# Attached and Detached Eddy Simulation

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ADES is not a new concept, but it represents a significant evolution from the original, or "Natural" DES concept (NDES), and we believe it could become widespread and the basis for turbulence treatment in most high-Reynolds-number applications once the computing power is sufficient. Therefore, its potential and the likely difficulties inherent in it deserve a detailed discussion.

## Motivation for ADES

The A in ADES could also stand for "Anticipated." The idea is to initiate Large-Eddy Simulation (LES) in the boundary layer, rather than letting it develop after separation, as in NDES. The motivation is pessimism regarding the possible accuracy of Reynolds-Averaged Navier-Stokes (RANS) turbulence models in non-simple boundary layers and separation bubbles. The original motivation for DES was a similar pessimism about RANS models in massively-separated flows, a pessimism which now appears to be a matter of consensus. For instance, very few people hope to accurately compute the flow past a circular cylinder as fully time-averaged, or even with Unsteady RANS (URANS) which resolves the vortex shedding but only the largest of eddies. The HRLM community agrees that the separated regions require LES (even if only mean forces are needed), meaning that the simulation is chaotic, with a wide range of resolved scales, limited only by the grid spacing.

This is achieved by NDES, but two weaknesses are known. First, the location of the separation point is still controlled by the RANS model, which is of course far from perfect. Second, the development of resolved eddies starting from a RANS layer after separation or even in a mixing layer suffers from "grey area" phenomena, and tends to be too slow and grid-dependent. Separation bubbles are especially irksome. Effective remedies have been found by reducing the grid length scale and therefore the eddy viscosity in a non-zonal manner, but it is also common to inject synthetic turbulence which is a zonal approach. This could be called Stimulated DES, and it represents a clear departure from NDES. NDES has the advantages of being non-zonal and very simple to formulate, in one line, but the field is moving away from that simplicity.

ADES in a sense is the opposite of Delayed DES (DDES), a useful concept in which inaccurate modeling is prevented in boundary layers with ambiguous grids (grid spacing between RANS and LES), by steering the model to RANS. This is logical, and DDES is considered the "standard" non-zonal version of DES, but again it places all the responsibility for separation on the RANS model.

The position shift mooted here is that we would abandon RANS models not only for massively-separated regions, but also for any challenging region in a boundary layer. Shock-induced separation would be a prime example. We would admit the existence of a "glass ceiling" for accuracy in RANS, which is not high enough, now that we are well into the 21$^{st}$ century and the trend for progress in RANS models is almost imperceptible. In particular, Reynolds-Stress models are becoming more accessible, but not more logical or well-understood, and they are not delivering higher accuracy than modern simpler models "automatically," as could have been expected.

The pressure on RANS models and turbulence treatments in general is mounting because grid convergence is now within reach for simple wings, and is becoming conceivable for complex configurations such as airplane high-lift systems, especially if we assume automatic unstructured grid adaptation flourishes. This will leave the turbulence errors as the dominant source of inaccuracy.

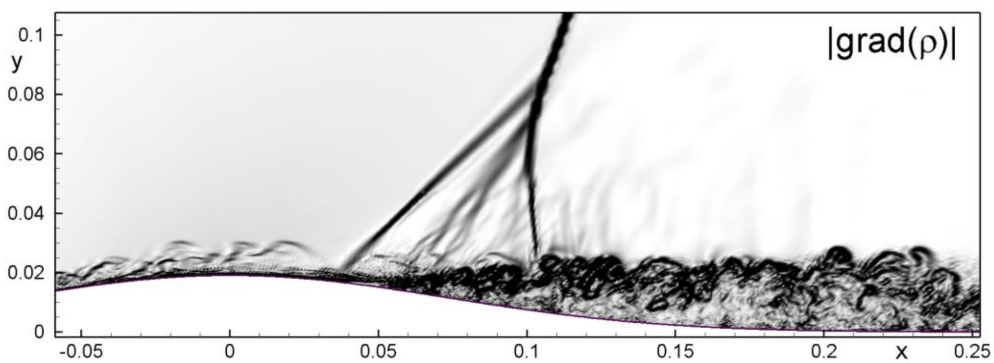
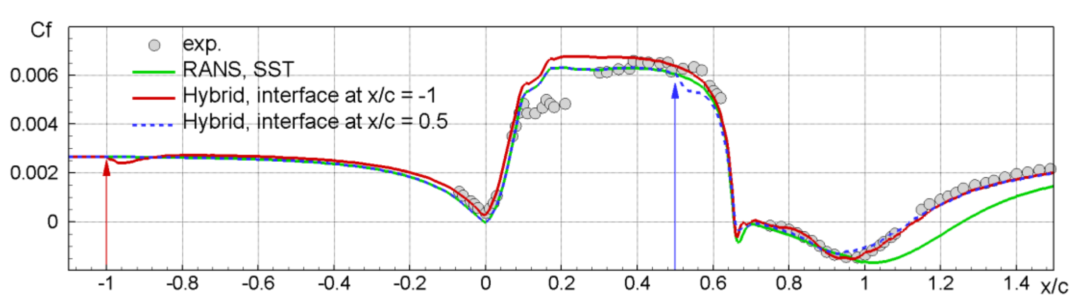



Figure 1. Wall-Modelled Large-Eddy Simulation of a transonic Gaussian bump (NTS work).

Figure 1 visualizes the concept as it applies to shock-induced separation, and Figure 2 illustrates a definite quantitative success of Wall-Modelled LES, in a similar flow which has defeated even the best RANS models.



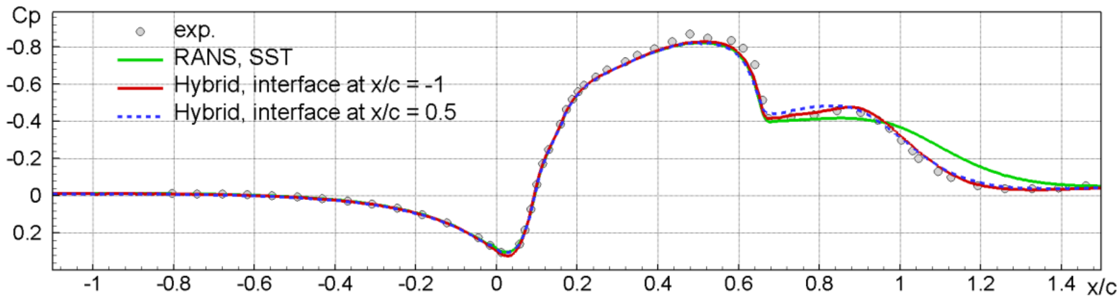



Figure 2. Skin friction and pressure distributions over the NASA hump. Comparison of RANS and (effectively) ADES.

We need to position ADES relative to pure LES, which some groups claim is ready for application at flight Reynolds numbers. We are considering the large-airplane problem as most valuable; it is possible that gas-turbine problems have Reynolds numbers which allow pure LES, but we doubt if even ground transportation or wind turbines do. The reasoning, from the 1997 DES paper, is well-known. Assuming Wall Modelling is successful (WMLES), each cube of the boundary layer will demand a given number, say $N_0$, of grid points. The value of $N_0$ will be debated, but for good accuracy, it seems that $32^3$ would be a plausible minimum. The number of points is then $N_0 \times N_{cubes}$, where $N_{cubes}$ is the number of cubes needed to fill the boundary layer, and is (assuming perfect grid generation) the integral of $1/\delta^2$ over the surface, where $\delta$ is the boundary-layer thickness. This quantity is shown over the CRM wing at flight Reynolds number, with a *turbulent* attachment line (and therefore a thicker boundary layer there than if it had been laminar).

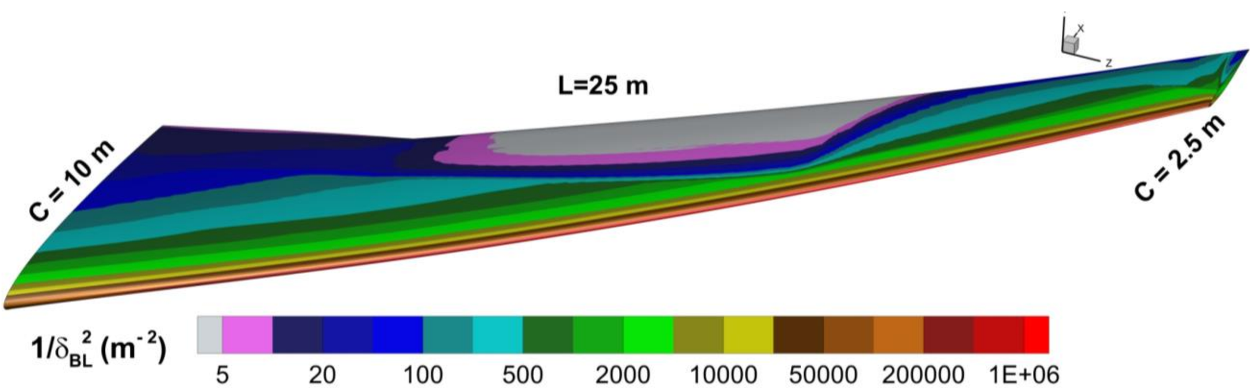



Figure 3. Contour plot of $1/\delta^2$ over the surface of the Common Research Model. Notice the exponential scale for contour levels (NTS work).

The figure has two striking features. First, the integrand takes very large values, nearing $10^6/m^2$. This is over a band of area roughly $10m^2$ for the full wing, leading already to $N_{cubes}$ in the 25-million range, and roughly $10^{12}$ points, minimum. This is not doable today, and with the recent trend to a saturation of Moore's law, the estimate we made around 2000 that it would be doable in 2045 is probably too optimistic. In other words, practical methods will be RANS-LES hybrids (and the HRLM workshop has a bright future).

The second feature is how rapidly of $1/\delta^2$ falls, away from the attachment line. By the 10% chord line, it is down by a factor of 500, and therefore the local cost of LES has become manageable (in addition, the time step is proportional to the grid spacing). Based on $1/\delta^2 \sim 2000/m^2$ and a wetted area of $600m^2$, $N_{cubes}$ becomes about 1 million, and the grid count if $32^3$ is sufficient is $4*10^9$, which is in the "grand challenge" range. The hybrid simulation is possible, with a zonal approach combining RANS in the very thin region and WMLES for the rest. Again, this is not a new concept, and our purpose here is not to impose the name ADES upon it. Embedded LES is also descriptive.

A fortunate feature of this strategy is that the regions of the boundary layer that are treated by RANS are relatively easy to predict, often having favorable pressure gradients; also, by nature the thinnest regions have the weakest pressure gradients, if the gradient is normalized by the skin friction and the thickness. In other words, the remaining demands on the RANS model are fairly low. In addition, a model that is active only in boundary layers could be calibrated specifically for such flows, forsaking good performance in free shear flows.

## Prospects for ADES

While very plausible, this strategy leads to at least two questions, both difficult: first, the logistics of implementing ADES, especially in an industrial context. Second, the probability of truly "breaking the glass ceiling" RANS has in terms of accuracy, and/or the resolution required to achieve that.

The implementation as a reliable and non-expert-user engineering tool will require many non-trivial achievements and, in simple terms, much artificial intelligence. The system has not only grid sequencing, but "turbulence treatment sequencing." Preliminary steady (possibly not fully converged) RANS solutions will be obtained, to establish the inviscid part of the flow, and the trailing vortices. This must be done with acceleration to steady state, rather than at the low speed of (time-accurate) WMLES. These solutions will involve automatic grid adaptation, including the important task of matching the region with RANS or LES resolution to the boundary layers and to the turbulent wake layers and vortices. Based on the boundary-layer thickness, the system will then set the RANS and the LES zones, and generate grids accordingly. These will not be ambiguous. A Synthetic Turbulence Generator will be installed along the RANS-LES interface, and needs to produce rapid transition from modelled to resolved turbulence with almost no gap in skin friction. All these steps need to be robust, and free of specific user inputs, while providing clear information in post-processing, such as marking the RANS and LES regions on the surface.

Another difficulty will appear when the accurate solutions move the shock, or the separation line and wakes, to a place different from that predicted in the preliminary solutions. The system will need to adapt the grid again. In extreme cases, separation could appear where it did not at first, or else disappear, causing large-scale changes in the flow, so that the re-adaptation would be extensive. In summary, this approach to turbulence will be very involved, but we have failed to envision any simpler one that would have the same ultimate potential.

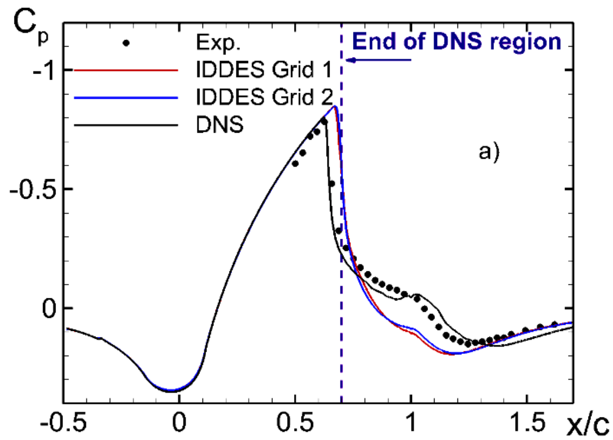



Figure 4. Pressure distribution for Bachalo-Johnson flow. LES Grid 1, $4.7 \times 10^8$ cells; LES Grid 2, $1.6 \times 10^9$ cells; DNS grid, $8 \times 10^9$ cells (NTS work, ETMM11 symposium).

The accuracy question is also daunting. Just like Reynolds-Stress models have so far denied the hopes for "automatic" improvement over simpler RANS models, could WMLES fail to reward all our efforts and "logical" expectations?

In Figure 4, we show a current example of this possibility, in results we just presented at the ETMM11 symposium. The Bachalo-Johnson flow contains shock-induced separation over an axisymmetric bump, and has been a primary validation case since the 1980's. WMLES gives inaccurate shock positions and post-shock pressure distributions, even though it was conducted on two grids, with a large number of points and with quite a significant difference between the two. Grid refinement, which normally is discriminating for LES, gives no warning that the solutions are not very accurate. Grid 2 has about $5 \times 10^5$ points in a cube of boundary layer, which is far larger than $32^3$, and therefore the resolution is not marginal by any standard. DNS with the same code, and a reduced domain size, agrees much better with experiment. Auxiliary tests show that the flat-plate boundary layer is simulated accurately on a similar grid at the same Mach and Reynolds number, leaving the pressure gradient as the likely cause of the discrepancy. Unfortunately, LES was supposed, precisely, to accurately render the effects of pressure gradients and compressibility once the grid was fine enough.

Of course, the SGS and Wall Models used are only one of many available, and we are hoping for competing studies in the near future, but the results of this exercise are worrisome. A possibility is that safe grid resolutions for LES even with wall modelling will turn out to be very costly, say of the order of $10^6$ for each cube, rather than $10^4$ to $10^5$ as some observers are hoping. Whether for RANS or LES, testing in simple flows, even at high Reynolds number, can be misleading.

In summary, we have named ADES and discussed a turbulence CFD strategy which extends DES in that it begins with RANS and leads to LES, but initiates WMLES in the boundary layer as soon as it is thick enough. We believe such an approach will impose itself due to the realities of turbulent shear layers at high Reynolds numbers and the well-known weaknesses of both RANS and LES, but we also pointed out how complex it will be to implement, and how much remains to be learned about the grid resolution which will be needed to reach the desired level of accuracy.