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Unstable and unsteady aerodynamics : compared information from different numerical models

I. Abalakin[*], M. Braza[†], S. Camarri[‡], A. Dervieux[§], B. Koobus[¶], T. Kozubskaya[‖], P. Rodes[**], M.-V. Salvetti[††]

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Abstract: We review a few recent investigations concerning LES (Large Eddy Simulation), OES (Organised Eddy Simulation), and Statistical Modelling works with two-equation RANS models aiming at preparing short term improvement of industrial tools for a good representation of separated, unsteady flows, involving vortex shedding. A focus will be proposed on OES modelling and on the use of wall laws. Examples will concern vortex shedding behind cylinders and airfoils, dynamic stall of multi-body airfoil. This paper is dedicated to Pierre Perrier at the occasion of the NFD2000 symposium organised in his honour.

[*] IMM, Miuskaya sq., 4a, Moscow, Russia
[†] IMFT, avenue Professeur C. Soula, 31400 Toulouse, France
[‡] University of Pisa, Via Caruso, 56126 Pisa, Italy
[§] INRIA, 2004 Route des Lucioles, BP. 93, 06902 Sophia-Antipolis, France
[¶] University of Montpellier II, CC.051, 34095 Montpellier, and INRIA, France
[‖] IMM, Miuskaya sq., 4a, Moscow, Russia
[**] IMFT, avenue Professeur C. Soula, 31400 Toulouse, France
[††] University of Pisa, Via Caruso, 56126 Pisa, Italy

Unité de recherche INRIA Sophia Antipolis
2004, route des Lucioles, B.P. 93, 06902 Sophia Antipolis Cedex (France)
Téléphone : 04 92 38 77 77 - International : +33 4 92 38 77 77 — Fax : 04 92 38 77 65 - International : +33 4 92 38 77 65

Key-words: fluid, turbulence, large eddy, organised eddy, statistical modelling, compressible, finite volumes

Aérodynamique instable et instationnaire : informations comparées sur dfférents modèles numériques

Résumé : On passe en revue quelques investigations en LES, OES et en modélisation statistique (à deux équations) tendant à préparer des progrès à court terme des outils industriels pour la prédiction dans de bonnes conditions des écoulements instationnaires détachés, avec des lachers de tourbillons. Une attention spéciale est portée aux modélisations OES et à l'application de lois de parois. Les exemples proposés concernent les détachements de tourbillons autour d'obstacles cylindriques et de profils d'ailes, des décrochements dynamiques autour de profils multi-corps. Ce papier est dédié à Pierre Perrier à l'occasion du Colloque NFD2000 organisé en son honneur.

Mots-clés : fluide, turbulence, grandes structures, structures organisées, modélisation statistique, compressible, volumes finis

1 Introduction

The needs in simulation in aeronautics concern increasingly more predictions of unstable and unsteady phenomena. This is related to the study of larger, more comfortable, less noisy aircrafts. Then numerical models should allow a good representation of separated, unsteady flows, involving vortex shedding. At the same time, it appears that the calculation of complex unsteady flows involving the prediction of vortices of medium size is progressively industrially reachable with available meshes, as far as turbulence models allow it.

It is today unclear whether or not direct simulation (DNS) will be affordable in the next ten years for such predictions. Instead, many techniques are studied for the modeling of some features of a given turbulent flow while some others are predicted.

Reynolds Averaged Navier-Stokes models (RANS) address the prediction of mean flow. They can combine a rather easy and inexpensive calculation with a rather complex modeling, involving for example *transport equations* for quantities related to the energy and to the filter between fluctuations and average. An important subset of RANS relies on a turbulent viscosity that reduces the effective Reynolds number of the computation, i.e. the *numerical Reynolds number* (if numerical artificial viscosity and upwinding are neglected), and this makes the computation possible, with today's methods, meshes and computers.
However, RANS is, before all, theoretically designed to produce steady numerical outputs and not to produce flows involving unsteadiness, such as periodic structures, or instabilities.

Large Eddy Simulation (LES), in which only large scale motion is directly simulated, has produced from its beginning many computations that were much more accurate than RANS. However, it remains a very expensive method. Indeed, good results are produced only by fine meshes, corresponding to Reynolds numbers not much higher than those offerdable with DNS. Intuitively, it seems that a good LES study needs to resolve the main turbulent structures, or in other terms, it cannot work when only a limited number of rather organised structures are solved.

Many attempts have been done and are done in the CFD community for *combining the advantages of RANS and LES.*

- RANS-LES or DES: Combining RANS and LES is referred as RANS-LES by Speziale ([35]) who proposed an Algebraic Reynolds Stress Model with a progressive switch to DNS by weighting the turbulent Reynolds stress in the equations.
In the work of Spalart *et al.*, a similar approach is referred as DES, Detached Eddy Simulation, and relies on an extension of the Spalart-Allmaras model ([34]). Schiestel *et al.* ([15]) have also proposed some zero-, one- and two-equation models in this direction.

-OES: In the Organised Eddy Simulation approach ([22]), the modeling is focused on studying a flow where a quasi-periodic structure dominates the unsteady behaviour.
The phase averaging ([14],[*Ibid.*]) of such a flow will then produce a (theoretically) perfectly periodic flow reproducing with accuracy the above structure.
The RANS-LES or DES approach has the advantage of applying a more sophisticated model to an LES-like approach, but it may inherit some disadvantage of both methods, in some intermediate range, since the LES mechanism seems predictive only when the numerical flow is at high Reynolds number and turbulent, while RANS is not adapted to organised structures.

It is clear for us that many interesting outputs can be expected from the *combination of OES and LES*, with an emphasis on the selection of a few organised dominant structures, that is, with a ratio between physical and numerical Reynolds number much higher than in existing RANS-LES or DES. With *numerical Reynolds number* we intend the Reynolds number which corresponds to the global viscosity existing in the numerical model, due to both turbulence model and artificial upwind.

This standpoint will, hopefully, allow to address industrial problems, in which physical Reynolds number is generally of the order of several millions,

in which the geometry is rather complex, and thus software is often of unstructured type, with a large amount of numerical viscosity.
Our work will then focus on such a type of numerical technology, involving in particular wall laws for RANS modeling.

But before building an OES-LES approach, we have to analyse a few situations where these models and numerical methods should be improved in order to both apply in better conditions than standard version.

Our programme for combining OES and LES then involves:

(A) Identify inexpensive RANS models that would produce predictions of vortices and separation with an acceptable accuracy.

(B) Identify in which conditions standard LES methods can be coupled with RANS models in order to be used into industrial numerical codes.

(C) Adapt/extend RANS to the calculation of a class of large eddies, following the OES methodology.

It is a great pleasure for us to dedicate this work to Pierre Perrier. Thank you, Pierre, for the many impassioning discussions about fluids, numerics,... but also linguistics, and architecture that make a CFD congress in Rome or Athens a different experience!

2 Inexpensive RANS for separated flow

The purpose of this section is to demonstrate that a very cheap and standard RANS model, after a few very slight modifications, can become a rather predictive model of several types of separated flows.
We shall concentrate on $k-\varepsilon$ models and more precisely on two rather inexpensive boundary models:

- the Reichardt wall law,

- the two-layer Chen-Patel model.

and to the adaptation to these $k-\varepsilon$ models of a limitation to the turbulent viscosity due to Menter.

2.1 Wall treatment

The calculation of a turbulent boundary layer is made difficult by the stiff behavior of closure variables. It is rather well acepted that near the wall, one-equation models are more robust and much cheaper; this made popular some models like the Spalart-Allmaras one, or the two-layer Chen-Patel $k-\varepsilon$ model (**TLCP**). We shall use the latter in the sequel, in a version fully compatible with the compressible logarithmic law, as defined in [19] and [20].

CFD engineers easily adhere to the idea that the effort for applying a RANS model to a flow calculation is directly determined by the number of closure equations. We do not agree this. Instead, we consider that the main cost is related in mesh generation, that models involving wall laws, if predictive enough, are in fact among the most efficient ones. We describe now the Reichardt wall law (**RL**).
Let U^+, y^+ be non-dimensional parameters defined as follows:

$$U^+ = \frac{\overline{U}}{U_\tau} \quad , \tag{1}$$

$$y^+ = \frac{\rho U_\tau}{\mu} y \quad . \tag{2}$$

in which $\overline{U}$, ρ, μ and y are average tangential velocity, density, molecular viscosity and normal distance to the wall respectively. The velocity U_τ, also called friction velocity, is defined as

$$U_\tau = \sqrt{\frac{\tau_p}{\rho}} \quad . \tag{3}$$

The Reichardt wall-law (see e.g.[29], [36]) allows to connect the laminar sublayer flow with the logarithmic zone of the boundary layer. It can be written as follows:

$$U^+ = \frac{1}{\kappa} ln \left(1 + \kappa y^+\right) + 7.8 \left(1 - e^{-\frac{y^+}{11}} - \frac{y^+}{11} e^{-0.33 y^+}\right) \quad . \tag{4}$$

in which κ is the Kolmogorov constant.
This wall-law is suitable to describe the flow for an incompressible boundary layer; it can be employed to study slightly compressible boundary layers without appreciable errors.

Reichardt wall-law has the advantage of describing once for all the three types of behavior of the turbulent boundary layer, viz, the laminar layer, the logarithmic one and the intermediate layer, that is generally not described in usual wall laws.

2.2 Limitation to the turbulent viscosity

In both TLCP and wall law models, we can apply an adaptation of the *Menter correction* [30], which is inspired by the one-equation model of Johnson and King in which the turbulent stress tensor is assumed to be proportional to the turbulent kinetic energy in the logarithmic region of the turbulent boundary layer. Initially developed for being inserted in the $k - \omega$ model of Wilcox, the Menter correction redefines the turbulent viscosity in order to satisfy this proportionality.

More precisely, this model relies on the Bradshaw relation which defines the variation of the stress tensor as a function for the turbulent kinetic energy $\tau = \rho a k$ where a is a constant.

Production $\mathcal{P}$ and dissipation D terms write:

$$\mathcal{P} = \mu_t \left(\frac{\partial \overline{u}}{\partial y}\right)^2 \quad \text{et} \quad D = \rho \varepsilon$$

in which $\mathcal{P} = D$ whenever a local equilibrium holds. Starting from the definition of the local turbulent shear stress given by the Boussinesq assumption:

$\tau = \mu_t \partial u / \partial y$ and from the definition of the turbulent viscosity $\mu_t = c_\mu \rho k^2 / \varepsilon$, we can re-write the turbulent stress tensor as follows

$$\tau = \rho \sqrt{c_\mu} \sqrt{\frac{\mathcal{P}}{D}} k$$

By identification, we derive a value for the constant a, equal to $\sqrt{c_\mu}$ in the case of a local equilibrium. Using the Bradshaw assumption, Menter redefines the turbulent viscosity as follows:

$$\mu_t = \frac{\rho \sqrt{c_\mu} k}{\max\left(\frac{\varepsilon}{\sqrt{c_\mu} k}, \left| \frac{\partial u}{\partial y} \right| F \right)} \tag{5}$$

with

$$F = tanh\left(\psi^2\right), \quad \psi = \max\left(2 \frac{k^{\frac{3}{2}}}{y \varepsilon}, \frac{500 \mu c_\mu k}{\rho \varepsilon y^2 Re} \right)$$

The Menter model (5) allows to correct the turbulent viscosity when there is a local non-equilibrium between turbulence production $\mathcal{P}$ and dissipation D.
When the gradient of the normal velocity becomes weaker, i.e. out of the boundary layer, we recover the usual turbulent viscosity.

The adaption of (5) to the TLCP model is done, according to [19], as follows:

$$\mu_t = \frac{\rho \sqrt{c_\mu} k}{Max\left(cond, \left| \frac{\partial u}{\partial y} \right| F \right)} \sqrt{\frac{f_\mu}{f_\varepsilon}} \tag{6}$$

with

$$cond = \alpha \frac{\varepsilon}{\sqrt{c_\mu} k} \sqrt{\frac{f_\mu}{f_\varepsilon}} + (1 - \alpha) \frac{\sqrt{k}}{\sqrt{c_\mu} l_y \sqrt{f_\mu f_\varepsilon}}, \quad \alpha = \min\left(\max\left(\frac{R_y - 200}{20}, 0 \right), 1 \right)$$

where α is a weighting coefficient (see [19] for details); the correction functions f_μ et f_ε are defined as usually in the Chen-Patel model, and the length scale l_y is defined by $l_y \;=\; \kappa \; {c_\mu}^{-3/4} \; y$.

2.3 Static stall of high lift airfoil system

We first discuss the ability of $k - \varepsilon$ models in predicting separated flows such a static stall around an airfoil; more details can be found in [1].

We consider a high lift 2D problem; the geometry is a two-body NLR 7301; it was considered in an experiment by van den Berg [37]. The Reynolds number is $2.51 \cdot 10^6$ and the Mach number is 0.185. A series of angles of attack were taken from 0 deg. to 16 deg.
The case is well known as a test case of an European project [21]. See [25] for a recent calculation. Distributions of C_p are available, together with the lift, and this lift shows a strong static stall for angles of attack bigger than 15 deg. According to experimental measurements, an abscissa of 0.03 is specified for the shift from laminar to turbulent in both models.

A common mesh is used for both models. This is possible since the wall law model relies on an analytic layer thickness δ that is prescribed by user and not through the thickness of the first mesh row. In the sequel, we have observed that best results were obtained with:

$$\delta = 0.0001.$$

For this kind of flow, this is a figure four times smaller than the ones used for matching with the middle of the *log* region, and we are thus matching our models in the upper region of the *buffer zone.*

We now summarize the important remarks that arise from the comparison of TLCP and Reichardt law with respect to the stall prediction:

- the TLCP appears not able to predict the stall exceptif the Menter correction is applied, see in Fig. 1 a sketch of this type of calculation [20].

- the RL is not either able to predict the stall; combining the Menter correction carries some improvement, bur is not sufficient for, obtaining a good stall angle prediction [1].

Clearly, the level of turbulent viscosity, as controlled by the Menter "limiter" plays a crucial role in the ability of the two models. Both models will be still used in the sequel for a flow with pronounced unsteadiness.

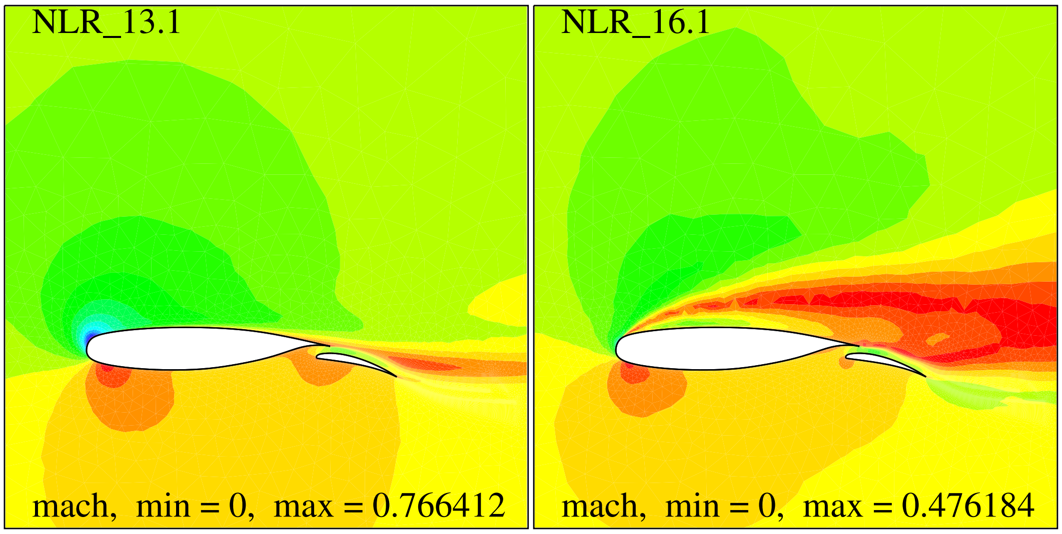

Figure 1: *prediction for a NLR airfoil (two-layer model and Menter correction): angle of attack for left picture is 13.1, and for right, 16.1 (courtesy of J. Francescatto)*

2.4 Unsteady flow past a square cylinder

To examine the unsteady behavior of the considered models, we choose a second typical flow experimented by Lyn *et al.* ([28]), in which the Reynolds number is $22,000$. The flow is dominated by a main quasi 2D organised eddy of von Karman type. This case is reachable with RANS in 2D and 3D and with LES (in 3D).

In [17], it has been shown that the $k - \epsilon$ model, combined with the Reichardt wall law, produces a rather good prediction of the unsteadiness, in both 2D (15896 nodes) and 3D calculations (43154 nodes).

Conversely, in [19], computations showed that the $k - \epsilon$ model, combined with the TLCP boundary treatment, did not produce a valuable prediction of the vortex shedding time constants.
When the Menter correction is introduced, the results significantly improve and become of comparable accuracy, if not better, than the $k - \epsilon$-Reichardt calculation.

3 Coupling a LES model with an RANS wall law

The introduction of a LES model in industrial applications lead to several problems:

- very fine 3D meshes and small "explicit-like" time steps are not possible for economical reasons,

- most standard industrial numerics for compressible flows exhibit properties of poor compatibility with LES: numerical viscosities, time dissipation of implicit time advancing,

- of course it is not possible to resolve the boundary layer, due to the very high Reynolds number.

In [13], (see also [11] and [12]), it is shown that both the Smagorinsky model and the dynamic Germano model can be successfully adapted to an unstructured, implicit upwind CFD code by the coupling of these models with the above Reichardt wall law, combined with a careful treatment and tuning of the numerical dissipation.
This is illustrated again on the low-Reynolds square cylinder flow which is now computed with the present LES method with a (3D) mesh of 100,000 nodes. An idea of the Smagorinsky sub-grid scale viscosity is given in Fig.2. We give in Table 1 a few bulk outputs obtained in large-eddy simulations with different

	$\overline{C_l}$	$C_{l,rms}$	$\overline{C_d}$	$C_{d,rms}$	S_t	l_r
LES	-.03,.02	.39,.91	1.9,2.13	.06,.12	.13,.15	1.24,1.58
RANS-2D Reichardt			1.97		0.137	
RANS-3D Reichardt			2.31		0.141	
RANS-2D TLCP+M			2.15		0.138	
LES from [33]	$-.3, .03$	$.38, 1.79$	$1.66, 2.77$	$.10, .27$	$.066, .15$	$.9, 2.9$
RANS from [5]	-	-	1.63,2.0	-	$.134, .143$	$1.2, 2.8$
Exper. Lyn *et al.*	-	-	2.1	-	0.135	1.4

Table 1: *Bulk coefficients for the square cylinder test case: comparison of LES and RANS calculations (Reichardt wall law or two-layer Chen-Patel with Menter correction) with experimental data and with other simulations described in the literature.*

boundary conditions, domain size and grids. These global parameters are quite well reproduced in our LES: the maximum error on the Strouhal number is of 15% and that on the drag coefficient is approximately 10%. A satisfactory agreement has also been obtained for the recirculation length, which appeared to be a critical parameter in previous LES [9] and RANS [5]. This results

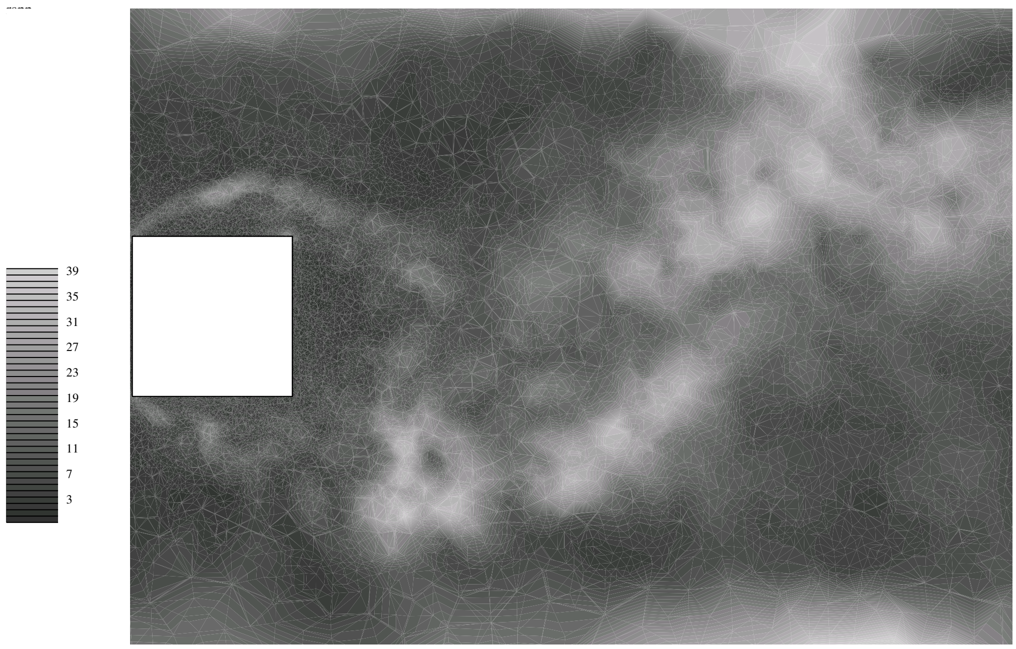

Figure 2: *LES calculation of a flow around a square cylinder: ratio between the Smagorinsky viscosity and the gas viscosity (range : 1 to 40)*

seem to validate the coupling of a LES model with a RANS wall law. This conclusion is however limited by two remarks: the CPU cost is already high, and this works today only for a Reynolds number that is rather low; further, the level of turbulent viscosity (Fig.2) illustrates the fact that we are more or less computing (not very accurately) an equivalent flow with a Reynolds number 40 times larger the physical Reynolds number.
It is then interesting to consider a coupling in which the RANS-type model is

applied in a larger part of the flow, which means that we have to extend the capabilities of RANS-type models towards unsteady flows with large organised structures.

4 Far-from-wall modelling by OES

4.1 Main features of OES

The potential of RANS-type models for unsteady flow is limited *a priori* by (a) a standard theory that does not consider unsteadiness, but, instead, a steady mean flow, and (b) the usual use of Boussinesq assumption in industrial applications, which tends to prevent unsteadiness.

We concentrate on the standard context of Organised Eddy Simulation, in

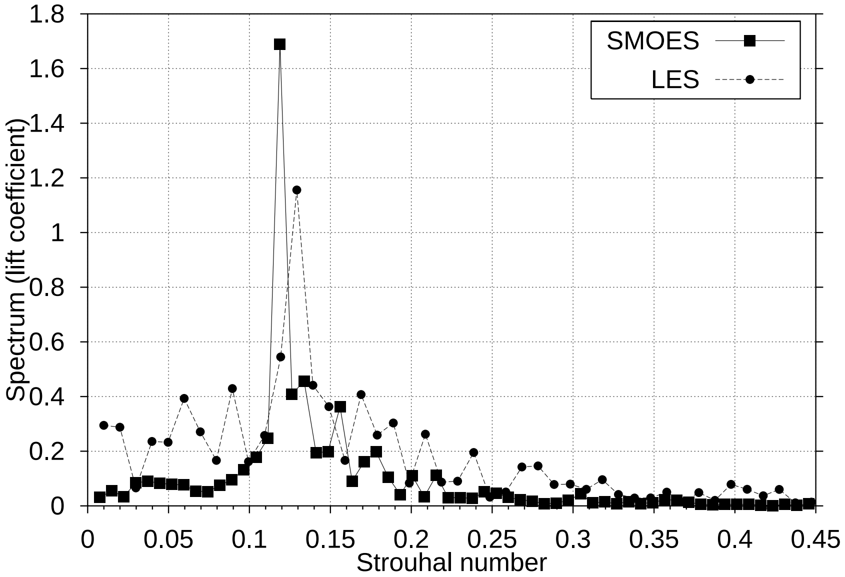

Figure 3: *Comparison of lift coefficient spectra obtained with time-averaged-OES and with LES*

which there exists an energy spectrum involving a peak concentrated on a par-

ticular frequency, allowing a pronounced quasi-periodic behavior.
This method consists of splitting the energy spectrum to one part regrouping all the organised modes and coherent motion of the flow system (e.g. the distinct frequency peaks of the spectrum) and to a second part, corresponding to the incoherent, chaotic part of the motion (e.g. the continuous part of the spectrum near the peak).
The first part of the spectrum is predictable by the unsteady operator of the Navier-Stokes equations, provided a physically suitable averaging with respect to the spectrum decomposition. This is the phase-averaging, which is a measurable quantity and not only a mathematical concept. The continuous part of the spectrum has to be modeled. This part extends from the low to the high frequency range and it is does not regroup only the high wavenumbers as in the case of LES.
Therefore, the criterion of distinction of the structures to be predicted from those to be modeled in OES is their physical nature and not their size (as in the case of LES). Based on these fundamental assumptions, OES is not intrinsically 3D as the LES.

In the time-domain, the fundamental hypothesis of OES leads to employ the decomposition of each unknown quantity in *two parts*, the one being the phase-averaging (which is a time-dependent periodic operator) and the other the random fluctuation.
Therefore the phase-averaged Navier-Stokes equations have the same form as the equations of the statistical averaging (Reynolds averaging), plus the time-dependent term. However, the physical significance of each term is totally different from the statistical averaging equations.

The property of the extension of the continuous part of the spectrum in OES from the low to the high wavenumbers precisely allows models of the incoherent motion by employing hypotheses coming from the statistical modelling of turbulence. For these reasons, OES can be very efficient for high-Reynolds number predictions. However, the present continuous spectrum does not fill a priori the conditions of an equilibrium spectrum, in the sense of the statistical Kolmogorov theory.
This comes from the main physical reason, that the externally supplied energy

is attributed not only to sustain the Kolmogorov cascade, from the large energetic eddies to the smaller ones, but essentially to sustain also the organised modes.

For these reasons, the length and time scales derived from equilibrium spectra and yielding the standard constants in the case of statistical modelling have to be entirely reconsidered in the present case of non-equilibrium spectra. This explains why OES does not have to be confused with the so-called *un-*

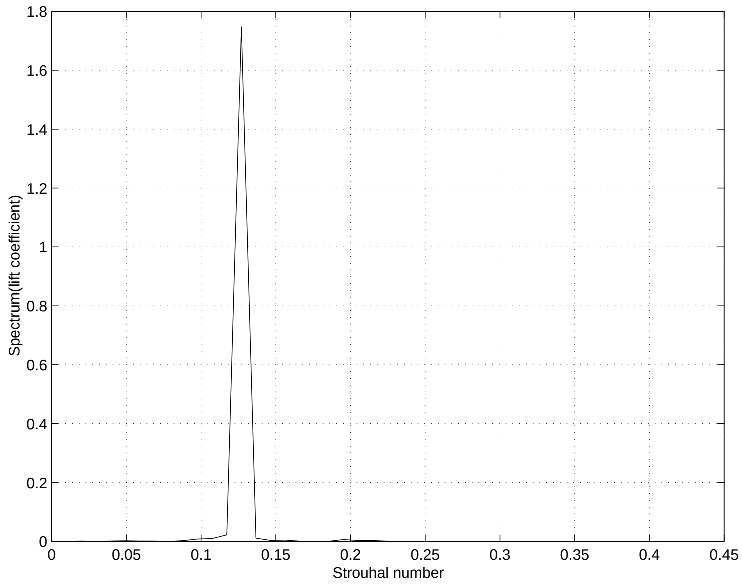

Figure 4: *Lift coefficient spectrum with improved LES*

steady RANS approach, consisting of *running* the standard Reynolds-averaged modelling in a time-marching way.

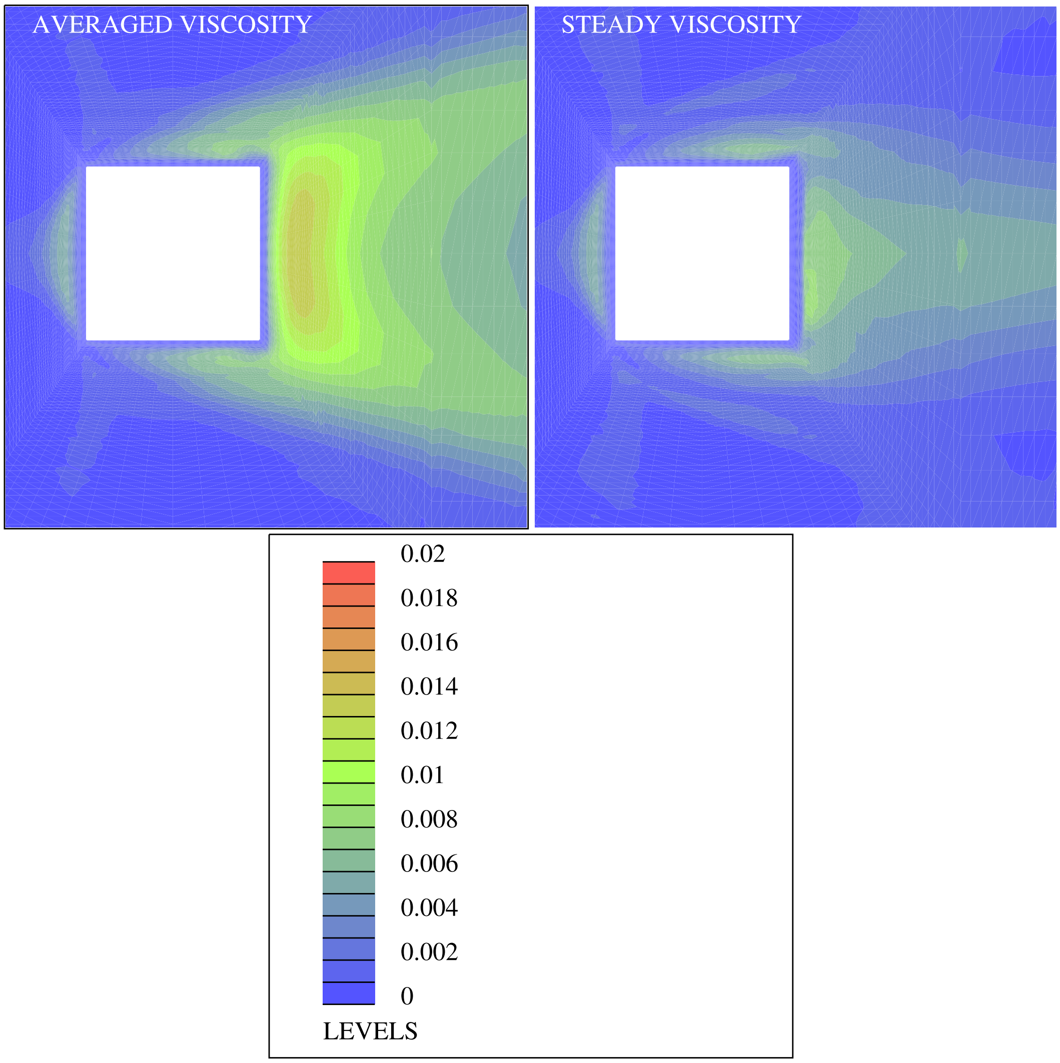

Figure 5: *Comparison of the time-averaged eddy viscosity for a quasi-periodic solution (ν_t) and of the steady eddy viscosity obtained from solving the $k-\varepsilon$ equations with time-averaged velocities (steady eddy viscosity ν_{ts})*

In order to understand the possible impact of the OES approach and its relation to RANS, we consider the decomposition of the instantaneous flow variable u into three components:

$$u = \bar{u} + \tilde{u} + u' \ , \tag{7}$$

in which $\bar{u}$ is steady, and $\tilde{u}$ is periodic.
We shall not use this three-term decomposition, for deriving a new model, because it would lead to a highly complex system. At the contrary, we suggest to consider the models derived from the two-terms decompositions.

For statistical modelling, the average is $\bar{u}$, that is a steady flow. In phase averaging, the average is $\bar{u} + \tilde{u}$, a periodic flow. The averaging processes of both theories lead to essentially to two versions of the same basic model, e.g. $k - \varepsilon$ for their averaged flows. In each of these versions, a turbulent energy accounts for the part of the flow that is not in the average flow.
If we consider the energy spectrum of the flow at any point of the flow domain, it appears that the turbulent energy of the steady (RANS) closure is the sum of the analogous one for phase-averaging OES closure with the energy of $\tilde{u}$. As a consequence, the OES energy should be smaller than the RANS one, and the corresponding turbulent viscosities should also satisfy this inequality.
One *a priori* advantage would be that unsteadiness would be more easily captures by such OES models.

4.2 An analysis of the triple decomposition

We examine again the square cylinder case. As observed in Sec. 2.5, the RANS model produces a rather good (and periodic) prediction of u_1.

Then $\bar{u}$ can be estimated by a *time averaging* , which consists in:
- estimating the period,
- computing $\bar{u} = \int u_1 dt$ over the period.

Then a new k_{ts} and a new ϵ_{ts} can be derived from a *steady* closure, and thus a steady ν_{ts} is derived, that would be identical to ν_t in case where amplitude of the unsteadiness would be very small.

A numerical calculation [2] shows that the steady turbulent viscosity ν_{ts} deduced from time averaging is smaller than the usual one by a factor between two and three in regions of unsteadiness, while, as expected, it keeps the usual value in other regions. We illustrate this in Figure 4, in which distribution of (a) the average of unsteady RANS turbulent viscosity and (b) the steady turbulent viscosity produced by the above method are plotted near the square cylinder.

It is then interesting to FFT analyse the lift coefficient (Fig.3). In the case of an usual RANS $k-\varepsilon$ model, the flow is essentially periodic, so that only one frequency appears. In the case of an LES calculation, the spectrum can be widely expanded around the main frequency. In a more recent work, depicted in Fig.3, the LES calculation has been improved and its time extended in order to reach a very organised spectrum: only very low energy is contained at a different frequency from ($St \simeq 0.2$), a figure closer to the OES result, and to experiment. In particular, the proposed OES model prediction is well situated inside the interval of the more expensive LES predictions.

4.3 OES modelling from RSM

As already noted, the above calculation ie made possible because the RANS model performs well in predicting the unsteadiness; the main output, proposing a 2-3 times smaller viscosity is coherent with many known results.

The Reynolds Stress Transport (RSM) modelling (second-order closures) are not submitted to the restrictions of the Boussinesq approximation, and the solution of individual equations for the phase-averaged stresses provides an improved prediction of the normal stress anisotropy in the near wall region. Therefore, they are very suitable in the context of OES, for the prediction of the present category of unsteady flows, of a priority interest in the Aeronautical industry nowadays. Studying their application has been undertaken by IMFT in the last five years.
However, the implementation of RSM in OES includes a high number of transport equations and the unsteady character of the flows may lead to a heavy task to be carried out by the Aeronautical industry. For these reasons, we present a way to adapt the C_μ coefficient for the more popular two-equation

models (in this case the $k - \varepsilon$ model), coming from the RSM modelling.

We precise that the RSM modelling used here is applied up to the real wall and not only in an outer region as it is usually done in a *zonal* RSM, where a first order closure is employed near the wall. That simplification, largely adopted to facilitate numerical convergence, would make lost of all the benefits expected by RSM with respect to the normal-stress anisotropy. Despite the difficulties of convergence in absence of the *beneficial* eddy-viscosity, this study has been carried out in the whole region around the obstacle, by employing adapted damping functions for RSM, coming from Shima's study ([39]) . The Gibson & Launder version ([38]) of RSM is adopted in the outer region.
Beyond the benefits of eddy-viscosity free assumptions, the RSM closures provide a much more physical modelling continuous part of the spectrum than the first-order closures, because the modelling hypotheses are done at the level of the third correlation terms and not at the level of the second correlation ones. This yields a much more universal character for the modelling of the continuous part of the energy spectrum.

The C_μ scaling is derived as follows: the computation of the whole phase-averaged Reynolds stress tensor gives access to its normal stress components (whose sum provide the phase-averaged kinetic energy and the RSM modelling computes also the ε equation).
After computation over more than twenty periods of the fundamental mode, the time-averaging of the turbulent kinetic energy and of the dissipation rate are provided by post-treatment of the time- dependent, phase-averaged results.

As an example, the flow around a NACA0012 airfoil at high angle of attack (20^0) is considered, at Reynolds number 10^5. The experimental results are those of the group *Aerodynamique Subsonique Instationnaire* of LABM, in Marseille (Favier *et al.* [18]). The experiments measure directly the phase-averaged quantities.

In that case, the $k - \varepsilon$/OES model involving Chien damping functions in the near-wall region, and with standard C_μ value 0.09 fails completely in producing a separation or vortex shedding.

The RSM/OES model provides a physically correct transition from the laminar upstream boundary-layer region to the turbulent downstream one.
The $k-\varepsilon$/OES with standard constants values damps this transition and provides a fully turbulent attached boundary layer, even in the leading-edge region, due to the excessive diffusion scaling, as explained above.
Fig.6 presents the efficiency of the RSM/OES to provide the unsteady separation and vortex shedding downstream, with respect to the amplification of a von Karman instability, in accordance with the physical experiment. The frequency of the oscillations (Strouhal number) is 1 in dimensionless values.

The values of an equivalent eddy-diffusion coefficient evaluated as specified in the previous paragraph are presented in Table 2. A suggested order of magnitude of this value is 0.02. This order of magnitude is close to the one derived by the iterative procedure at INRIA for a strongly detached and unsteady flow around a square cylinder and also by experimental studies by Aubrun *et al.*[4] in a mixing layer with coherent structures and by numerical studies by Kourta in a backward facing step flow (private communication).

When the new value of C_μ is applied, separation and vortex shedding are predicted correctly. Fig.7 shows the development of the coherent structures in the wake, through the vorticity field.

5 Conclusions and Discussion

The contribution of this short review is twofold.
Firstly, we have brought some preliminary elements for the qualification of a $k-\varepsilon$ model with Reichardt law and Menter correction, for being the basic ingredient of a RANS-LES approach for the capturing of organised and rather large eddies, with an industrial-type numerical technology.

Secondly, we have presented some arguments pointing out that RANS-LES blending can be replaced by OES-LES blending with the benefit of restricting

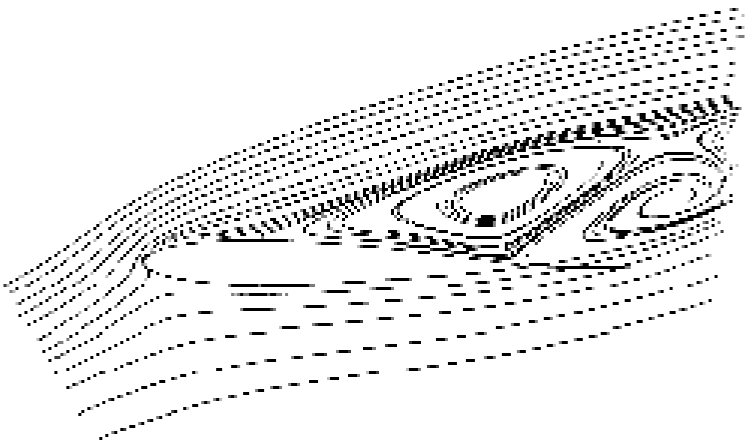

Figure 6: *RSM-OES: unsteady separated flow*

Figure 7: *K-EPS-OES with new C_μ: unsteady separated flow*

the "large eddies capturing" to the capture of a smaller number of organised and energetic structures, at a much lower computational cost.

One key approach is the computing of a time average of the flow, in order to apply the steady RANS methodology. This produces the "time averaged RANS model", in which the turbulent viscosity is time independant.

Our arguments are summed up now.

x/C	y/C	C_μ équivalent
0.036	0.032	0.0158
0.45	0.057	0.01859
0.9064	0.015	0.01938
1.41	-0.678	0.0178
1.23	0.11	0.0172
0.73	0.19	0.024

Table 2: C_μ *table as resulting from RSM*

In OES, a smaller part of the spectrum is modelised; this corresponds to a smaller energy; therefore it is natural to expect that the OES turbulent viscosity be smaller that for steady RANS. We have illustrated that, on the contrary, usual URANS involve larger amount of tubulent viscosity than steady RANS. The proposed time-averaged RANS model should then be considered as an *upper bound* to the turbulent viscosity to be applied in OES.
One way to even lower this viscosity level is to measure the energy of the organised structure and to take it into account in a correction of the time-averaged RANS viscosity in order to obtain a lower -still steady- OES turbulent viscosity.

A variant consists in designing the C_μ viscosity coefficient from the time averaging of Reynolds stresses and then apply a OES model with unsteady turbulent viscosity.

The above process needs to start from an unsteady flow calculation. In some case (our first example), an unexpansive two-equation URANS is able to provide it, in some other case (second example), it produces only a steady solution. An unsteady flow can be seeked either with a more sophisticated URANS, or a first attempt in OES by lowering the C_μ. This applies to only one flow at a time. A strategy using as a first calculation an LES or a DNS is reserved to method analysis, and not to industrial case solving.

Further experiments are still mandatory for the consolidation of the presented study and are the object of current investigations.

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Unité de recherche INRIA Sophia Antipolis
2004, route des Lucioles - B.P. 93 - 06902 Sophia Antipolis Cedex (France)

Unité de recherche INRIA Lorraine : Technopôle de Nancy-Brabois - Campus scientifique
615, rue du Jardin Botanique - B.P. 101 - 54602 Villers lès Nancy Cedex (France)
Unité de recherche INRIA Rennes : IRISA, Campus universitaire de Beaulieu - 35042 Rennes Cedex (France)
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