinity of a separation region.

3.5.4 CNRS-Saclay – New LES-Langevin model for turbulence

A new model of turbulence was proposed for use in large-eddy simulations (LES). The turbulent force, represented here by the turbulent Lamb vector, is divided in two contributions. The contribution including only subfilter fields is deterministically modeled through a classical eddy-viscosity. The other contribution including both filtered and subfilter scales is dynamically computed as solution of a generalized (stochastic) Langevin equation between periodic reinitializations. This equation is derived using Rapid Distortion Theory (RDT) applied to the subfilter scales. The general friction operator therefore includes both advection and stretching by the resolved scale. The stochastic noise is derived as the contribution from the energy cascade described by the aliasing. The LES model is thus made using an equation for the resolved scale, including the turbulent force, and a generalized Langevin equation integrated on a twice-finer grid.

The model was first validated by comparison to DNS and tests against classical LES models for isotropic homogeneous turbulence, based on eddy viscosity. It was shown that the inclusion of backscatter through the Langevin equation results in a better description of the flow. The model was then implemented in a numerical code solving the Navier-Stokes equations in the shear like geometry. This has been the subject of the Ph. D thesis of R. Dolganov [67], [68] defended successfully on May 26th 2009.

It was finally shown that the model provides an enhancement of the turbulent motions in the channel center with respect to pure dissipative models. Further improvement of the model is required to take into account the contribution of elongated streaks that

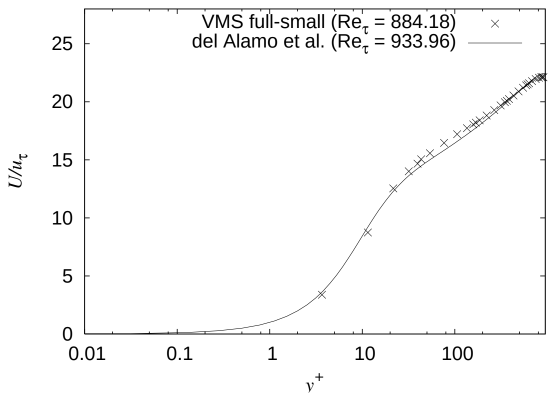


Figure 21: Spectral element VMS-LES results for plane channel flow at $Re_\tau = 950$. Mean velocity profile

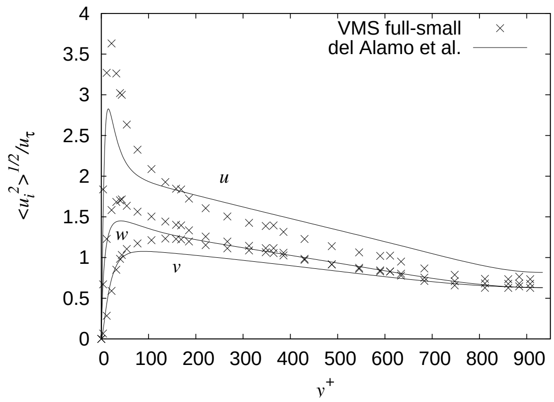


Figure 22: Spectral element VMS-LES results for plane channel flow at $Re_\tau = 950$. RMS velocities profile

are currently badly represented by our model. Possible solutions involving relaxation equations derived from statistical mechanics were investigated by a post-doc and are still under investigation.

3.5.5 FFI – variational multiscale LES model

FFI worked on the implementation of a variational multiscale (VMS) LES model using a high-order spectral element solver with applications to turbulent channel flow. The Variational Multiscale model was recently proposed as a tool for LES modelling by Hughes et al. [69]. The key idea of the approach is to use variational projection of the governing equations as a filtering operation. In the VMS methodoloy, subgrid scale modelling is only applied at the finer scales, whereas the larger scales are left undisturbed. Simulations using this method have shown promising results for wall-bounded flows, see e.g. [70, 71, 72].

In the present work, the polynomial basis functions were partitioned into large-scale and small-scale spaces, in which the large-scale space comprises approx. 70% of the one-dimensional modes, i.e. approx. 35% of the full three-dimensional polynomial spectrum. A constant coefficient Smagorinsky model was applied to the small scales. The resulting spectral element VMS LES method can, without tuning, give results that compare well with DNS data for turbulent channel flow up to $Re_\tau = 950$ with relatively coarse meshes, having typically $\Delta y^+ \approx 3$ at the wall and 60 grid points across the channel at the highest Reynolds number, as we can observe in Figs. 21–22 (see D5.16). A revised version of this report was accepted for publication in the Journal of Computational Physics [73].

3.5.6 TUCz – LES of turbulent channel/bump flow

The main task of TUCz in the frame of WP5 was to perform LES calculations of a few test cases, mainly turbulent channel flows with ZPG and APG, especially paying attention to the proper treatment of the near wall flows. For this purpose it was decided to apply the SAILOR code, which was initially designed to solve free flows problems like iso- and nonisothermal (variable density) free flows (round and plane jets, temporal and mixing layers, diffusion flames). For the purpose of WALLTURB project the code was redesigned to treat the wall bounded flows as well [74].

The code in the final version is based on the projection method for the pressure−velocity coupling. The time integration is performed by the corrector−predictor scheme Adams-Bashforth/Adams-Multon. The spatial derivatives are approximated by Fourier approximation in the spanwise direction and a high−order compact scheme in the wall normal and streamwise direction. The next activity was a theoretical study and an implementation of the new subgrid scale models. Apart from dynamic Smagorinsky with Germano procedure, the main effort was put on the analysis of two others models: the velocity estimation type model of Domaradzki (2002) and the WALE model of Nicoud and Ducros (1999) ([D5.4.1], [D5.4.2], [D5.11]). Supplementary activity concerns the implementation, into the code, and the verification of inflow boundary conditions generation method.

After some tests, it was decided to apply a method very similar to the modified Spalart approach of Lund et al. (1998), based on the self-preserving extent of the boundary layer ([D5.15]). The approach is based on the idea of a recycling station, where turbulent motion is transformed from the recycling station located somewhere in the domain cross-section into the inlet plane. Additionally, to have a possibility to perform the calculations of a channel with curved walls with structural mesh code, the procedure of mathematical mapping from physical coordinates to Cartesian ones of Marquillie *et al.* (2008) was implemented ([D5.8]). Before coming to more difficult cases the assessment of various implemented subgrid models on the solution has been analyzed based on turbulent channel flow at $Re_\tau = 180$ and 550 [75]. It appears that there was no big discrepancy between various subgrid-scale models, while additional application of high-order discretisation scheme with sufficient density of the grid in the wall vicinity reduces the influence of discretisation errors on the solution.

The last activity was the simulation of converging-diverging channel flows, where the first case was a channel with the geometry corresponding to the blade passage of axial compressor [76], while the other was the turbulent channel flow with varying pressure gradient calculated within the DNS study by LML [77]. Both channel geometries cause the existence of the adverse pressure gradient which induces the boundary separation. The inlet Reynolds number based on the friction velocity was assumed to be equal $Re_\tau = 395$. The influence of the mesh spacing and the subgrid scale models (SGS) has been investigated. Two SGS models were considered: WALE and the Smagorinsky with the damping function. Finally, in common work with LML group, the impact of the LES solver on the solution was analyzed [66]. The main conclusion is that the results are sensitive to the numerical code (derivation schemes) and highly dependent to the number of grid points in the configuration. A sufficient streamwise resolution is required in order to capture the small separation region at the lower wall.

3.5.7 TUM - wall modeling in implicit LES

With the help of the thin boundary-layer (TBLE) approach, the restrictive resolution requirements at solid wall for standard LES is eased. A region close to the wall, preferably reaching into the logarithmic layer, is treated with the TBLE within the implicit LES framework already available at TUM. The method developed during the course of the project, solves the wall-normal TBLE locally, taking into account the streamwise pressure gradient to allow for the simulation of flows with pressure gradients more accurately. The boundary conditions for the TBLE come from the LES in the regions away from the wall.

After successful validation calculations ([D5.6], [D5.7.1]) with channel flows of Reynolds numbers extending to $Re_\theta = 2000$ (from Jimenez, UPM), simulations for boundary-layer flows were conducted. In a last stage, the bump flow as simulated with DNS and LES by LML for comparison, was investigated. As the TBLE itself cannot develop a separation bubble in itself, the separation bubble that is to be examined needs to extend into the LES part of the simulation for the method to reproduce separation properly. As the separation region in the LML case was very shallow, the results are not as accurate as for LES with finer resolution at the wall. Figures 23 and 24 show the mean flow over the pressure-gradient bump flow and the comparison with the Reynolds stresses from LES and DNS from partners within WALLTURB ([78]).

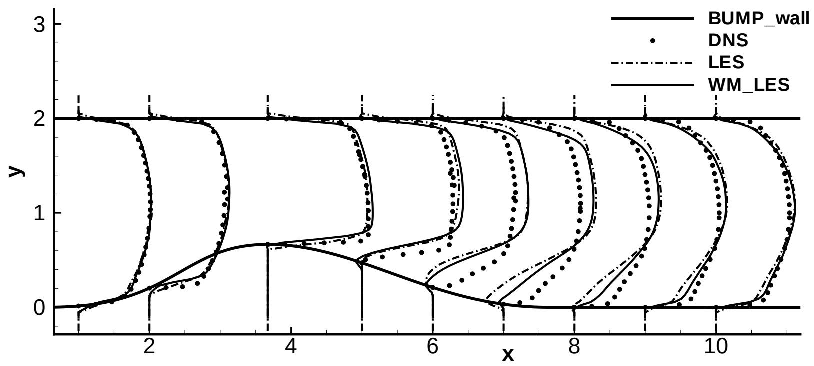


Figure 23: Mean streamwise velocity comparison at several streamwise locations.

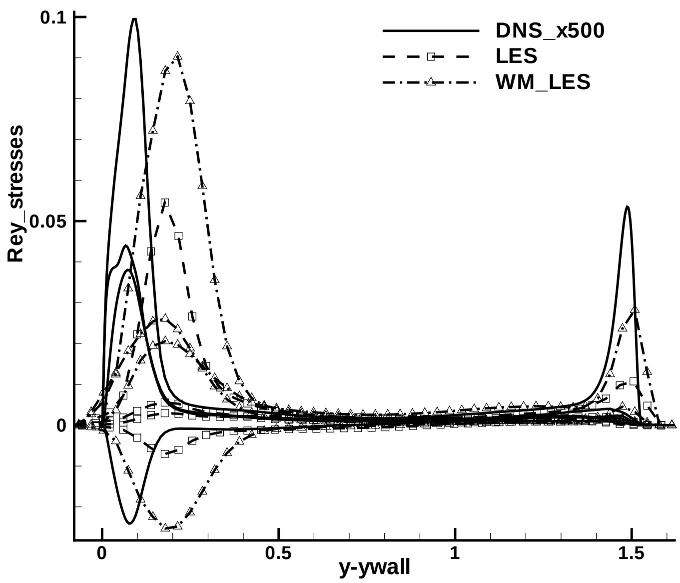


Figure 24: Reynolds stresses comparison at streamwise location $x = 500$.

The resolution for the presented results is $172 \times 64 \times 32$ points in the downstream, wall normal and spanwise direction, respectively. This is very coarse to show the performance of the method with the least number of points.

3.5.8 Conclusion

The LES workpackage within the WALLTURB project has successfully developed high level LES methodology to tackle complex flows which exhibit favourable and adverse pressure gradients. The geometry chosen (the bump) was highly suitable to investigate the performance of sub-grid scale models and wall modeling in the existing LES codes. With the variational multiscale method (VMS), the WALE approach and the implicit LES with TBLE wall modelling, the work package contributions have shown the capabilities of the methods and the effectiveness of the approaches. The relatively coarse resolutions reached for a level of admissible results show the prospective application of LES methods to flows with complex geometries and adverse pressure gradients subject to possible separation.

3.6 WP 6: LODS modelling

Work Package manager: LEA

3.6.1 Objectives

The global objective of WP6 was to use low order descriptions (LODS/ROM) of the flow near boundaries to help reducing the size of LES, especially when wall bounded flows are concerned. In this project, focus was put on near wall conditions to be prescribed in a section parallel to the wall, far enough from the wall ($y \sim 50^+$ to 100^+), in order to save a significant amount of grid points. The Proper Orthogonal Decomposition (POD) was extensively used and two complementary approaches were addressed: POD-Galerkin (LIMSI), System Identification (LEA).

This was the most prospective workpackage, as it is based on recently developed mathematical approaches which are at the leading edge of research in fluid mechanics.

3.6.2 Main results

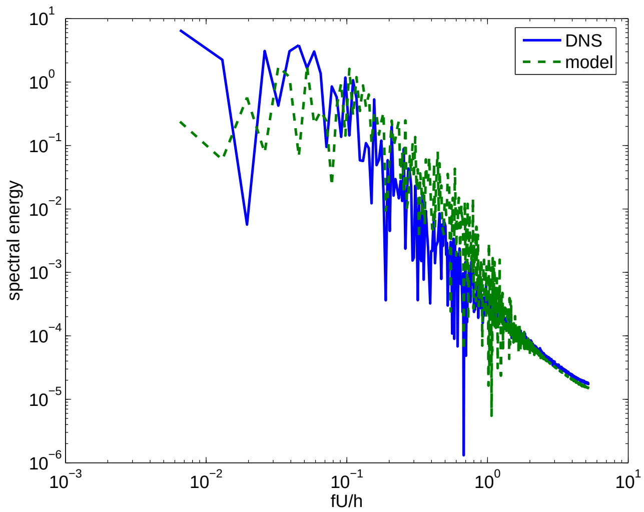
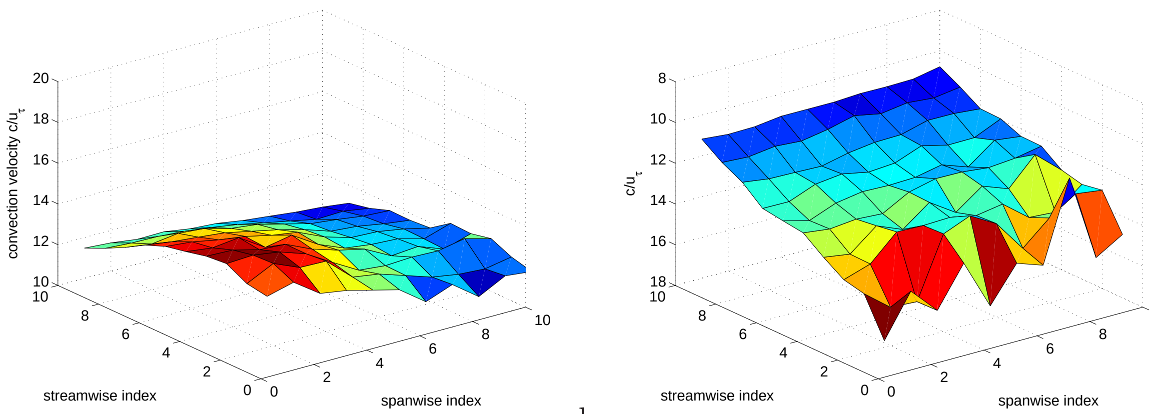


Figure 25: Power density spectrum of the P.O.D zero streamwise modes a_{04}

For the POD-Galerkin approach, the focus of LIMSI was on plane channel flow. The goal was to develop a model for the very near-wall turbulence and to explore coupling strategies for LODS and LES. Building on the pionnering work of Lumley and co-workers, LIMSI has developed a fully 3-D approach, which leads to a model for the entire near-wall layer. The model was based on and compared with results from a direct numerical simulation provided by UPM. The dynamical system equations were derived by Galerkin projection of the Navier-Stokes equations onto the spatial basis of POD eigenfunctions. Closure assumptions for the model were obtained from direct application of turbulence modelling theory. For realistic comparison with the simulation, the number of modes retained had to be fairly large (around 200). It was then found that the dynamics predicted by the model agreed well with those found in the direct numerical simulation. The effect of the modelling assumptions was also examined and found to have a moderate influence on the statistics of the model ([79], [80], [D6.2.1], [D6.2.2]). Integration of these models have been used to generate a wall boundary condition for LES, and preliminary results appear promising. These tests were carried out very close to the wall ($y+ \sim 20$) and will have to be repeated at higher locations.



a, b,

Figure 26: Convection velocity defined as $c_{lk} = -\dfrac{L_x}{2\pi l}\dfrac{Im[< a^*_{lk} da_{lk}/dt >]}{< a_{lk} a^*_{lk} >}$ a) in the DNS b) in the model

LES/LODS coupling was a primary direction of investigation during the WALLTURB project, and some steps towards generation of appropriate boundary conditions have been made. The starting point was a planar velocity field which could be used as a near wall boundary condition for the LES. One issue to address is the mutual dependence of the simulation and the LODS: to which extent does the flow resolved by the LES affect the state of that in the near-wall region? Another is the treatment of small scales, which will typically be excluded from LODS. To explore the interaction between the inner and the outer region, instantaneous realizations of the flow in the inner layer were compared with reconstructions based on outer-layer information (the outer layer is included in the zone $50 < y+ < 200$) as well as POD spatial eigenfunctions. The quality of the reconstruction was found to depend on the signature of the POD structures in the outer layer and therefore the wall normal organization of these structures over the layer. It was found that long, narrow structures hovered very close to the wall and therefore could not be well estimated, while wider, shorter structures were found further away from the wall and were correctly accounted for in the reconstruction. This description appears to agree with other observations [81]. In particular, it appears that around a given height y, predominant structures would be characterized by a wavenumber $(2\pi k_x, 2\pi k_z)$ such that $k_z = k_0 + 2k_x$, with $k_0 \sim 1/y$ ([82], [D6.4.1]).

The System Identification approach of LEA [83] was developped and applied on both numerical and experimental databases shared by Wallturb partners. In the framework of the LML joint experiment of WP2, a specific measurement was performed in particular to help building LODS for WP6. This time resolved PIV database, carefully validated by [84], corresponds to planes parallel to the wall, for various Reynolds number ($\Re_\theta = 7\ 500$, 9 000 and 20 000), with a spatial resolution between 4 and 12 wall units. This data set allowed a good convergence of the POD modes and the computation of time derivatives (1000 packets of short time records and two long records for validation) for identifying dynamical systems.

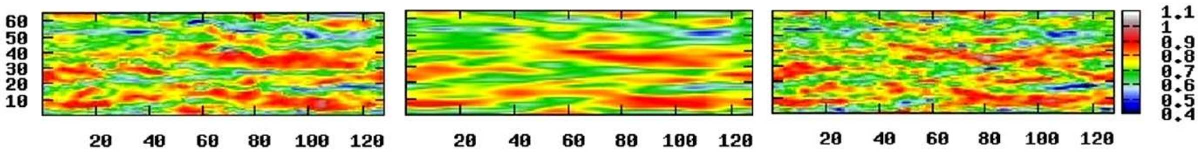


Figure 27: Virtual reconstructions of instantaneous fields of longitudinal velocity (m/s) by LEA from LML LES database: ¿From left to right: original snapshots, exact contribution of the $N_T = 49$ most energetic POD modes (half of the turbulent kinetic energy) and addition of the stochastic contribution of the highest order POD modes.

At LEA, the POD analysis of the various databases has revealed the high complexity of the mode hierarchy which represents the spatial flow organisation in planes parallel to the wall within boundary layers [85]. The 10 to 20 first POD modes clearly yield a distinct behaviour, by comparison with a large group of less energetic POD modes whose energy evolution could have been related to the classical Kolmogorov turbulent cascade. A large number of modes have to be taken into account to represent a significant part of the turbulent kinetic energy through the whole plane parallel to the wall. Accordingly, the virtual-wall modelling strategy determined was based both on using LODS to represent the coherent largest scales (with the lowest order/most energetic modes) and a complementary stochastic modelling approach for the highest order modes.

The analysis of the correlation dimension of the most energetic POD signals has confirmed that only the first group of (10 to 20) POD modes yield a deterministic behaviour and can thus be represented by LODS. Nevertheless, the stabilisation of the long term behaviour of these LODS is still an open question. This issue has been particularly investigated during the project, based on various approaches (robust implicit time integration, spectral noise filtering of the time signals, regularisation procedures or automatic research of initial conditions) [86].

Some preliminary virtual wall / LES coupling simulation have been carried out, jointly with LML. They were based on velocity fields rebuilt either from the exact most energetic modes only or from these exact POD modes combined with stochastic signals for the contribution of the highest order modes (respecting their spectral content) (see figure 27).

Here again, the results, if not perfect, are encouraging.

Alternative approaches will have now to be considered. These are based on a more robust parametric definition of the LODS parameters in a probabilistic framework and improved generalized scaling laws to incorporate a physically representative phase information between the highest modes.

3.6.3 Conclusion

Although this workpackage was a risky part of the project, as it was based on the most recent turbulence theories, significant progress could be made. Dynamical systems representative of the near wall turbulence could be built and compared to the real flow. All the problems encountered could not be solved, but the results available give good hope that low order dynamical systems can represent fairly correctly the main features of near wall turbulence. The question of coupling such a system to a LES solver is still open but is worth to investigate in a future project.

4 Conclusion

The WALLTURB project was a really challenging project, involving 14 Academic and research institutions and 2 key industrial from aeronautics. The program was quite ambitious as it aimed, in 4 years, at making significant progress in near wall turbulence modelling.

Although it cannot be claimed that all the initial objectives were reached, this final summary clearly illustrates that valuable work was performed, that some ambitious challenges were tackled and that globally, the project is bringing new results and new insight in wall turbulence. That it is also opening new questions of real interest : what is the real rôle of the external large scale motions? Is the Kolmogorov scaling of real universality? Is an instability generally hidden in the APG boundary layer?...

Beside these questions, which are of hot fundamental and practical interest, significant work has been performed on turbulence modelling, leading to the improvement of existing models and to the development of new ones. This particularly true in RANS modelling, where models developed in the frame of the project was tested by Airbus in its in-house code with some good success. The work done on LES has shown the potential of the method and its applicability to adverse pressure gradient flows of industrial interest. This is surely a modelling approach of the future which should see soon industrial partners entering into the game. The Low Order Dynamical System approach has more long term perspectives but has shown here its ability to represent relatively faithfully the main features of near wall turbulence. The coupling with a LES solver is still an open question.

Globally, it should be said that, although the time scale of turbulence model development is much larger than that of this project, the WALLTURB consortium can claim that a real step forward was done, thanks to the unique possibility offered by this type of project: a tight cooperation, at the highest level of competence, between scientists of different origins and different skills, supported by a good amount of funding.

5 Deliverables

REPORTS & DATABASES

[NL1] WT_nl_1_LML_060630: WALLTURB first newsletter, June 2006.

[NL3] WT_nl_3_LML_ 080515: WALLTURB third newsletter, May 2008.

[Rome Workshop] A European Synergy For The Assessment of Wall Turbulence, Open WALLTURB and ERCOFTAC International Workshop, Viterbo (Italy), March 22-23 2007.

[Lille Workshop] Progress in Wall Turbulence : Understanding and modelling, International WALLTURB and ERCOFTAC workshop, Lille (France), April 21-23 2009.

[D2.6] WT_060515_TR_LEA: Minutes of the manufacturing of the HW rake for WP2.1 Experiment, J. Delville, May 15 2006

[D2.8] WT_060110_TR_TUCz_1: DESIGN OF NEW TEST SECTION FOR FLAT PLATE BOUNDARY LAYER INVESTIGATION, M. Materny, W. Elsner, January 2006.

[D2.9] WT_070627_TR_USur: Tests on 1/5th-scale bumps in order to select bump profile, P. Nathan and P. Hancock, June 27 2007.

[D2.10] WT_060414_TR_TUCz: DETERMINATION OF INFLOW CONDITIONS AND TEST SECTION CHECKS, M. Materny, W. Elsner, April 2006.

[D2.11] WT_070831_TR_TUCh: Set-up of Anemometers and Data Acquisition system, P. Johansson, August 2007.

[D2.12.1] WT_070219_TR_UPM_1: A direct numerical simulation code for incompressible turbulent boundary layers, M. P. Simens, J. Jimenez, S. Hoyas, G. Hauet, S. Vaux,February 2007.

[D2.13] WT_081016_Tr_URS_1: DNS of turbulent channels with a moving wall for turbulence closures. P. Orlandi, S. Leonardi, November 2007.

[D2.17] WT_070717_TR_USUR: Preliminary tests on an adverse pressure gradient flow with separation (AGP+SEP), P. Nathan, P. Hancock, July 2007.

[D2.20.1] WT_311007_TR_USur: Oil Film Interferometry a Complete Derivation including: Methodology, Optimisation, and Ray Tracing Simulation, P. Nathan, March, 2008.

[D2.20.2] WT_260308_TR_USur: The Oil Film Equation Derivation from First Principles, including Solutions and Analysis. P. Nathan and P. E. Hancock, October, 2007.

[D2.21] WT_061129_TR_TUCz: Preliminary analysis of boundary layer under adverse pressure gradient, M. Materny, W. Elsner, S. Drobniak, M. Wysocki, november 2006.

[D2.29.1] WT_061009_TR_ONERA: Friction measurement in zero and adverse pressure gradient boundary layer using oil film interferometric method, G. Pailhas, Ph. Barricau, L. Perret*, Y. Touvet, December 2006.

[D2.29.2] WT_081005_TR_TUCh: Structure of Zero Pressure Gradient High Reynolds Number Turbulent Boundary Layers, M. Tutkun, october 2008.

[D2.30] WT-070728-TR-TUCz-1: Data Base - DB8_TUCz_APG_inlet, M. Materny, W. Elsner, july 2007.

[D2.33] WT-080404-TR-TUCz-1: Hot-wire experiment of boundary layer under adverse pressure gradient, A. Drozdz, W. Elsner,April 2008.

[D2.34] WT_090406_TR_USur: Hot-wire and oil-film measurements in an adverse pressure gradient flow with separation (AGP+SEP), P. Nathan and P. E. Hancock, January, 2009.

[D2.35] WT_080331-TR-TUCz-1: Skin friction measurements with oil film interferometry technique, A. Drozdz, W. Elsner, S. Drobniak, March 2008.

[D2.37] WT_090930_TR_URS: DNS and ζ - f closure in turbulent channels with a moving wall, P. Orlandi, D. Borello, April 2009.

[D2.40] WT_090930_TR_USur: Status and summary of results from the WALLTURB project and the database, D2.40, D3.28, P. E. Hancock, September, 2009

[D2.41] WT_080405-DB-TUCz-1: Data Base DB8_TUCz_APG on adverse pressure gradient boundary layer, A. Drozdz, W. Elsner, April 2008.

[D3.2] http://lmlm6-62.univ-lille1.fr/db/, database on flat plate boundary layer.

[D3.3] http://torroja.dmt.upm.es/ftp/, database on channel flow DNS.

[D3.4] WT_060404_TR_ENSTA: Entropic-skins geometry to describe wall turbulence intermittency, D. Queiros Condé, April 2006.

[D3.5] http://lmlm6-62.univ-lille1.fr/db/, database on adverse pressure gradient boundary layer.

[D3.10] http://lmlm6-62.univ-lille1.fr/db/, database on WALLTURB joint experiment for flat plate boundary layer.

[D3.11] http://lmlm6-62.univ-lille1.fr/db/, database on WALLTURB joint experiment for APG boundary layer.

[D3.13] WT_090630_DB_USur, database on key data for the Surrey bump experiment.

[D3.14.1] http://torroja.dmt.upm.es/ftp/, database on adverse pressure gradient boundary layer DNS.

[D3.14.2] WT_081229_DB_URS, database on Couette-Poiseuille flow DNS.

[D3.15] WT_081105_TR_ENSTA: Entropic-skins geometry to describe wall turbulence intermittency Application to a turbulent boundary layer (XZ2 PIV database of LML), D. Queiros Condé, November 2008.

[D3.16.1] WT_070730_DB8-inlet_TUCz, database on the inlet conditions of TUCz APG boundary layer experiment.

[D3.16.2] WT_070730_DB8-inlet_TUCz,database on the inlet conditions of TUCz APG boundary layer experiment.

[D3.21] WT_090630_DB_Usur, database of the Surrey bump experiment.

[D3.23] WT_090109_TR_ENSTA: Entropic-skins geometry applied to a turbulent channel flow obtained by Direct Numerical Simulation (database from UPM, Madrid), D. Queiros-Conde and H. Kassem, January 2009.

[D3.26] WT_080405_DB APG_TUCz, database on TUCz APG boundary layer experiment.

[D4.3] WT_061015_TR_LML: Length scales in the flat plate and APG boundary layers, S. Herpin, J. Kostas, M. Stanislas, October 2006.

[D4.4] WT_080225_TR_ONERA_2: Analysis of direct numerical simulations, B. Aupoix, February 2008.

[D4.5] WT_070220_TR_LEA: Derivation of Explicit Algebraic Models, A. G. Oceni, R. Manceau, T. Gatski, February 2007.

[D4.8] WT_070112_TR_UCY: ASBM with elliptic wall-blocking scheme and LSE-equation for near-wall turbulence (preliminary), S.C. Kassinos, C.A. Langer, S. Ma, January 2007.

[D4.9] WT_090415_TR_ONERA: Comparisons of standard turbulence models with project experiments, B. Aupoix, April 2009.

[D4.10] WT_071215_TR_LEA: Explicit algebraic modelling of channel flows, A. G. Oceni, R. Manceau, T.Gatski, December 2007.

[D4.11] WT_071002_TR_FFI: Implementation and validation of a nonlinear v2 - f model, M. Mortensen and B. A. Pettersson Reif, April 2007.

[D4.13] WT_080326_TR_LEA: A hierachy of Explicit Algebraic Models for wall-bounded flows, A. G. Oceni, R. Manceau, T. Gatski, February 2007.

[D4.14] WT_080325_TR_UCY: Application of the ASBM for the zero pressure gradient boundary layer (preliminary), C.A. Langer and S.C. Kassinos, March 2008.

[D4.16] WT_060206_Paper_FFI: Towards a nonlinear eddy-viscosity model based on elliptic relaxation, B. A. Pettersson Reif, February 2006.

[D4.17] WT_090914_TR_LEA: RANS modelling of the APG boundary layer, A. G. Oceni, R. Manceau, T. Gatski, June 2009.

[D4.18.1] WT_081010_TR_FFI: Assessment of a nonlinear V2F model for flow in an adverse pressure gradient boundary layer, M. Mortensen, B. A. Pettersson Reif, October 2008.

[D4.18.2] WT_081007_TR_FFI: Assessment of the finite volume method applied to the v2-f model, M. Mortensen, B. A. Pettersson Reif, C. E. Wassberg, October 2008.

[D4.19] WT_090415_TR_UCY: Progress in the ASBM for Wall Bounded Flows, C. A. Langer, April 2009.

[D4.20.1] WT_091016_TR_AIRBUS: Evaluation of v2-f and ASBM turbulence models for transonic aerofoil RAE2822, J.J.Benton, October 2009.

[D4.21] WT_090920_TR_LEA: Explicit algebraic modelling using elliptic blending for wall-bounded flows, A. G. Oceni, R. Manceau, June 2009.

[D4.23.1] WT_090721_TR_ONERA: Improving near-wall EARSM modelling, B. Aupoix, June 2009.

[D4.24] WT_090922_TR_UCY: Final near-wall ASBM proposal, S. C. Kassinos, June 2009.

[D5.2] WT_051001_TR_LML: Smagorinsky modelling as a preliminary numerical test to RDT LES approach, R. Dolganov, J.P. Laval, october 2005.

[D5.3] WT_060403_TR_LML: LES of channel flow with adverse Pressure Gradient, R. Dolganov, J.P. Laval, M. Marquillie, April 2006.

[D5.4.1] WT_051205_TR_TUCz_1: LES simulations with DSM of ZPG BL from LML, the SAILOR code - algorithm, discretization method, solution procedure. Implementation of the dynamic Germano subgrid model, A. Tyliszczak, W. Elsner, December 2005.

[D5.4.2] WT_060615_TR_TUCz_2: LES simulations with DSM of ZPG BL from LML, verification of the dynamic Germano subgrid model in wall bounded flow A. Tyliszczak, M. Soltysiak, W. Elsner, june 2006.

[D5.5] WT_081001_TR_LML_1: Comparison of LES of plane channel flow with DNS, R. Dolganov, J.P. Laval, October 2008.

[D5.6] WT_070430_TR_TUM: On implicit subgrid-scale modeling in wall-bounded flows S. Hickel, N. A. Adams,April 2007.

[D5.7.1] WT_070430_TR_TUM : Wall modeling within implicit LES, J. Berland, C. Stemmer, April 2007.

[D5.8] WT_080405_TR_TUCz: LES simulation of APG BL, L. Kuban, A. Tyliszczak, W. Elsner, April 2008.

[D5.9] WT_090109_TR_LML_1: Comparison of LES of converging diverging channel flow with DNS, J.P. Laval, January 2009.

[D5.11] WT_070515_TR_TUCz: Theoretical study and implementation of the unresoloved scale estimation model for flow in the periodic channel, W.Elsner, A. Tyliszczak, May 2007.

[D5.15] WT_081014_TR_TUCz: Test Case from TUCz with WALE model. Comparison of LES simulation results for Smagorinsky and WALE model, L. Kuban, W. Elsner, October 2008.

[D5.16] WT_160408_TR_FFI: Variational multiscale turbulence modelling in a high order spectral element method, C. E. Wasberg, T. Gjesdal, B. A. Pettersson Reif, . Andreassen, April 2008.

[D6.2.1] WT_061110_TR_LIMSI: Global and Local Aspects of P.O.D representations, B. Podvin, L. Lorang, November 2006.

[D6.2.2] WT_061110_TR_LEA: LODS MODELLING, J. Delville, November 2006.

[D6.4.1] WT_070630_TR_LIMSI: Low-dimensional models for the zero pressure gradient wall layer of a turbulent channel flow, B. Podvin, June 2007.

PUBLICATIONS

[1] M. Stanislas. WALLTURB : A european synergy for the assessment of wall turbulence,. In *45th AIAA Aerospace Sciences Meeting and Exhibit*, 8 - 11 Jan 2007, Reno, Nevada, USA, 2008.

[2] M. Stanislas, J.-M. Foucaut, J.-P. Laval, S. Coudert, J. Lin, N. Perenne, L. Perret, J. Kostas, and S. Herpin. Some insight in wall turbulence based on stereo particle image velocimetry. In *Proc. of the 8th International Symposium on Particle Image Velocimetry- PIV09, August 25-28, 2009, Melbourne, Victoria, Australia*, 2009.

[3] A. Bernard, J. M. Foucaut, P. Dupont, and M. Stanislas. Decelerating boundary layer : a new scaling and mixing length model. *AIAA Journal*, 41(2):248–255, 2003.

[4] M. Tutkun. *Structure of Zero Pressure Gradient High Reynolds Number Boundary Layers*. PhD thesis, Chalmers University of Technology, Goteborg, Sweden, October 2008, 2008.

[5] S. Herpin. *Study of the influence of the Reynolds number on the organization of wall-bounded turbulence*. PhD thesis, Thèse de l'Ecole Centrale de Lille (France), PhD of Monash University (Australia), 2009.

[6] C. H. Atkinson, S. Coudert, J.-M. Foucaut, M. Stanislas, and J. Soria. Tomographic particle image velocimetry measurements of a high Reynolds number turbulent boundary layer. In M. Stanislas, J. Jimenez, and I. Marusic, editors, *Progress in wall turbulence : understanding and modelling*, ERCOFTAC Series, Villeneuve d'Ascq, France, April 21-23 (to appear), 2009. Springer.

[7] C. Atkinson, S. Coudert, J.-M. Foucaut, M. Stanislas, and J. Soria. Thick and thin volume measurements of a turbulent boundary layer using tomographic particle image velocimetry. In *Proc. of the 8th International Symposium on Particle Image Velocimetry- PIV09, August 25-28, 2009, Melbourne, Victoria, Australia*, 2009.

[8] S. Coudert, J. M. Foucaut, J. Kostas, M. Stanislas, P. Braud, C. Fourment, J. Delville, M. Tutkun, F. Mehdi, P. Johansson, and B. George. Double large field stereoscopic piv in a high reynolds number turbulent boundary layer. In *7th International Symposium on Particle Image Velocimetry*, September 11-14 2007.

[9] S. Coudert, J.-M. Foucaut, J. Kostas, M. Stanislas, C. Braud, C. Fourment, J. Delville, M. Tutkun, F. Mehdi, P. Johansson, and W. K. George. Double large field stereoscopic piv in a high reynolds number turbulent boundary layer,. *submitted to Experiments in Fluids*, 2009.

[10] J. Delville, C. Fourment, M. Tutkun, P. V. Johansson, W. K. George, J. Kostas, S. Coudert, J.-M. Foucaut, and M. Stanislas. High reynolds number flat plate turbulent boundary layer experiments using a hot-wire rake synchronized with stereo PIV. In *Proc. of the 5th International Symposium on Turbulence and Shear Flow Phenomena, TU Munich 27–29 August 2007*, 2007.

[11] J. Delville, P. Braud, S. Coudert, J.-M. Foucaut, C. Fourment, W.K. George, P.B.V. Johansson, J. Kostas, F. Mehdi, A. Royer, M. Stanislas, and M. Tutkun. The WALLTURB joined experiment to assess the large scale structures in a high reynolds number turbulent boundary layer. In M. Stanislas, J. Jimenez, and I. Marusic, editors, *Progress in wall turbulence : understanding and modelling*, ERCOFTAC Series, Villeneuve d'Ascq, France, April 21-23 (to appear), 2009. Springer.

[12] J.-M. Foucaut, S. Coudert, J. Kostas, M. Stanislas, P. Braud, C. Fourment, J. Delville, M. Tutkun, F. Mehdi, P. B. V. Johansson, and W. K. George. Study of the unsteady aspects of turbulence in the near wall region of a boundary layer using high speed SPIV. In *Proc. of the 7th International Symposium on Particle Image Velocimetry, 11 - 14 September 2007, University La Sapienza Roma, Italy,*, 2007.

[13] J.-M. Foucaut, S. Coudert, M. Stanislas, J. Delville, M. Tutkun, and W.K. George. Spatial correlation from the spiv database of the wallturb experiment. In M. Stanislas, J. Jimenez, and I. Marusic, editors, *Progress in wall turbulence : understanding and modelling*, ERCOFTAC Series, Villeneuve d'Ascq, France, April 21-23 (to appear), 2009. Springer.

[14] J.-M. Foucaut and S. Coudert. Study of the near wall region of a turbulent boundary layer using high repetition stereoscopic piv. In *Proc. of the 8th International Symposium on Particle Image Velocimetry- PIV09, August 25-28, 2009, Melbourne, Victoria, Australia*, 2009.

[15] J.-M. Foucaut, S. Coudert, M. Stanislas, and J. Delville. Full 3d correlation tensor computed from double field stereoscopic piv in a high reynolds number turbulent boundary layer. In *Proc. of the 8th International Symposium on Particle Image Velocimetry- PIV09, August 25-28, 2009, Melbourne, Victoria, Australia*, 2009.

[16] S. Herpin, C. Y. Wong, M. Stanislas, and J. Soria. Stereoscopic piv measurements of a turbulent boundary layer with a large spatial dynamic range. *Experiments in Fluids*, 45(4):745–763, 2008.

[17] S. Herpin, S. Coudert, J.-M. Foucaut, J. Soria, and M. Stanislas. Study of the vortical structures in turbulent near wall flow. In M. Stanislas, J. Jimenez, and I. Marusic, editors, *Progress in wall turbulence : understanding and modelling*, ERCOFTAC Series, Villeneuve d'Ascq, France, April 21-23 (to appear), 2009. Springer.

[18] S. Herpin, J.-M. Foucaut, J. Soria, and M.. Stanislas. Coherent structures in near-wall turbulence. In *Sixth International Symposium on Turbulence and Shear Flow Phenomena*, pages 641–646, Seoul, Korea, 22-24 June, 2009, 2009.

[19] S. Herpin, S. Coudert, J.-M. Foucaut, M. Stanislas, and J. Soria. The structure of near-wall turbulence: a comparison between boundary layer spiv data and channel flow dns data. In *Proc. of the 8th International Symposium on Particle Image Velocimetry- PIV09, August 25-28, 2009, Melbourne, Victoria, Australia*, 2009.

[20] P. Johansson, M. Tutkun, B. George, M. Stanislas, J. M. Foucaut, J. Kostas, S. Coudert, and J. Delville. Adverse pressure gradient boundary layer experiments using synchronized PIV and a hot wire anemometry rake. In *Bulletin of the American Physical Society, 59th Annual Meeting of the APS Division of Fluid Dynamics*, volume 51 (9), November 19-21 2006.

[21] J. Lin. *Etude détailée des structure cohérentes de la zone tampon de la turbulence de paroi à l'aide de données de PIV stéréoscopique.* PhD thesis, University of Lille, 2006.

[22] J. Lin, J.-P. Laval, J.-M. Foucaut, and M. Stanislas. Quantitative characterization of coherent structures in the buffer layer of near-wall turbulence. part 1: streaks. *Experiments in Fluids*, 45(6):999–1013, 2008.

[23] M. Stanislas, L. Perret, and J. M. Foucaut. Vortical structures in the turbulent boundary layer: a possible route to a universal representation. *J. Fluid Mech.*, 602:327–382, 2008.

[24] M. Stanislas, J.-M. Foucaut, S. Coudert, M. Tutkun, W.K. George, and J. Delville. Calibration of the WALLTURB experiment hot wire rake with help of PIV. In M. Stanislas, J. Jimenez, and I. Marusic, editors, *Progress in wall turbulence : understanding and modelling*, ERCOFTAC Series, Villeneuve d'Ascq, France, April 21-23 (to appear), 2009. Springer.

[25] M. Tutkun, P. B. V. Johansson, W. K. George, M. Stanislas, J.-M. Foucaut, J. Kostas, S. Coudert, and J. Delville. Zero pressure gradient flat plate boundary layer experiments using synchronized piv and a hot wire anemometry rake. In *Bulletin of the American Physical Society, 59th Annual Meeting of the APS Division of Fluid Dynamics, November 19-21, 2006, Tampa Bay, Florida, USA*, volume 51 (9), page 207, 2006.

[26] M. Tutkun, W. K. George, J.-M. Foucaut, S. Coudert, M. Stanislas, and J. Delville. Cross-spectral analysis of cross-plane data from 143 hot-wires in zero-pressure gradient turbulent boundary layer at $r_theta = 9800$ and $19,100$. In *Bulletin of the*

American Physical Society, 60th Annual Meeting of the APS Division of Fluid Dynamics, November 18-20, 2007; Salt Lake City, Utah, USA, volume 52 (17), 2007.

[27] M. Tutkun, P. B. V. Johansson, W. K. George, J. Kostas, S. Coudert, J.-M. Foucaut, M. Stanislas, C. Fourment, and J. Delville. Highly time- and space-resolved experiment on a high reynolds number turbulent boundary layer. In *ADVANCES IN TURBULENCE XI, Proceedings of the 11th EUROMECH European Turbulence Conference, June 25-28, 2007, Porto, Portugal. Editors: J.M.L.M. Palma and A.Silva Lopes Springer Proceedings in Physics 117, Springer, Heidelberg*, pages 346–348, 2007.

[28] M. Tutkun, W. K. George, J. Delville, J.-M. Foucaut, S. Coudert, and M. Stanislas. Space-time correlations from a 143 hot-wire rake in a high reynolds number turbulent boundary layer. In *AIAA-Paper: 2008-4239, 5th AIAA Theoretical Fluid Mechanics Conference, Seattle, Washington, USA, June 2008*, 2008.

[29] M. Tutkun, W. K. George, J.-M. Foucaut, S. Coudert, M. Stanislas, and J. Delville. Large scale structures of high reynolds number turbulent boundary layers. In *Cambridge University, Isaac Newton Institute for Mathematical Sciences, Workshop on Wall Bounded Shear Flows: Transition and Turbulence, Cambridge, UK, 8 12 September 2008.*, 2008.

[30] M. Tutkun, W. K. George, J.-M. Foucaut, S. Coudert, M. Stanislas, and J. Delville. Two-point cross-spectral and pod analysis of high reynolds number zero pressure gradient turbulent boundary layer. In *Bulletin of the American Physical Society, 61th Annual Meeting of the APS Division of Fluid Dynamics, November, 2007; San Antonia, Texas, USA*, volume 53 (15), 2007.

[31] M. Tutkun, W. K. George, J.-M. Foucaut, S. Coudert, M. Stanislas, and J. Delville. In situ calibration of hot wire probes in turbulent flows,. *Experiments in fluids*, 46(4):617–629, 2009.

[32] M. Tutkun, W. K. George, J. Delville, M. Stanislas, P. B. V. Johansson, J. M. Foucaut, and S. Coudert. Two-point correlations in high Reynolds number flat plate turbulent boundary layers. *JOURNAL OF TURBULENCE*, 10(21):1–23, 2009.

[33] M. Tutkun, W. K. George, M. Stanislas, J.-M. Foucaut, S. Coudert, and J. Delville. Pod of high reynolds number turbulent boundary layers,. In *Submitted to ETC12, Marburg (Germany), Sept 7-10, 2009*, 2009.

[34] M. Tutkun, W.K. George, M. Stanislas, J. Delville, J.-M. Foucaut, and S. Coudert. Two-point correlations and POD analysis of the WALLTURB experiment, using the hot-wire rake database. In M. Stanislas, J. Jimenez, and I. Marusic, editors, *Progress in wall turbulence : understanding and modelling*, ERCOFTAC Series, Villeneuve d'Ascq, France, April 21-23 (to appear), 2009. Springer.

[35] G Pailhas, P. Barricau, Y. Touvet, and L. Perret. Friction measurement in zero and adverse pressure gradient boundary layer using oil droplet interferometric method. *Exp. Fluids*, 47(2):195–207, 2009.

[36] G. Pailhas, P. Barricaut, and L. Perret. Wall shear stress measurement in a TBL using the oil droplet interferometric technique. In M. Stanislas, J. Jimenez, and I. Marusic, editors, *Progress in wall turbulence : understanding and modelling*, ERCOFTAC Series, Villeneuve d'Ascq, France, April 21-23 (to appear), 2009. Springer.

[37] P. Nathan and P. E. Hancock. Two-point correlations of velocity and wall shear stress in the near-wall layer of a separating turbulent boundary layer. In *Submitted to ETC12, Marburg (Germany), Sept 7-10, 2009.*, 2009.

[38] P. Nathan and P. E. Hancock. Two-point near-wall measurements of velocity and wall shear stress beneath a separating turbulent boundary layer. In M. Stanislas, J. Jimenez, and I. Marusic, editors, *Progress in wall turbulence : understanding and modelling*, ERCOFTAC Series, Villeneuve d'Ascq, France, April 21-23 (to appear), 2009. Springer.

[39] P. Nathan and P. E. Hancock. Oil film wall shear stress measurements through separation. In M. Stanislas, J. Jimenez, and I. Marusic, editors, *Progress in wall turbulence : understanding and modelling*, ERCOFTAC Series, Villeneuve d'Ascq, France, April 21-23 (to appear), 2009. Springer.

[40] M. Materny. Experimental analysis of a turbulent boundary layer under the adverse pressure gradient., 2009.

[41] M. Materny, A. Drozdz, S. Drobniak, and W. Elsner. Experimental analysis of a turbulent boundary layer under the influence of apg. *Achives of Mechanics*, 60:1–18, 2008.

[42] M. Materny, A. Drozdz, S. Drobniak, and W. Elsner. The structure of turbulent boundary layer with adverse pressure gradient corresponding to turbomachinery conditions. In *SYMKOM'08 conference, 15 - 17 September, 2008, Ldz, Poland.*, 2008.

[43] A. Drozdz, W. Elsner, and S. Drobniak. Application of oil-fringe interferometry for measurements of wall shear stress in turbulent boundary layers,. In *SYMKOM'08 conference, 15 - 17 September, 2008, Ldz, Poland.*, 2008.

[44] S. Drobniak, W. Elsner, A. Drozdz, and M. Materny. Experimental analysis of turbulent boundary layer with adverse pressure gradient corresponding to turbomachinery conditions. In M. Stanislas, J. Jimenez, and I. Marusic, editors, *Progress in wall turbulence : understanding and modelling*, ERCOFTAC Series, Villeneuve d'Ascq, France, April 21-23 (to appear), 2009. Springer.

[45] J. Jiménez and S. Hoyas. Turbulent fluctuations above the buffer layer of wall-bounded flows. *J. Fluid Mech.*, 611:215–236, 2008.

[46] M. P. Simens. *The study and control of wall-bounded flows*. PhD thesis, Aeronautics, U. Polit. Madrid, 2008.

[47] M. P. Simens, J. Jimenez, S. Hoyas, and Y. Mizunoa. A high-resolution code for turbulent boundary layers. *Journal of Computational Physics*, 228(11):4218–4231, 2009.

[48] M. Bernardini, P. Orlandi, S. Pirozzoli, and F. Fabiani. Statistics and flow structures in couette-poiseuille flows. In M. Stanislas, J. Jimenez, and I. Marusic, editors, *Progress in wall turbulence : understanding and modelling*, ERCOFTAC Series, pages 228–234, Villeneuve d'Ascq, France, April 21-23 (to appear), 2009. Springer.

[49] M. Marquillie, J.-P. Laval, and R. Dolganov. Direct numerical simulation of separated channel flows with a smooth profile. *J. Turbulence*, 9(1):1–23, 2008.

[50] J.-P. Laval and M. Marquillie. Direct numerical simulations of converging-diverging channel flow. In M. Stanislas, J. Jimenez, and I. Marusic, editors, *Progress in wall turbulence : understanding and modelling*, ERCOFTAC Series, Villeneuve d'Ascq, France, April 21-23 (to appear), 2009. Springer.

[51] S. I. Shah, M. Stanislas, and J.-P. Laval. A specific behavior of adverse pressure gradient near wall flows. In M. Stanislas, J. Jimenez, and I. Marusic, editors, *Progress in wall turbulence : understanding and modelling*, ERCOFTAC Series, Villeneuve d'Ascq, France, April 21-23 (to appear), 2009. Springer.

[52] J.C. Del Álamo and J. Jiménez. DNS of the very large anisotropic scales in a turbulent channel. In *Advances in turbulence IX , I.P. Castro, P.E. Hancock and T,G. Thomas (Eds). CIMNE.*, 2002.

[53] J.C. Del Álamo and J. Jiménez. Spectra of the very large anisotropic scales in turbulent channels. *Phys. Fluids*, 15(6):L41–L44, 2003.

[54] J. Jiménez, J. C. Del Álamo, P. Zandonade, and Moser R. D. On the characteristics of spanwise vorticity in moderate reynolds number turbulent channels. In *Proc. Am. Phys. Soc. Ann. Meeting (Fluid Mech.), Dallas, TX.*, 2002.

[55] J. Delville, L. Perret, J.-P. Bonnet, and R. Manceau. Turbulent mixing layers: a test case for coupling experiments, theory and unsteady computations. AIAA paper 2007-4618, Miami, FL, USA, june 2007.

[56] S. Hoyas and J. Jiménez. Reynolds number effects on Reynolds-stress budgets in turbulent channels. *Phys. Fluids.*, 20(10):101511, 2008.

[57] J. Jiménez, S. Hoyas, M. P. Simens, and Yoshinori Mizuno. Comparison of turbulent boundary layers and channels from direct numerical simulation. In *Sixth International Symposium on Turbulence and Shear Flow Phenomena*, pages 289–294, Seoul, Korea, 22-24 June, 2009, 2009.

[58] J. C. del Álamo and J. Jiménez. Corrections to Taylor's approximation from computed turbulent convection velocities. In M. Stanislas, J. Jimenez, and I. Marusic, editors, *Progress in wall turbulence : understanding and modelling*, ERCOFTAC Series, Villeneuve d'Ascq, France, April 21-23 (to appear), 2009. Springer.

[59] H. Kassem and D. Queiros Conde. A scale-entropy diffusion equation for wall turbulence. In M. Stanislas, J. Jimenez, and I. Marusic, editors, *Progress in wall turbulence : understanding and modelling*, ERCOFTAC Series, Villeneuve d'Ascq, France, April 21-23 (to appear), 2009. Springer.

[60] M. Stanislas. A new wall function for near wall mixing length models based on a universal representation of near wall turbulence. In M. Stanislas, J. Jimenez, and I. Marusic, editors, *Progress in wall turbulence : understanding and modelling*, ERCOFTAC Series, Villeneuve d'Ascq, France, April 21-23 (to appear), 2009. Springer.

[61] W.K. George and M. Tutkun. The mesolayer and Reynolds number dependencies of boundary layer turbulence. In M. Stanislas, J. Jimenez, and I. Marusic, editors, *Progress in wall turbulence : understanding and modelling*, ERCOFTAC Series, Villeneuve d'Ascq, France, April 21-23 (to appear), 2009. Springer.

[62] J. J. Benton. Evaluation of v^2-f and ASBM turbulence models for transonic aerofoil RAE2822. In M. Stanislas, J. Jimenez, and I. Marusic, editors, *Progress in wall turbulence : understanding and modelling*, ERCOFTAC Series, Villeneuve d'Ascq, France, April 21-23 (to appear), 2009. Springer.

[63] V. Levasseur, S. Joly, and J.-C. Courty. Turbulence modelling applied to aerodynamic design. In M. Stanislas, J. Jimenez, and I. Marusic, editors, *Progress in wall turbulence : understanding and modelling*, ERCOFTAC Series, Villeneuve d'Ascq, France, April 21-23 (to appear), 2009. Springer.

[64] B. Aupoix, S. Kassinos, and C. A. Lager. ASBM-BSL: An easy access to the structure based model technology. In *Sixth International Symposium on Turbulence and Shear Flow Phenomena*, pages 367–372, Seoul, Korea, 22-24 June, 2009, 2009.

[65] P. A. Durbin. Separated flow computations with the k-e-v2 model. *AIAA J.*, 33(4):659–664, 1995.

[66] J.-P. Laval, W. Elsner, L. Kuban, and M. Marquillie. LES modeling of converging diverging turbulent channel flow. In M. Stanislas, J. Jimenez, and I. Marusic, editors, *Progress in wall turbulence : understanding and modelling*, ERCOFTAC Series, Villeneuve d'Ascq, France, April 21-23 (to appear), 2009. Springer.

[67] R. Dolganov. *Développement d'un modèle LES basé sur la théorie de la distortion rapide*. PhD thesis, Thèse de l'Ecole Centrale de Lille, France, 2009.

[68] R. Dolganov, B. Dubrulle, and J.-P. Laval. LES-Langevin approach for turbulent channel flow. In M. Stanislas, J. Jimenez, and I. Marusic, editors, *Progress in wall turbulence : understanding and modelling*, ERCOFTAC Series, Villeneuve d'Ascq, France, April 21-23 (to appear), 2009. Springer.

[69] T. J. R. Hugues, L. Mazzei, and K. E. Jansen. Large eddy simulation and the variational multiscale method. *Comp. Visual. Sci.*, 3:47–59, 2000.

[70] T. J. R. Hugues, A. A. Oberai, and L. Mazzei. Large eddy simulation of turbulent channel flows by the variational multiscale method. *Phys. Fluids.*, 13:1784–1799, 2001.

[71] S. Ramakrishnan and S. Collis. Turbulence control simulation using the variational multiscale method. *AIAA journal*, 42(4):745–753, 2004.

[72] H. Jeanmart and G. S. Winckelmans. Investigation of eddy-viscosity models modified using discrete filters: A simplified regularized variational multiscale model and an enhanced field model. *Phys. Fluids*, 19(055110):1–16, 2007.

[73] C. E. Wasberg, T. Gjesdal, B. A. Pettersson Reif, and O. Andreassen. Variational multiscale turbulence modelling in a high order spectral element method. *accepted for publication in the Journal of Computational Physics*, 228(19):7333–7356, 2009.

[74] A. Tyliszczak. An efficient implementation of compact-pseudospectral method for turbulence modeling. *TASK Quarterly*, 10(2):125–138, 2006.

[75] W. Elsner and A. Tyliszczak. Subgrid scale modelling of wall-bounded turbulent channel flow,. In *7th ERCOFTAC Int. Symp. on Eng. Turb. Modelling and Measurements, Limassol, Cyprus, 4 - 6 June 2008*, 2008.

[76] W. Elsner, L. Kuban, and A. Tyliszczak. LES of turbulent channel flow with pressure gradient corresponding to turbomachinery condition. In M. Stanislas, J. Jimenez, and I. Marusic, editors, *Progress in wall turbulence : understanding and modelling*, ERCOFTAC Series, Villeneuve d'Ascq, France, April 21-23 (to appear), 2009. Springer.

[77] W. Elsner, L. Kuban, and A. Tyliszczak. Subgrid scale modeling of turbulent channel flow with adverse pressure gradient. *PAMM, Proc. Appl. Math. Mech. (to be publish)*, 2009.

[78] Z. Chen, A. Devesa, M. Meyer, E. Lauer, C. Hickel, S. Stemmer, and N. A. Adams. Wall modelling for implicit large eddy simulation of favourable and adverse pressure gradient flows. In M. Stanislas, J. Jimenez, and I. Marusic, editors, *Progress in wall turbulence : understanding and modelling*, ERCOFTAC Series, Villeneuve d'Ascq, France, April 21-23 (to appear), 2009. Springer.

[79] B. Podvin. A proper-orthogonal-decomposition-based model for the wall layer of a turbulent channel flow. *Phys. Fluids*, 21(1):015111, 2009.

[80] B. Podvin, Y. Fraigneau, J. Jouanguy, and J.-P. Laval. A POD-based reconstruction method for the flow in the near-wall region,. In *Submitted to ETC12, Marburg (Germany), Sept 7-10, 2009*, 2009.

[81] J. C. del Álamo, J. Jiménez, P. Zandonade, and R. D. Moser. Self-similar vortex clusters in the logarithmic region. *J. Fluid Mech.*, 561:329–358, 2006.

[82] B. Podvin. A POD-based model for the turbulent wall layer. In M. Stanislas, J. Jimenez, and I. Marusic, editors, *Progress in wall turbulence : understanding and modelling*, ERCOFTAC Series, Villeneuve d'Ascq, France, April 21-23 (to appear), 2009. Springer.

[83] L. Perret, Collin E., and J. Delville. Polynomial identification of POD based low-order dynamical system. *J. of Turbulence*, 7(17), 2006.

[84] J.-M. Foucaut, S. Coudert, and M. Stanislas. HR SPIV for dynamical system construction. In M. Stanislas, J. Jimenez, and I. Marusic, editors, *Progress in wall turbulence : understanding and modelling*, ERCOFTAC Series, Villeneuve d'Ascq, France, April 21-23 (to appear), 2009. Springer.

[85] G. Lehnasch, J. Jouanguy, J.-P. Laval, and J. Delville. POD based ROM for prescribing turbulent near wall unsteady boundary conditions. In M. Stanislas, J. Jimenez, and I. Marusic, editors, *Progress in wall turbulence : understanding and*

modelling, ERCOFTAC Series, Villeneuve d'Ascq, France, April 21-23 (to appear), 2009. Springer.

[86] G. Lehnasch and Delville J. A reduced-order model based strategy for realistic near-wall data/simultion coupling. In 39^{th} *AIAA FLuid Dynamic Conference and Exhibit, San Antonio, TX, USA*, number AIAA-2009-3901, 2009.