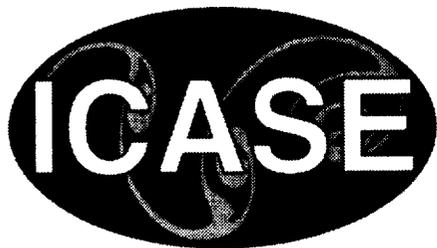


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Turbulence Modeling Workshop

Edited by

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March 2001

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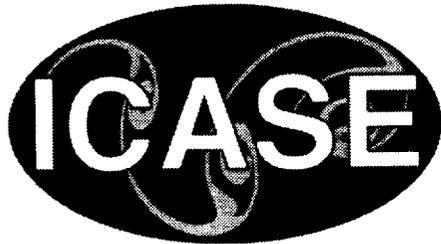
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TURBULENCE MODELING WORKSHOP

EDITED BY R. RUBINSTEIN¹, C.L. RUMSEY², M.D. SALAS³, AND J.L. THOMAS⁴

Executive Summary. Advances in turbulence modeling are needed in order to calculate high Reynolds number flows near the onset of separation and beyond. To this end, the participants in this workshop made the following recommendations. (1) A national/international database and standards for turbulence modeling assessment should be established. Existing experimental data sets should be reviewed and categorized. Advantage should be taken of other efforts already underway, such as that of the European Research Community on Flow, Turbulence, and Combustion (ERCOFTAC) consortium. Carefully selected “unit” experiments will be needed, as well as advances in instrumentation, to fill the gaps in existing datasets. A high priority should be given to document existing turbulence model capabilities in a standard form, including numerical implementation issues such as grid quality and resolution. (2) NASA should support long-term research on Algebraic Stress Models and Reynolds Stress Models. The emphasis should be placed on improving the length-scale equation, since it is the least understood and is a key component of two-equation and higher models. Second priority should be given to the development of improved near-wall models. Direct Numerical Simulations (DNS) and Large Eddy Simulations (LES) would provide valuable guidance in developing and validating new Reynolds-averaged Navier-Stokes (RANS) models. Although not the focus of this workshop, DNS, LES, and hybrid methods currently represent viable approaches for analysis on a limited basis. Therefore, although computer limitations require the use of RANS methods for realistic configurations at high Reynolds number in the foreseeable future, a balanced effort in turbulence modeling development, validation, and implementation should include these approaches as well.

Key words. turbulence, high Reynolds number, separation, modeling, DNS, LES

Subject classification. Fluid Mechanics

1. Introduction. In 1996 John Lumley summarized the importance of turbulent flows and our ability to calculate them as follows. “Rational design of aircraft, automobiles, nuclear reactors and all sorts of industrial mixing and forming process, ... are dependent on an ability to calculate the effects of turbulent transport reliably. Unfortunately, we cannot do that. One hundred years of intense effort have brought us very good qualitative understanding of turbulent flows in nearly all practical respects, but have not brought us the ability to calculate reliably.” [1] While this view by Lumley is correct, there has been considerable progress in the calculation of turbulent flows for some restricted classes of flows. The December 1999 report of the Airframe Systems Subcommittee of NASA’s Aerospace Technology Advisory Committee (ASTAC) concluded that while great success has been achieved with computational fluid dynamics in accurately predicting attached flow, current turbulent modeling capabilities are unable to reliably predict separation onset. Indeed, the report considered

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separation onset as presenting a greater challenge than dealing with massively separated flows. This is perhaps a debatable conclusion (see Bradshaw's presentation in Appendix C). In order to assess our current capabilities and future needs for accurate computations of high Reynolds number turbulent separated flows at flight conditions, a turbulence-modeling workshop was held in Reno, Nevada on January 12-13, 2001. The workshop was sponsored by NASA Langley Research Center (LaRC) and organized by ICASE. Approximately 40 technical experts, covering a wide range of knowledge, were invited to participate. Ajay Kumar, representing NASA LaRC, opened the workshop by establishing its purpose and the expectations he had from the workshop participants. Mark Anderson, Chair of the Airframe Systems Subcommittee presented the committee views on current capabilities and shortcomings of turbulence modeling. Later that morning and early afternoon, five summary talks were presented. Philippe Spalart, Boeing, Brian Smith, Lockheed Martin Aeronautics, and Thomas Gatski, NASA LaRC, presented their own perspectives of the state-of-the-art in turbulence modeling, emphasizing high Reynolds number separated flows.⁵ Katepalli Sreenivasan, Yale University, gave an overview of the physics of this flow regime and Roger Simpson, Virginia Tech, spoke about issues associated with experimental methods. The rest of the workshop was planned around group discussions by the attendees. In order to provide some structure to the discussions, the following three topics were chosen:

- a) turbulence modeling for vortical flows,
- b) turbulence modeling for time dependent separated flows, and
- c) turbulence modeling for juncture and mixing flows.

However, the three topics were not intended in any sense to limit the discussion. The 40 participants were divided into three groups and each group was asked to discuss the adequacy of current turbulence models, experimental difficulties, numerical issues, and alternative approaches as they related to the three topics above. This document summarizes the results of the workshop.

The organization of this document is as follows. In Sections 2 through 4, summaries of the discussions held in each of the three groups are given. These summaries are broken into the following subsections: importance of the modeling of turbulence, assessment of current methods, directions for improvement of turbulence models, and conclusions and recommendations. Section 5 gives final overall conclusions from the workshop, including an assessment of current methods and recommendations for future development. The appendices include an agenda from the workshop, a list of participants, and a copy of the workshop presentations.

⁵A fourth talk by Peter Bradshaw was planned, however Bradshaw was unable to attend the workshop. His slides are included in Appendix C.

2. Group I – Summary Findings and Recommendations. Facilitators: C.L. Rumsey (LaRC) and J.B. Anders (LaRC)

2.1. Importance of the Modeling of Turbulence

2.1.1. Vortical flows. The following list gives examples of different types of vortical flows of interest to the aeronautics/aerospace community:

- Wing tip vortex
 - Interaction with tail
 - Far downstream
- Chine vortex
 - Interaction with wing boundary layer, including pressure gradient effects
- Strake
- Vortex bursting
- Fuselage at high alpha and ogive cylinder
- Vortex generators in boundary layer
- Internal vortices (separation)
 - Including vortex breakdown
- Vortex instabilities
- Flap/junction vortex
 - Mixing enhancers (Chevrons) on engines

Most vortical flow types on this list fall into one of the following categories: free shear flow or vortex/boundary layer interaction. Free shear flow is generally easier to compute, but also tends to be less important from the point of view of the aerospace industry (in other words, unless a free vortex comes near a surface, it is not so important to compute it accurately for aircraft design). For example, computing wing tip vortices accurately can be important when they impinge upon or come near a downstream body (horizontal tail, following aircraft). The chine is a protuberance on the outside of the engine nacelle that generates a vortex that can interact with the wing boundary layer. The strake (sometimes called strakelet) is a leading edge piece near the wing-body intersection on some fighter aircraft, for example, that creates a vortex that passes back over the body and can interact with the wing, body, or tail boundary layer. Strake vortices on fighters have been associated with vertical tail buffet (vortices that burst induce unsteady loads on the vertical tails as they pass near).

It can be more instructive to redefine the above list in terms of physical categorizations, as follows:

- Free vortex zero pressure gradient (ZPG)
- Free vortex with pressure gradient
- Free vortex with and without axial flow
- Vortex interaction with boundary layer (BL), with and without separation
- Vortex interaction with shock
- Interacting vortices (co-rotating and counter-rotating)
- Smooth body cross-flow separation

This physical categorization gives a broader representation of the types of vortical flows that can occur. Predicting vortex details is not always important from the point of view of the aerospace industry. It depends on the case, and tends to be more important when there is an interaction of a vortex with a downstream surface. An example was given from Boeing for which loads and moments were accurately predicted in spite of the Spalart-Allmaras (SA) turbulence model (which adds too much eddy viscosity in the vicinity of vortices) diffusing the vortex prior to the vortex interaction with the tail. Also, it is important to note that engineers in the aircraft industry are often looking for accurate predictions of *trends*, and not absolute levels. On the other hand, the prediction of absolute levels of drag is critical to airplane manufacturing and represents one of the most difficult challenges in the aerospace industry.

Generally, Reynolds number is not too important in turbulent free shear flows. However, for free vortex flows, the Reynolds number of the vortex-forming device affects the initial vortex formation. If there is turbulence decay in a vortex, then viscous transport becomes more important. Far downstream, as the flow becomes quasi-laminar, the Reynolds number becomes important.

2.1.2. Separated/time-accurate flows. The category of separated/time-accurate flows can be broken down into several physical categorizations:

- Curvature (response to normal straining) and pressure gradient
- Unsteady (hysteresis, time lag)
- Post-separation physics
- Post-curvature physics
- 2-D smooth separation
- 3-D smooth surface separation
- 2-D shock-induced separation
- 3-D shock-induced separation
- Vortex/BL interaction

Most separated flows can be categorized in terms of one or more of these physical categories. In addition to pressure gradient effects, curvature can affect separation location from a smooth body. Convex surface curvature

reduces turbulence whereas concave curvature enhances turbulence. Beyond a separated region, a flow may reattach and “recover” from separation. This post-separation physics is often important to compute accurately. For example, it is often possible to predict shock location on a wing correctly, but if there is shock-induced separation, its extent and possible reattachment location downstream are often not predicted well. Post-curvature physics refers to recovery downstream of curvature. Smooth surface separation and shock-induced separation are of particular interest to the aerospace community, because of the frequent occurrence of these flow types for aerospace vehicles.

During this discussion, the issue of Reynolds number scaling was brought up. The comment was made that there is no evidence to suggest that Reynolds number scaling is a turbulence modeling issue.

2.1.3. Juncture and mixing flows. Other types of flows (for example, jets and mixing layers) are probably far more important than that of juncture flows from the point of view of the aerospace industry. Accurate computation of secondary vortices is probably not important for most typical industrial needs. A prioritized list of flows of importance for turbulence modeling is presented in the Conclusions and Recommendations section below.

2.2. Assessment of Current Methods

2.2.1. Vortical flows. Often, the problem with capturing vortex interaction effects has less to do with the turbulence model than it does with lack of grid refinement in the region where the vortex exists. In this regard, automatic grid refinement or adaptation (putting enough grid in the right place) might go a long way toward helping to achieve more accurate vortical flow computations.

Nonetheless, many existing turbulence models are deficient for turbulent vortical flows. To get the details right, a turbulence model needs to correctly represent the relationship between stress and curvature. Many models, particularly eddy viscosity models (EVM), cannot do this well. Many models erroneously produce eddy viscosity in the vicinity of free vortices, which causes the vortices to be excessively diffused above and beyond the effects of insufficient grid resolution.

A general “Pros and Cons” list for turbulence model types is given here, as related to vortical flows (“- (minus)” indicates con, and “+ (plus)” indicates pro):

- EVM - too diffusive
- EVM+suppression + suppresses diffusion
 - not necessarily at the correct rate ($v'w'$ radial vs. $u'v'$ axial)
- ASM/EASM - needs curvature correction
 - + represents normal stress differences
- RSM - cost/robustness
 - + can reproduce correct behavior
- LES/DES - cost
 - + should correctly predict any free shear flow
(no consensus on this “pro” statement)

Key: EVM=eddy viscosity model, EVM+suppression indicates eddy viscosity models with one of many available simple fixes that make the model “turn off” within vortices, ASM=algebraic stress model, EASM=explicit algebraic stress model, RSM=Reynolds stress model, LES=large eddy simulation, DES=detached eddy simulation.

Based on the breakdown of vortical flows into physical categorizations given earlier, a table is presented here to list the model types that are capable of solving each category. Note that this table should be viewed as a framework only. The group did not have the time or all the information necessary to adequately complete it. A question mark was used when there was some uncertainty. For example, if a model type has been validated only for a single specific case (and some uncertainty as to the model’s validity remains) then that model was assigned “Y?”. Similarly, limited success in a validation earned a “Y?” and a belief that a model *should* be capable in spite of its not yet being validated also earned a “Y?”. The two items with “N / Y?” are labeled as such because of differing opinions given by members of the group.

Note that DES should work for all cases except boundary layer interaction. The other flows are all free shear flows, for which DES defaults to LES. And for any free shear flow, LES should yield good results on a sufficiently fine grid, regardless of the Reynolds number (assuming that the spectral content of any inflow boundary condition is known, or that the spectral content is not important).

TABLE 2.1

	EVM	EVM with suppression	ASM/EASM	RSM
A. Free vortex with zero pressure gradient	N	Y	Y	Y
B. Free vortex with pressure gradient	N	Y?	?	Y
C. Free vortex with and without axial flow	N	?	?	Y?
D. Vortex interaction with BL (with and without separation)	N / Y?	Y?	Y with tweak	Y
E. Vortex interaction with shock	N	?	?	Y?
F. Interacting vortices (co-rotating and counter-rotating)	N	?	?	Y?
G. Smooth body cross-flow separation	N / Y?	Y?	?	Y?

The fixes used in “EVM+suppression” models (tuning to be sensitized to a curvature parameter such as Richardson number) may work well for vortices in which straining in the stream-wise direction is relatively weak. However, they do not work in general for vortices interacting with a boundary layer. Also, in more complex environments (such as in adverse pressure gradients, in the presence of additional shear, when there is significant stream-wise strain, or when there are circulation changes) these simple fixes may not work either. An example of one such complex flow is an internal flow in which the shear stresses decay rapidly, but the normal stresses do not, so a nearly isotropic turbulence results downstream. In this region, the turbulent kinetic energy is fairly high.

“EVM+suppression” may get the representation of the shear stresses right, but it will not be able to compute the high turbulent kinetic energy.

As seen in Table 2.1, RSM is the lowest order model that is generally capable of solving *all* of the above seven flow categories, even though some modeling of terms is required. If a model provides the correct relationship between stresses and strains (as implied in the exact Reynolds stress transport equation), then that model should be able to yield a good representation of vortices. One pays a price each time a simplification to the equations is made. For example, in simplifying from RSM to ASM/EASM, assumptions are made regarding the diffusion term and the convective terms for the stresses, which can lead to misrepresentation in certain circumstances. The diffusion term can be important in the region of the centerline of the vortex. However, ASM/EASM does capture the interaction between stresses and strains as embodied in the stress generation terms.

In general, there has not been enough CFD validation on many of the above seven flow categories. However, validation requires either experimental or full simulation (LES/DNS) data. There are many experimental studies that include vortical flows, but the group participants knew of only two direct numerical simulation (DNS) studies in this area (both DNS studies are unpublished Ph.D. theses). Clearly, this is an area that could use some additional attention. Many of the existing experimental data are very old (for example, Langley facility data). Also, many experimental datasets have been taken for delta wings, including vortex breakdown. A thorough survey of existing data and its relevance and quality would be helpful.

2.2.2. Separated/time-accurate flows. Using the physical categorizations for separated/time-accurate flows given earlier, the following table lists the model types that are capable of solving each category. As with the table above, this table should be viewed as a framework only. Question marks indicate uncertainty, and boxes with both N and Y indicate differing opinions offered by the group.

Note that post-separation physics and post-curvature physics stand out as a challenge to most models, including RSM. For shock-induced separation, models often can get the shock location accurately, but the separated region itself (downstream of the shock) may be poorly predicted. This behavior is case-dependent. It may in part be related to post-separation physics.

In attempting to assess the capability of existing turbulence models for separated/time-accurate flows, it is often difficult to separate whether poor predictions are due to turbulence modeling or other issues. For example, transition is often a big problem; if the transition region is unknown in the experiment, then comparing using fully turbulent CFD can cause discrepancies. Aeroelasticity, if not accounted for, can also lead to discrepancies.

Often a given experiment is too complex to be helpful toward isolating specific failings of turbulence models. For example, the trapezoidal wing experiment will likely be useful for validation, but is not simple enough for improving turbulence models. Simple unit problems are most useful for isolating specific failings of turbulence models and guiding modelers toward improvements. (Unit problems isolate a *specific* aspect of turbulence and are also usually geometrically simple so they remove geometric fidelity considerations from the CFD modeling, and are easier to grid-converge.)

TABLE 2.2

	EVM	EVM + fixes	ASM/EASM	RSM
A. Curvature (response to normal straining) including pressure gradient	N	N/Y	Y	Y
B. Unsteady (hysteresis, time lag)	Y	Y	Y	Y
C. Post-separation physics	N	N	N	N/Y?
D. Post-curvature physics	N	N	N	N/Y
E. 2-D smooth surface separation	N/Y	Y	Y	Y
F. 3-D smooth surface separation	N	N/Y	Y	Y
G. 2-D shock-induced separation	Y?	Y?	Y	Y
H. 3-D shock-induced separation	?	?	?	?
I. Vortex-BL interaction	N/Y?	Y?	Y	Y

In the area of unit problem experiments, further axisymmetric bump experiments are the type that may be helpful for exploring shock-induced separation. However, turbulence models have been very successful in the past on simple problems like this. 3-D flows are more challenging. Therefore, in spite of the difficulty inherent in defining and carrying out good unit problems for 3-D separation, the turbulence modeling community is definitely in need of more "3-D unit problem" experiments.

2.2.3. Juncture and mixing flows. There is a lot of evidence that full Reynolds stress models (RSM) are required for many of these types of flows (for example, horseshoe vortices). It is also well known that nonlinear terms are required in a turbulence model for it to be able to compute secondary motions induced by turbulent normal stress differences. In other words, if a turbulence model is a linear eddy viscosity model (LEVM), then the turbulent stresses are proportional to the strain (Boussinesq assumption) and the model cannot predict turbulent normal stress differences.

2.3. Directions for Improvement of Turbulence Models. Due to time constraints, the group only addressed directions for improvement of separated/time-accurate flows. In order to improve turbulence models for separated/time-accurate flows, both experiments and turbulence modeling itself must move forward hand-in-hand. Turbulence modelers generally like to have, from an experiment: three components of velocity (both mean and fluctuating) profiles, temperature profiles, skin friction coefficient, and pressure coefficient. Also, although difficult to obtain, some measure of the length scale would be extremely helpful, because the modeling of the length scale is currently one of the biggest uncertainties in turbulence modeling. Experimental techniques that are currently helpful, and may benefit from further exploitation are: particle image velocimetry (PIV), laser Doppler velocimetry (LDV), oil film, liquid crystal, and any other non-intrusive technique. Where experiments are lacking (such as in obtaining length-scale information), full simulations may be the only way to move forward.

Some goals for improvement in prediction of separated flows are listed here:

- Increase generality of turbulence model formulation
- Need naturally good behavior near walls
- Must include effects of curvature
- Separation control into modeling
- Continued exploration of DES
- Overall, should increase the role of DNS/LES for prediction modeling

The issue of turbulence modeling implementation is also important. Often, different individuals implement a given model differently (for example, different numerical methods, limiters, constants, and/or damping functions may be used). Or sometimes, different versions of a given model exist in the literature, yet, when implemented, they are referred to by the same name. It is not a trivial task to ensure uniformity, however. In an effort at NASA Langley, it took one month for three individuals to modify three existing codes to have identical implementation of an EASM model [2]. It is difficult to validate/improve models when such differences exist. (This problem, although a much greater problem for more complex models like EASM and RSM, even exists for simple models like SA. For example, some major codes in use in industry today employ an unpublished modification to SA that can delay the location of transition compared to the published version. Most users are not aware that this modification has been employed.)

2.4. Conclusions and Recommendations. The conclusions and recommendations given here are fairly general, not specifically geared toward any one of the flow categories. First of all, it is important to attempt to prioritize various flow categories, for which turbulence modeling efforts should be focused. From the point of view of the participants, this prioritization is (starting with the most important):

- Separation (including incipient separation)
- Vortex flows
- Jets and mixing layers
- Unsteady flows
- Other (Juncture flows, Heat transfer (scalar transport), Flow-induced noise, Compressibility, Cavity flows)

Naturally, this prioritization is subjective. What areas are considered important depend on who is doing the prioritizing. However, the top four items in this list seem to the group to represent flows of interest and of importance to a great number of people in many disciplines.

Some specific recommendations follow. First, an effort should be undertaken to make numerical implementations for RSM (and other models) efficient (so people will want to use them). There should be standards set up to guarantee completeness in reporting details on how turbulence models are implemented (for repeatability). Furthermore, details on proper use of models should be published. For example, the guidelines document published by ERCOFTAC are a step in this direction [3].

An organized validation effort should be undertaken on a set of simple standard cases. In addition, the turbulence modeling community also needs to build up to a more complex set of standard cases.

After two days of discussion, a lot of attention was given to RSM, as an unspoken goal toward which turbulence modeling efforts should be directed in the future. However, the issue was brought up as to whether this goal is appropriate or desirable. Is full Reynolds stress modeling an “abyss”? I.e., is it do-able, or is it too much? Is it necessary? RSM has been traditionally less robust than simpler models. Can this state of affairs be improved? A thorough validation effort is necessary for the existing simpler models before they are discounted. What are specific documentable failings that are unambiguously due to turbulence model and not some other factor like grid resolution or poor geometric fidelity? (This applies to *all* turbulence models.)

The issue of length-scale modeling stood out as one that really needs a lot more focus in the future. This will require considerable help from experiments and/or simulations.

A large concerted effort is needed to evaluate and select from *existing* experimental databases (such as ERCOFTAC). The group did not want to advocate a slew of new experiments when so many old ones exist that might serve perfectly well. After a thorough evaluation, some areas may be evident where new or updated experiments may be required. Members of the group mentioned some existing experimental databases: trapezoidal wing, ROCK wing, and plane swept bump in channel. As a part of compiling an experimental database, a good set of unit problem experiments for validation/model improvement is particularly needed. Some suggestions included some sort of axisymmetric bump or a modified axisymmetric bump.

The group made some recommendations for experimental approaches that would be most helpful for turbulence modeling validation. These included use of PIV for spatial correlations, LDV, and other non-intrusive methods. It is imperative that well-defined boundary conditions be given, for use in CFD computations. Key measurements needed are three-component velocity profiles (mean and fluctuating), temperature profiles, surface pressure coefficient, and surface skin friction coefficient.

The following final summary represents a “balanced plan” for turbulence modeling. These items are discussed more fully below:

1. Mine old experiments
 - Validate old data
 - Quantify uncertainty
 - Correlate data to particular physical phenomena
2. Develop advanced instrumentation
 - For both wind tunnel and flight? (no consensus here)
3. Develop effort to assess/screen existing models
4. Assess, improve, and document numerical implementation
5. Collaboration needed
 - Funding commitment required

6. Continue model development targeted to relevant flows

- Maintain relevance to whatever collaborative plan evolves

After assessing old datasets, new experiments may be called for to supplement, fill in, or replace where needed. In new experiments, an emphasis should be placed on unit problems, particularly for obtaining 3-D data. All old and new (proposed) experiments should be assessed as to their relevance to engineering challenges that arise out of this workshop. It is important to have experimental efforts both in flight as well as in wind tunnels. Data for validation should be organized and collected into a national or international database, similar to the existing European ERCOFTAC consortium effort. All experimental data should carefully provide CFD with boundary conditions (e.g., actual wing shape in flight, transition location, etc.).

In the effort to assess/screen existing models, models need to be classified in some way. How should the assessment proceed? Should there be collaboration around multiple codes? It is probably best to have more than one code, but probably more than three would be unmanageable. Opening up this type of effort to too many codes has not worked in Europe in the past. Does the validation effort fall under NASA's domain? It might be helpful to form a sub-committee to devise a strategy for performing the assessment. Grid resolution and quality issues must be included in any study, and Navier-Stokes codes should be employed (although boundary layer codes can be useful both to calibrate the models and to serve as a check on the more complex implementation in the Navier-Stokes solvers). The validation/assessment should have a balance between old models and new ones. As a part of the numerical implementation assessment, consistency among different implementations of the same model should be a goal. Model and implementation robustness should be assessed.

In any collaborative effort, the "right" people need to be involved. The current participants may not adequately represent certain segments of the aerospace industry. Other areas might have different priorities than those determined in the current venue. For example, the collaboration of more people working in the area of propulsion may be needed. As models continue to be refined and developed, any collaborative effort needs to make sure not to suppress new ideas that come from people outside of the "group." Also, new models may arise both from experimental data as well as from mathematics and theory.

3. Group II – Summary Findings and Recommendations. Facilitators: J.L. Thomas (LaRC) and R.A. Wahls (LaRC)

3.1. Importance of the Modeling of Turbulence. The general importance of the modeling of turbulence is indicated below for transport aircraft vehicles and then for more general vehicle types. The key engineering prediction needs in the current CFD environment for transport aircraft are:

- Reynolds Number Effects on Separation
- Control Surface Effectiveness
- 3-D High-Lift

These areas are discussed more fully below.

3.1.1. Reynolds number effects on separation. This area is important for cruise performance, since increased performance is tied to designs that delay separation to higher Mach numbers or higher angles of attack. Transonic wings are typically designed with a mid-chord shock position and an aft-loaded section at cruise conditions. As the angle of attack is increased beyond cruise, the shock position moves aft, with a corresponding nonlinear increase in lift; a separation bubble with reattachment downstream occurs at shock Mach numbers on the order of 1.3. Correspondingly as the angle of attack is increased, the trailing edge separation moves forward, leading to a decrease in lift coefficient. These two effects are compensatory and quite sensitive to Reynolds number at transonic speeds. Many times, a definite change in lift curve slope occurs at the onset of separation; the maximum lift (and a positive pitching moment increment) occurs as the separation from the trailing edge reaches the separation at the shock. This sensitivity to Reynolds number is believed by some to be the root cause of the discrepancies between the lift levels at buffet onset in flight with the lift levels generated either by high Reynolds number testing or computation (see presentations by A. Kumar of NASA and M. Anderson of Boeing at this workshop, Appendix C). For example, with the MD-11 airframe, both wind tunnel and CFD show a much more pronounced break in the lift curve slope at the onset of trailing edge separation, with a consequent loss of lift in comparison to the flight test results at angles of attack near the observed flight buffet onset. F. Lynch of Boeing-retired observed that wing-body calculations on the MD-11 with the Johnson-King model agreed with the trend from flight and differed from the SA and Menter's k-omega shear-stress transport (SST) turbulence model results; the Johnson-King model has not been extended to full configurations and, thus, results for the full configuration are not available. The MD-11 experience is not universal, however, since some comparisons of separated flow with both flight test and ground-based experiments are quite good. There is general agreement that modeling of 3-D separated flows is a major area of uncertainty. Reynolds number effects on separation are also especially important to airframe-propulsion integration problems, typified by juncture/corner regions (wing-nacelle-pylon intersections) in adverse pressure gradient and shock-induced separations. In general, there is an adverse Reynolds number effect (i.e., a decrease in effectiveness with a Reynolds number increase) associated with these flows; this effect limits the design tradeoffs than can be made at lower Reynolds numbers (~6 million) in transonic ground-based facilities.

3.1.2. Control surface effectiveness. This is an area in which heavy reliance is made on ground-based testing because of the lack of confidence in CFD. The biggest deficiency is in 3-D applications with significant spanwise flow for which adverse Reynolds number effects occur. For example, F. Lynch of Boeing-retired cited an adverse Reynolds number effect as regards outboard aileron effectiveness on the DC-10 wing, whereas favorable effects were cited for the MD-11 wing; tuft observations indicated a significantly greater spanwise component of flow on the DC-10 wing. The adverse Reynolds number effects have not been encountered in 2-D.

3.1.3. 3-D high-lift. This area is the ultimate prediction challenge because of the many flow physics issues involved that are sensitive to Reynolds number effects, including trailing and leading edge separations, confluent boundary layers and wakes, off-body separation, corner/juncture flows, and strake/chine flows. This is an area where extensive reliance on experiments is necessary, largely because of the lack of confidence in predicting separated flows. Separation on the flap is the most important driver at approach conditions, especially for advanced three-component high-lift configurations. Chineses/strakes on the nacelle create vortices, which interact beneficially

with the upper surface viscous flow to control separation at high-lift conditions; these devices are generally determined through cut-and-try parameter variations in ground-based and flight tests. These chines and the wing-nacelle-pylon integration are the most important drivers to determining the maximum lift.

The key engineering prediction needs for multiple vehicle types (i.e., military, rotorcraft, reusable launch vehicles, etc.) are summarized as follows:

- Vortex Flow Breakdown and Interactions
- Buffet
- Active Flow Control
- Store Separation
- Maneuver-induced Unsteadiness (Time Lags and Hysteresis)
- Jet Impingement and Ground Interactions
- Ducts (including Unsteady Separation)
- Cavities
- Rotor Blades (Turbomachinery, Helicopters)
- High Lift
- Transitional Flows
- High Freestream Turbulence
- Wake Interactions
- Shock Boundary Layer Interactions
- Wall Heating (Heat Transfer)

We do not discuss these areas in detail. The above engineering prediction needs can be translated into a general set of flow physics issues, which cut across vehicle lines. A partial list is below. These issues could form the basis for a framework to classify existing experiments or advocate for new key experiments to be conducted.

- Separation onset, progression, and reattachment, including a range of onset conditions, pressure gradients, crossflows, Reynolds number, and shock strength variations. The three types of separation typically encountered are geometry-driven (backward-facing steps), adverse pressure gradient (smooth surface), and shock-induced separations. Topologies of open and closed separation should be considered.
- Transient evolution of transonic separated flows, including control surface deflections, Reynolds number, shock variations, and corner/juncture flows
- Vortical flows, especially vortex breakdown, including stability drivers for different modes of breakdown, and the impact of unit Reynolds numbers

- Passive and active flow control devices, such as vortex generators and zero mass flow (synthetic) jets, including detailed data for turbulence model enhancements and the development of global, rather than local, models
- Mixing layers, including merging boundary layers and wakes from the main element, flap, and slat, with adverse pressure gradient and Reynolds number effects
- Curvature effects, especially recovery from curvature
- Transition prediction and control, including trip and roughness calculations for correlation of wind tunnel to flight and for lower Reynolds vehicles, such as uninhabited air vehicles (UAV)

3.2. Assessment of Current Methods. From the standpoint of vehicle prediction needs, it is clear the calculations involve a multitude of fluid interactions and it is often the weakest link in the elements of the overall process (i.e., geometry modeling, numerical method, turbulence modeling) that determines the success of the calculation. R. Cosner of Boeing cited the F-18 wing drop phenomena as an example of the interaction of the various elements. The wing drop problem is a flight control difficulty that was only uncovered during flight tests; such surprises have a significant negative impact on program schedules and cost. The problem was addressed with CFD, ground-based experiments, and flight tests. The anomaly that caused the problem—an abrupt change in the lift curve slope at transonic speeds before maximum lift—was noted in wind tunnel tests before flight. However, it was judged to be a problem that would disappear at flight Reynolds numbers. The phenomena turned out to be Reynolds number insensitive. Initial CFD computations showed only a fraction of the lift loss that the wind tunnels showed and the turbulence model was the chief suspect. However, doubling the grid produced results that agreed much more satisfactorily with ground-based tests. At the end of the study, the program managers indicated that CFD gave results to within wind tunnel accuracies through the entire wing drop phenomena. This particular experience is not uncommon; turbulence model inadequacies are often blamed in practice for insufficient resolution of three-dimensional computations.

In general, as noted in the talks presented at this workshop and elsewhere, the current capability of second moment closures in applications are no better than the simpler, less expensive models such as SA or SST for many of the key engineering predictions. For instance, extensive two-dimensional high-lift development and validation studies conducted through cooperative efforts by Boeing and NASA have shown that the EASM and either SA or SST turbulence models give quite similar results. Neither predicts maximum lift very closely, although this may be due to the influence of sidewall boundary layers. Studies to simulate the sidewall boundary layer should be completed in order to make a more definitive assessment of the turbulence model capabilities for this particular flow. However, there is growing confidence in the ability of Reynolds stress models to be applicable to general situations for which no experimental information exists. As an example, systematic comparisons of EASM additions to baseline models (k-epsilon or k-omega) have been recently conducted by A. Johansson of KTH [4] for a series of shock-induced turbulent separations for $M=5$. The results show a quantum increase of accuracy over the baseline methods with the EASM additions, in both the length of separation and the variation of separation with

shock strength. In these computations, much of the improved result is attributed to improvements in the near wall asymptotic behavior gained through EASM. The comment was made that these flows could also probably be accurately computed with the SST or SA models, in which case the improvement is attributed to the variable eddy viscosity coefficient term rather than the nonlinear terms. Additional examples were cited of engineers at European car companies routinely using EASM-type models in calculations using tens of millions of grid points with notable improvements over linear eddy viscosity models (LEVM) for separated flows.

As encouraging as the results using these second-moment closure methods have been, the possibility was discussed to circumvent the EASM class of models in favor of going directly to the RSM class. However, the numerical difficulties were considered so great with this class that the EASM approach should not be bypassed, since EASM allows many additional effects to be included rather easily into current numerical formulations.

Until recently with the advent of direct simulations, the only way to assess turbulence models was through systematic comparisons with experiments. These experiments fall into two categories. The first are application tests, involving measurements of specific aerospace configurations, such as wing-bodies or multi-element wings, which are useful to the practicing engineer as a basis for the acceptance/verification of methods. These tests are generally not appropriate for turbulence model development, since the measurements are usually limited to surface measurements, such as pressures, skin friction, and oil flows. The second type are unit problem experiments, intended to be representative of a limited number of specific types of flow physics issues encountered in application, that involved more detailed measurements such as velocity profiles or turbulent shear stresses. These experiments can supply global or local information useful to the development of turbulent models, as in integral method development or simpler half- or one-equation models. For example, the Bradshaw structural coefficient of the ratio of shear stress to kinetic energy has been observed to hold in many flows and is used by the lag entrainment integral method and the Johnson-King model. These unit problem experiments can be quite expensive to conduct, but serve as definitive benchmark tests of turbulence models.

For the second-moment closure-type models, experiments are not used for development, but only for verification/assessment, since most of the modeling is done for homogeneous flows or low Reynolds number flows. In this respect, the last ten years have seen an increased usage of information from direct simulations in the development of these methods; this trend should increase proportionally to the computational capability available for direct simulations.

The turbulence modeling issues are listed below followed by a discussion of the current capabilities and limitations in these areas.

- Separation and Post-separation
- 3-D Effects
- Unsteadiness
- Length-scale Equation
- Role of Curvature

- Reynolds Number Scaling
- Vortical Flows

3.2.1. Separation and post-separation. Many of the current models seem to do reasonably well for the few two-dimensional test cases available; this has been achieved in the models through a variable eddy viscosity coefficient in the formulation, which has the effect of reducing shear stress levels at separation, which tends to improve the correlation with experiment of the models. Current models do not uniformly predict the region downstream of separation, including reattachment (see [5]). Although the Bachalo and Johnson axisymmetric bump flow [6] is generally predicted quite well in terms of pressures (and skin friction), the shear stress levels downstream of separation are underpredicted. Likewise, for the backward-facing step computations, the overall extent of separation seems to be predicted reasonably well by some models, but all models underpredict the shear stress levels.

3.2.2. 3-D effects. There is insufficient experimental data for wings with strong crossflow and separation effects to make a definite assessment between various models. For example, for transonic high aspect ratio wings, no boundary measurements are available near the trailing edge, even for attached flows. Since there is thought not to be a universal 3-D law of the wall behavior, methods based upon such an assumption would be less accurate. Thus, models that depended upon this law would have a major limitation in flows with significant crossflow effects. However, this limitation, if it exists, is not confirmed by the comparison of calculations with experiments to date, including those of 3-D calculations that use wall functions either in combination with one-equation, two-equation, or second-moment closures.

3.2.3. Unsteadiness. Some transonic separated flows over airfoils with boundary layer to chord ratios of nearly a half were cited as quite steady with no large-scale motions evident in flow visualizations. The general consensus is that the current models do quite well when there is a large distinction in the time scales associated with the turbulence and that associated with the reduced frequencies of the aircraft motion. Several recent calculations of the biconvex airfoil of McDevitt at transonic speeds, characterized by shock/boundary-layer interactions which induce alternating upper and lower surface separations, have shown results [7, 8], which show improvements using SA and EASM over algebraic turbulence models. As the separation zones become larger, as in spoiler or bluff body flows, the importance of incorporating DES models increases, although there is not consensus on the extent to which unsteady Reynolds Averaged Navier-Stokes (RANS) by itself can be pushed. F. Lynch of Boeing-retired noted that unsteady flow tended to occur at transonic conditions for airfoils with small upper surface curvatures, but that it was only a small effect for curved sections, such as encountered on modern aft-loaded transport sections.

3.2.4. Length-scale equation. This equation is viewed as quite ad hoc, even in attached flows and the contribution of the current modeling deficiencies for separated flows is currently unknown.

3.2.5. Role of curvature. As noted in the talks presented at this workshop, additional curvature terms are required for LEVM models, but appear to be less important for EASM. RSM can handle the effects of curvature without any additional modeling. The inclusion of curvature terms in 2-D multi-element high-lift computations has not appreciably changed the character of the results [9].

3.2.6. Reynolds number scaling. From the standpoint of turbulence modeling, it is more important to conduct an experiment with fully established turbulence than to conduct an experiment at high Reynolds numbers; the computation that reproduces the fully turbulent interaction, albeit at less than flight Reynolds number, can be made at higher Reynolds number with confidence. Most of the Reynolds number scaling problem is associated with wind tunnel to flight scaling, in which transition effects are paramount. In production testing, the objectives are usually quite different from establishing fully turbulent flow; for instance, it is common to locate the trips to match the boundary layer displacement thicknesses at the shock between wind tunnel and flight.

3.2.7. Vortical flows. A general consensus is that all of the LEVM models fail when streamwise vorticity is present, such as in the computation of vortex rollup and breakdown. Even though vortices are present for all airframe configurations, the resolution of these vortices is generally not a significant driver for airframe performance prediction except if they interact strongly with the flow field, such as in vortex breakdown for low aspect ratio wings or chine/strake vortex interactions with high-lift configurations.

3.3. Directions for Improvement of Turbulence Models. The goals for improvement of predictions in separated flows are listed below:

- Increased generality of the formulation
- Naturally good behavior near walls
- Curvature corrections, especially in EASM
- Improved modeling of active and passive flow control devices
- More extensive evaluation of Detached Eddy Simulation (DES) methods
- Increased role of DNS/LES for prediction modeling

To obtain funding support for the improvement along these fronts, it is necessary to advocate on the basis of the improved capability that is tied to the advances in turbulence modeling. For example, efficient wing designs can be pushed to higher cruise Mach numbers through advances in separation prediction. Simpler and cheaper and more effective high-lift performance can be attained through improved computations of active flow control devices. Much of the modeling improvement should be tied to the validation experiments needed to assess ongoing LES efforts and to the assessment of capabilities across the spectrum from RANS – Unsteady RANS (URANS) - DES - LES - DNS. There is a need to get a national consensus on a few canonical benchmark experiments. These experiments should be conducted jointly with modelers and carefully designed to provide irrefutable data for the assessment of our current capabilities. The required experiments are expensive and should capitalize on the sizeable investment of other government agencies in turbulence prediction and turbulence modeling. Directions for improved turbulence models and a discussion of additional needed experiments are presented below.

3.3.1. Improved turbulence models. Directions for improvement of current turbulence models are in the three areas below:

- Pressure-strain Modeling
- Near-wall Modeling

- **Length-scale Equation Modeling**

The pressure-strain modeling pertains to models based on Reynolds stress equations. The near-wall modeling and length-scale equation modeling difficulties, especially the latter, pertain to most models. These areas are discussed below.

3.3.1.1. Pressure-strain modeling. This modeling aspect has received extensive attention because it is the principal modeled term in homogeneous flows and can be studied in detail; thus, it can be judged as the most mature of the three areas, although the modeling in the near-wall region is still in question.

3.3.1.2. Near-wall modeling. The near-wall modeling problem is defined as the difficulty in the integration of the equations to the wall. This difficulty, usually arising in computations as an observed robustness problem, is the most significant limitation to usage of second-moment closure models in practice. The general approach is to model the equation based upon a known behavior, such as the log-law behavior for attached flows. At separation, this law breaks down. This is an area in which DNS is expected to be used with a reasonably high degree of confidence for model improvement and validation. DNS simulations have been completed with a smooth separation from a solid wall by prescribing the outer normal velocity in the simulation. Extension of these simulations to higher Reynolds number would be expected to provide an excellent source of information as to appropriate scaling through separation. An argument in favor of the Reynolds stress methods is that the equations could be formulated to be entirely independent of the wall, which one could never do with one- and two-equation models. A. Johansson of KTH indicated recent progress has been made in deriving and testing a second-moment closure method for simple flows based on realizability considerations with no wall damping terms [10]. This approach is preliminary but will be tested for more complex flows in the future. The comment was made that this approach should be in pressure-strain models only; one still needs damping in other parts of the equations.

3.3.1.3. Length-scale equation modeling. The length-scale equation modeling refers to the dissipation equation, which is a key ingredient to all of the two-equation or higher models. It is the area of greatest uncertainty. The modeling is highly questionable for separated flows or for any flows with disparate length scales that interact, as for example, a separated airfoil trailing edge region, with momentum transfer across the wake formed by the merging upper and lower surface fluid. A simple mixing layer is an example where the shear stress is predicted accurately with k -epsilon, but turbulent kinetic energy (k) is not. Thus, the eddy viscosity coefficient is consistent with an explicit algebraic stress model but one has to change epsilon to get k correct, clearly indicating a problem in the length scale equation. The length scale model changes as the models are changed from LEVM to EASM to RSM (i.e., production terms and diffusion terms are known slightly better with RSM since some of the terms are computed directly). Flows in which turbulent transport is important clearly require RSM approaches; however, the length-scale equation deficiency may be masking effects that should be otherwise accurate and computable. Advancements could be made by using DNS or spectral theory to suggest models accompanied by LES computations or experiments for model validation. The main concern with this area, as with all methods based on

DNS or LES, is the scaling of the results to flight Reynolds number associated with flight vehicles, since these simulations will not be practical for many years.

3.3.2. Needed experiments. The need of measurements in unit problems was discussed at length. These unit problems are used to demonstrate model improvements in treating deficiencies of current models, such as in post-separation regions. There are only a few test cases available to assess turbulence models for flow separation that are not plagued by three-dimensional interference effects. These include the Bachalo and Johnson axisymmetric bump [6], the Driver flow [11], and the separated flow of Simpson [12]. The latter two flows are very difficult to simulate with Navier-Stokes computations because of boundary conditions, but could be computed using inverse techniques to determine an effective wall shape, such as that used by Rumsey and Gatski [13]. Two-dimensional axisymmetric flows ($\delta/R \ll 1$) are recommended as unit problems since there is less influence of 3-D effects, as for instance from sidewall boundary layers and secondary flows, and the data collection is easier than a 3-D flow. These experiments could build upon the Bachalo and Johnson axisymmetric bump experiment; this experiment is characterized as a trailing-edge separation experiment in which the separation moves upstream to the shock and has been widely used to compare different models. It could be expanded using current CFD design methods to include shock-induced boundary layer separation or modified to induce controlled three-dimensional effects (through addition of sweep, suction, or a vortex generator, for example). The experiment would be simple enough in complexity to be computed by LES and/or DNS and, thus, serve as a validation case for such approaches at lower Reynolds number.

There were no specific recommendations proposed for 3-D experiments to serve as definitive benchmark datasets. Difficulties arise in measuring boundary layer information at transonic speeds at reasonable Reynolds numbers. In this regard, no velocity or shear stress data for transonic flows with strong 3-D effects at high Reynolds numbers is available. The NASA trapezoidal wing, high-wing, test case is viewed as a step along the way for 3-D high-lift validation, but lacks the key element of nacelle-pylon-chine integrations encountered on realistic airframes. Also, the flow is quite sensitive to the component rigging of the high-lift configuration and small adjustments can accentuate or mask certain intended flow interactions.

Adaptive turbulence models (also called zonal turbulence models)—using various turbulence models as they are appropriate to the local physics—are a possible way to circumvent the lack of a general purpose turbulence model applicable to all flows. Such techniques are not widely used largely because there is no a priori knowledge of the capabilities of a given turbulence model in a given situation. Establishment of a basis to determine the capability of a given model in a calculation would be quite useful. Methods to determine the error associated with the discretization of a given set of partial differential equations and use that as a basis for adapting the grids to attain a specified error tolerance are now being pursued. Also, guidelines/standards to ensure sufficiently accurate 3-D computations are now emerging, as noted in the recent ERCOFTAC [3] referenced above. However, capabilities for determining the accuracy of complex-geometry separated flow computations are just in their infancy. Moreover, for complex flow applications at high Reynolds number, there seems to be nothing on the horizon to account for the physical error embodied in the solution of a given set of turbulence models.

3.4. Conclusions and Recommendations. The general recommendations for this group focused on directions for improving turbulence models. The highest priority should be given to attacking the length-scale equation, since it is a key ingredient to all of the two-equation or higher models. Advancements could be made by using direct simulations and/or spectral theory to suggest models and then testing these models by comparing to DNS/LES computations or model validation experiments. The second priority should be in developing improved near-wall behavior, since the stiffness issues associated with this region pose a significant limitation to usage of second-moment closure models in practice. In this area, direct simulations could be used with a high degree of confidence for both model suggestion and validation. A principal concern with this approach is the ability to scale the results to flight Reynolds number.

4. Group III – Summary Findings and Recommendations. Facilitators: W.L. Sellers (LaRC) and R. Rubinstein (LaRC)

4.1. Importance of the Modeling of Turbulence

4.1.1. Vortical flows. Vortical flows are ubiquitous in aerodynamics. Flows around vortex generators are common examples. An interesting non-aerodynamic application of current interest is the hydrocycle centrifuge for removing impurities. Unsteady vortex bursting on fighter aircraft was identified as a source of fatigue damage through flow-structural coupling.

4.1.2. Separated/time-accurate flows. High Reynolds number separated flows occur in buffet onset. The claim that all models fail to predict the dependence of the lift coefficient on angle of attack helped motivate the present workshop. These flows also occur in high-lift airfoil configurations and in the evaluation of control surface effectiveness.

4.1.3. Juncture and mixing flows. Aerodynamic juncture flows include the flow around the wing-body nacelle strut, and the flows around pods and blisters, which are particularly important for military aircraft.

Mixing flows occur in confluent boundary layers, wake interactions with solid bodies in high-lift configurations, and in turbulent wake impingement in turbomachinery. Potential difficulties exist because the correct modeling of mixing of disparate turbulent flows remains somewhat obscure. If we think of a homogeneous region of turbulent flow as generated by forcing at some integral scale, then when two turbulent flows mix, it is not clear how the integral scale of the result should be determined. In unit problems like the penetration of turbulence generated by an oscillating grid into quiescent fluid, current models are frequently found inadequate.

4.2. Assessment of Current Methods

4.2.1. Vortical flows. The first general observation made was that vortex flows could pose significant numerical issues that are independent of any turbulent modeling consideration. Insufficient grid resolution alone will diffuse small tight vortices. There is considerable numerical research on adaptive gridding methods to identify and resolve vortices. The implementation of such methods on unstructured grids is especially important, and was addressed in some papers at the 2001 AIAA January meeting.

Otherwise, as noted earlier, vorticity-dominated flows present multitudinous problems for turbulence models. Eddy viscosity models (including the quadratically nonlinear models) incorrectly predict a rigid rotation profile of swirl velocity inside vortices. Cubic nonlinearity was suggested as a solution to this problem.

The Reynolds stress model (RSM) reduces the turbulent kinetic energy inside the vortex, correctly indicating the suppression of turbulence in the vortex core. This effect is not predicted by lower order models, even by lower order models with swirl corrections. Examples were given by Dr. Kim of FLUENT during the 2001 AIAA January meeting.

The flow around a 6:1 prolate spheroid provides an example of a vortical flow, since vortex interactions can occur, leading to unsymmetric forces on the body. Unsteady separation of these flows is important. There is a European effort in progress to calculate this flow. Preliminary findings are that the eddy viscosity models (EVM) are generally inadequate, but that the RSM is at least qualitatively correct.

4.2.2. Separated/time-accurate flows. Turbulent separated flows have proven to be difficult to compute. Earlier discussion of mixing and juncture flows, which are otherwise amenable to all current turbulence models, showed that separated cases of even these flows are hard to compute accurately.

There was general agreement that no model, even RSM, can predict recovery of turbulence downstream of separation. Associated with this fact are the observations that typically the models overpredict the turbulent time-scale, and that turbulence production takes too long to re-establish itself. It was noted more generally, that in many problems involving the recovery of turbulence, all models are inadequate. Recovery following shock interactions also belongs to this class. Very large-scale structures and long time scales characterize these flows. Consequently, even in DNS, it is necessary to integrate for a very long time to resolve the post-separation region.

Another motivation for this workshop had been the suggestion that there is a Reynolds number effect that is missing from all current models. Thus, if a code is validated against ground data, it may fail for flight conditions just because the Reynolds number is larger. After very careful discussion of this point, it was agreed that Reynolds number does certainly influence quantities like the thickness of boundary layers and the location of transition. However, existing models are properly sensitive to such effects. It was agreed that no other Reynolds number effect exists.

A question was raised about the accuracy required in calculations of lift and drag coefficients. Accuracy to the order of 1-2% seemed to be desired. However, none of the nominally universal constants of turbulence theory, such as the Kolmogorov constant, or the eddy-viscosity constant C_μ is known to within less than 10%. It is possible that the calculations are not very sensitive to the modeling constants, or that the model constants are empirically adjusted. Nevertheless, this question deserves serious consideration.

4.2.3. Juncture and mixing flows

4.2.3.1. Juncture flows. The main difficulty in predicting juncture flows is attributed to flow separation, particularly in 3-D flows. In the wing-body nacelle strut, local separation occurs, leading to a 1-2% drag increase. Two-equation models predict incorrect primary separation. The SST model gives better separation predictions, but

cannot predict secondary flow; however, secondary flow is not always important. For these flows, the RSM is adequate, and the EASM should work.

In 2-D separated flows of this class, eddy viscosity models such as the SA and SST are adequate, and in fact, no models are better. But in these cases, normal stresses are not important: prediction of normal stresses always requires higher-order models like the EASM or RSM.

An entirely different application of this type of flow is in icing calculations. It was noted that heat transfer is often underpredicted in these flows, leading to underprediction of ice growth.

Juncture flows often exhibit unsteady, chaotic, large-scale vortices. These vortices contribute to mixing and cannot be ignored. Nevertheless, there was speculation that any Reynolds-averaged model may suppress this type of effect. Phase-averaged models are a possible alternative.

4.2.3.2. Mixing flows. In the computation of confluent boundary layers, all current models (SA, SST, $k-\omega$, and EASM) provide satisfactory results for both the mean flow and turbulence quantities as long as the flow remains attached. The difficulties encountered with separated mixing flows must be attributed to separation rather than to mixing.

Similarly, for wake flows, including the wake from the main element of multi-element airfoils, all models provide satisfactory predictions in the near-wake region. In high-lift computations more generally, it is found that for low angle of attack, the unsteady slat flow is predicted well. In wind tunnels, this flow is transitional, and the transition prediction poses difficulties for models; however, in flight conditions, transition is not a problem, and models agree well with flight data.

4.3. Directions for Improvement of Turbulence Models

4.3.1. Vortical flows. Swirl and vorticity corrections to two-equation models were discussed extensively, but ultimately rejected as less satisfactory than EASM and RSM.

4.3.2. Separated/time-accurate flows. Further investigation of the failure of models to predict the re-establishment of turbulence is needed. Unfortunately, it was also agreed that no one really knew what specific weakness of current models is responsible for the problem.

4.3.3. Juncture and mixing flows. The difficulties posed by unsteady vortices raised the general issue that turbulence models are always more successful in predicting strain-dominated flows than vorticity-dominated flows. Some vortex flows are actually predicted better by purely inviscid methods. We need some way to identify these problems in advance, perhaps through a discriminant function.

4.4. Conclusions and Recommendations

4.4.1. Vortical flows. In general, RSM and EASM are satisfactory solutions to this class of problems. However, the numerical issues noted above remain. Continued progress on the numerical side will be important.

4.4.2. Separated/time-accurate flows. The existence of a “Reynolds number scaling” problem, understood as an intrinsic failure of turbulence models due only to high Reynolds number, was emphatically and unanimously rejected.

4.4.3. Juncture and mixing flows. In the absence of transition and separation, current models are adequate for aerodynamic mixing flows.

A possible limitation of Reynolds-averaged models was discussed, although there was not general agreement about this possibility.

Better models for vorticity-dominated flows, and methods for distinguishing strain-dominated from vorticity-dominated flows are needed.

A list of problems in which large discrepancies exist between CFD and data should be compiled.

5. Conclusions. This section is divided into two parts: an assessment of current methods, and recommendations for future development. These represent a collation of the key points and final summaries from the three groups. More detail regarding these assessments and recommendations can be found in the groups’ respective sections above.

5.1. Assessment of Current Methods.

1. Key areas, or flow categories, in the prediction of aerospace vehicle performance for which turbulence modeling improvements are particularly critical:
 - a. Separation, particularly separation onset and progression in three-dimensional flows
 - b. Vortex flows, particularly vortex breakdown and component interactions
 - c. Jets and mixing layers
 - d. Unsteady flows
2. No current model can predict post-separation (recovery) physics, and most models cannot predict post-curvedness (recovery) physics.
3. There is no evidence that Reynolds number scaling is an issue in turbulence models in the sense that if a model does well at low Reynolds number, it should have no trouble at high Reynolds number. However, ground-to-flight scaling remains an important issue because of transition and other effects. For a given configuration, the severity of adverse pressure gradients and the degree of spanwise flow increases with increasing Reynolds number. Thus, it may not be sufficient to validate turbulence models only at lower Reynolds numbers, and high Reynolds number experiments remain a critical part of the validation process.
4. Turbulence models are often blamed for problems that are caused by insufficient grid resolution, unaccounted-for transition effects, or geometry issues (such as aeroelastics). Isolation of turbulence model deficiencies requires a critical account of all of these effects.
5. The current capability of second moment closures in aerospace applications are no better than the best of the simpler, less expensive models such as SA or SST for a large number of key engineering predictions typically

dominated by thin shear layers. However, there is growing confidence in the ability of Reynolds stress models to compute not only this class of flows but also more complex turbulent flow classes.

6. There may be fundamental limitations in the ability of RANS approaches to predict critical industry needs for separation onset and progression at flight conditions. However, given that computer limitations force the use of RANS methods for realistic configurations at high Reynolds number in the foreseeable future, the ASM and RSM models with much additional development currently offer the best hope.

5.2. Recommendations for Future Developments.

1. Establish a national/international database and standards for turbulence modeling assessment
2. Focus modeling efforts on length-scale and near-wall modeling, with emphasis on second-moment closure (and derivative) models

The workshop participants strongly advocated either establishing a new database of high quality, well-documented experimental data or else tying into the European database (ERCOFTAC) already underway. The database should include “unit problems” that are simple and isolate specific aspects of turbulence. A thorough and exhaustive search and categorization of *existing* experimental databases should be conducted prior to creating new ones. New experiments, for instance three-dimensional flows with separation and crossflow effects, especially at high Reynolds numbers, can then be performed to either upgrade or fill in missing datasets. Continued development of advanced instrumentation would benefit future experiments by improving the quality of the data, or allowing quantities to be measured that currently cannot be easily obtained.

There are still many uncertainties regarding the precise failings and capabilities of existing turbulence models due to non-uniformity in coding and evaluation practices. The development of a standard process for assessment would be beneficial (see, e.g., [14, 15]). The workshop participants also identified the fact that numerical methods for model implementation and model-dependent mesh resolution requirements are relevant issues in the quest to improve turbulence models. Therefore, a part of the standard should include assessment and documentation of the mesh requirements and numerical implementation. The latter issue is important because of current non-uniformity in programming practices, which sometimes results in ostensibly the same model performing differently in different codes.

Continued turbulence modeling research and development is important, particularly in the areas of second-moment closure models such as RSM and EASM. Future development efforts should maintain relevance to the specific needs of the aerospace community. A significantly increased role for DNS and LES/DES for prediction modeling is possible because of emerging simulations with separated flows. Although still limited to low Reynolds numbers, DNS and LES should be able to serve as a foundation for the development of improved RANS models for the length-scale equation and the near wall treatment, because they can provide information on quantities which have a crucial role in turbulence modeling, but which are difficult to measure in laboratory experiments. The length-scale equation is a major deficiency and area of uncertainty with most current models from two-equation to

second-moment closure models. The modeling improvements could be used in the practical computations of flight vehicles at Reynolds number beyond the range of simulations.

Although not the focus of this workshop, DNS, LES, and hybrid methods currently represent viable approaches for analysis on a limited basis, and should remain a part of any balanced effort in turbulence modeling. These methods will be required for accurate predictions of highly unsteady turbulent flows in which scales of the Reynolds-averaged velocities and turbulent velocities are not widely separated.

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APPENDIX A

Workshop Agenda

Turbulence Modeling Workshop

January 12-13, 2001
Reno Hilton, Reno, Nevada

Friday, January 12, 2001

Nevada Room N6

8:00 - 8:30 a.m.	BREAKFAST (Catered) – Nevada Promenade
8:30 - 8:35 a.m.	Manuel Salas - Welcome
8:35 - 8:45 a.m.	Darrel Tenney - Introductory Remarks
8:45 - 9:00 a.m.	Ajay Kumar – Workshop Purpose and Expectations
9:00 - 9:20 a.m.	Mark Anderson – ASTAC/Airframe Systems Subcommittee Perspective
9:20 - 9:30 a.m.	BREAK – Nevada Promenade
9:30 - 10:10 a.m.	Philippe Spalart – Review of Turbulence Modeling
10:10 - 10:50 a.m.	Brian Smith – High Reynolds Number Turbulence Modeling Overview
10:50 - 11:30 a.m.	Thomas Gatski – Turbulence Modeling – A NASA Perspective
11:30 - 12:30 p.m.	LUNCH (Catered) – Nevada Room N6
12:30 - 1:10 p.m.	Peter Bradshaw * – Turbulence Modeling for High Reynolds Number Separated Flows
1:10 - 1:50 p.m.	Katepalli Sreenivasan – Physical Aspects of Turbulent High Reynolds Number Separated Flows
1:50 - 2:30 p.m.	Roger Simpson – Experimental Issues Related to Turbulent High Reynolds Number Separated Flows
2:30 - 3:00 p.m.	BREAK – Nevada Promenade
3:00 - 5:00 p.m.	Break into groups to review current capabilities & shortcomings Group 1: Topic A, Nevada Room N6 Group 2: Topic B, Nevada Room N5 Group 3: Topic C, Nevada Room N4
6:30 p.m.	GROUP DINNER AT ANDIAMO, RENO HILTON

* did not attend

Saturday, January 13, 2001

8:00 - 8:30 a.m. BREAKFAST (Catered) – Nevada Promenade
Nevada Room N6

8:30 - 8:45 a.m. Group 1 presentation of capabilities & shortcomings for Topic A

8:45 - 9:00 a.m. Group 2 presentation of capabilities & shortcomings for Topic B

9:00 - 9:15 a.m. Group 3 presentation of capabilities & shortcomings for Topic C

9:15 - 9:35 a.m. GENERAL DISCUSSION OF CAPABILITIES AND SHORTCOMINGS

9:35 - 9:45 a.m. BREAK – Nevada Promenade

9:45 - 11:45 a.m. Break into groups to discuss best strategies to improve capabilities & eliminate shortcomings

Group 1: Topic B, Nevada Room N2
Group 2: Topic C, Nevada Room N5
Group 3: Topic A, Nevada Room N6

11:45 - 12:45 p.m. LUNCH (Catered) – Nevada Room N1
Nevada Room N6

12:45 - 1:00 p.m. Group 3 presentation of best strategies for Topic A

1:00 - 1:15 p.m. Group 1 presentation of best strategies for Topic B

1:15 - 1:35 p.m. Group 2 presentation of best strategies for Topic C

1:35 - 1:55 p.m. GENERAL DISCUSSION

1:55 - 3:55 p.m. Break into groups to develop conclusions and recommendations

Group 1: Topic C, Nevada Room N2
Group 2: Topic A, Nevada Room N5
Group 3: Topic B, Nevada Room N6

3:55 - 4:05 p.m. BREAK – Nevada Promenade
Nevada Room N6

4:05 - 4:20 p.m. Group 2 presentation of conclusion & recommendation for Topic A

4:20 - 4:35 p.m. Group 3 presentation of conclusion & recommendation for Topic B

4:35 - 4:50 p.m. Group 1 presentation of conclusion & recommendation for Topic C

4:50 - 5:10 p.m. GENERAL DISCUSSION FOR CONCLUSION AND RECOMMENDATIONS

5:10 - 5:50 p.m. GENERAL DISCUSSION

5:50 p.m. ADJOURN

APPENDIX B

Workshop Participants and Groups

The attendees were divided into three groups, as follows:

GROUP 1

Anders, Ben * (LaRC)
Aupoix, B (ONERA)
Georgiadis, Nicholas (NASA Glenn)
Jou, Wen (Retired, Boeing)
Leschziner, M (Queen Mary College)
Morrison, J (NASA LaRC)
Om, Deepak (Boeing)
Panton, Ronald (U Texas, Austin)
Reynolds, William ** (Center for Turbulence Research, Stanford)
Rumsey, Chris * (LaRC)
Smith, Brian (Lockheed)
Spalart, Philippe (Boeing)
Wark, Candace (IIT)

GROUP 2

Beutner, Thomas (AFOSR)
Cosner, Ray (Boeing)
Girimaji, Sharath (TX A&M)
Huang, George (Univ. of KY)
Johansson, Arne (KTH)
Johnson, Dennis (NASA Ames)
Kumar, Ajay (LaRC)
Lynch, Frank (Retired, Boeing)
Malik, Mujeeb (HiTech)
Thomas, Jim * (LaRC)
Wahls, Rich * (LaRC)
Watson, Ralph (LaRC)

GROUP 3

Anderson, Mark (Boeing)
Ball, Doug (Boeing)
Bradshaw, Peter ** (Stanford)
Gatski, Tom (LaRC)
Haase, Werner (Damler Benz Aero)
Menter, Florian (AEA Tech, Gm)
Potapczuk, Mark (NASA Glenn)
Rubinstein, Bob * (LaRC)
Sellers, Bill * (LaRC)
Simpson, Roger (VT)
Sreenivasan, K (Yale)
Tsuei, Hsin-Hua (Concepts NREC)

* Facilitator

** did not attend

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APPENDIX C

Workshop Presentations

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APPENDIX C

- Ajay Kumar "Turbulence Modeling Workshop – Purpose and Expectations"
- M.O. Anderson "ASTAC Airframe Systems Subcommittee Perspective"
- Philippe Spalart "High-Reynolds-Number Separated Flows"
- Brian R. Smith "Turbulence Modeling Needs and Capabilities for Military Aircraft"
- T.B. Gatski "Turbulence Modeling: A NASA Perspective"
- Peter Bradshaw "Turbulence Modeling for High Reynolds Number Separated Flows"
- K. Sreenivasan "Some Physical Aspects of Separated Flows"
- Roger Simpson "Experimental Issues Related to Turbulent High Reynolds Number Separated Flows"

5/37

10P

Turbulent Modeling Workshop

Purpose and Expectations

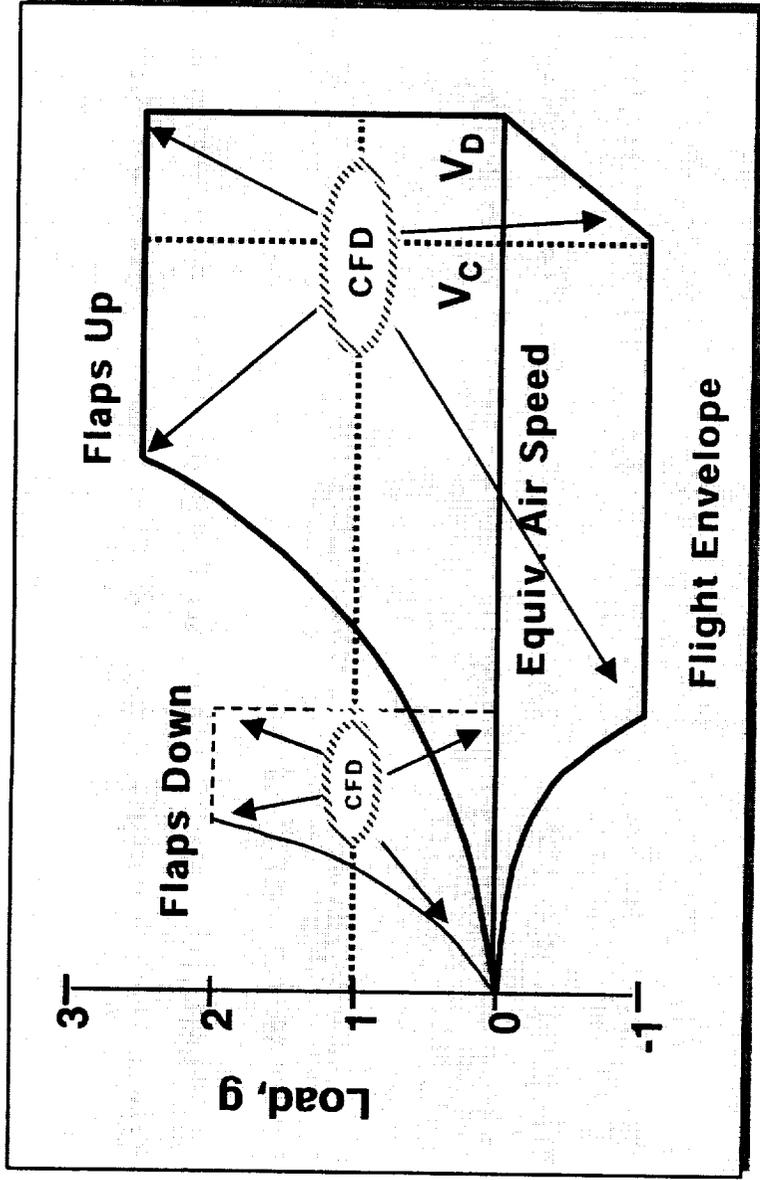
Ajay Kumar

January 12-13, 2001

Computational Tools for Aerodynamic Design

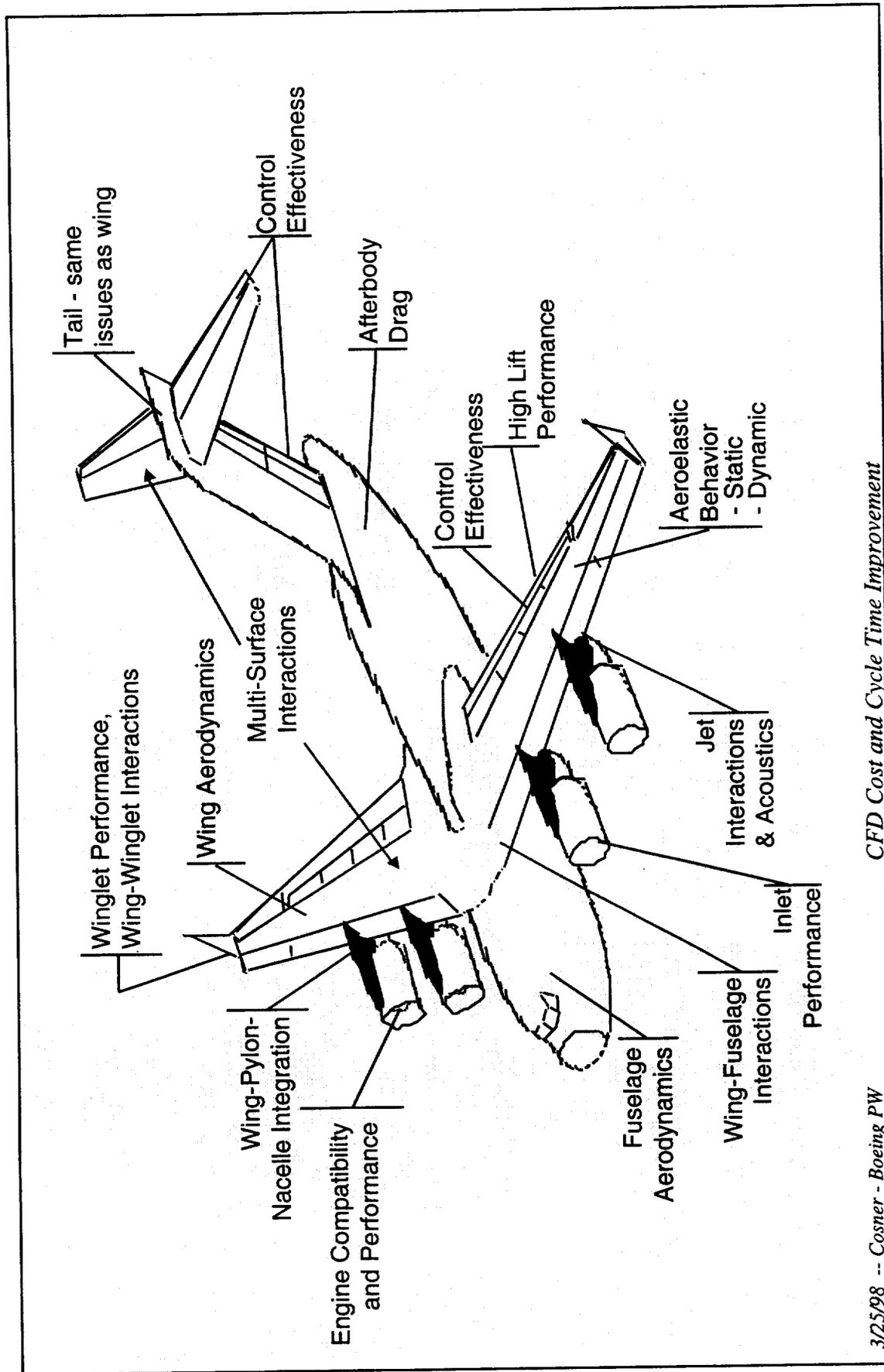
- **Current computational tools generally considered reliable only for conventional configurations at design conditions where the flow is mostly steady, attached, and fully turbulent**
- **Greatest uncertainty lies at the boundaries of the design space, where fast, low-fidelity tools are incapable of providing accurate information**
- **High-fidelity computational tools required in early stages of design process to more readily explore larger design space with greater confidence**
- **High-fidelity computational tools also provide ability to handle large changes in topology and shape**
- **Ultimate goal of advanced computational tools is to be able to predict absolute flight performance over the entire flight envelope with confidence**

Full-Envelope Simulation



Goal: To enable prediction of aircraft performance in flight over the complete flight envelope, thus allowing greater use of computational tools in the aircraft design process

Aircraft Design Requires Detailed Knowledge of Complex Aerodynamic Interactions

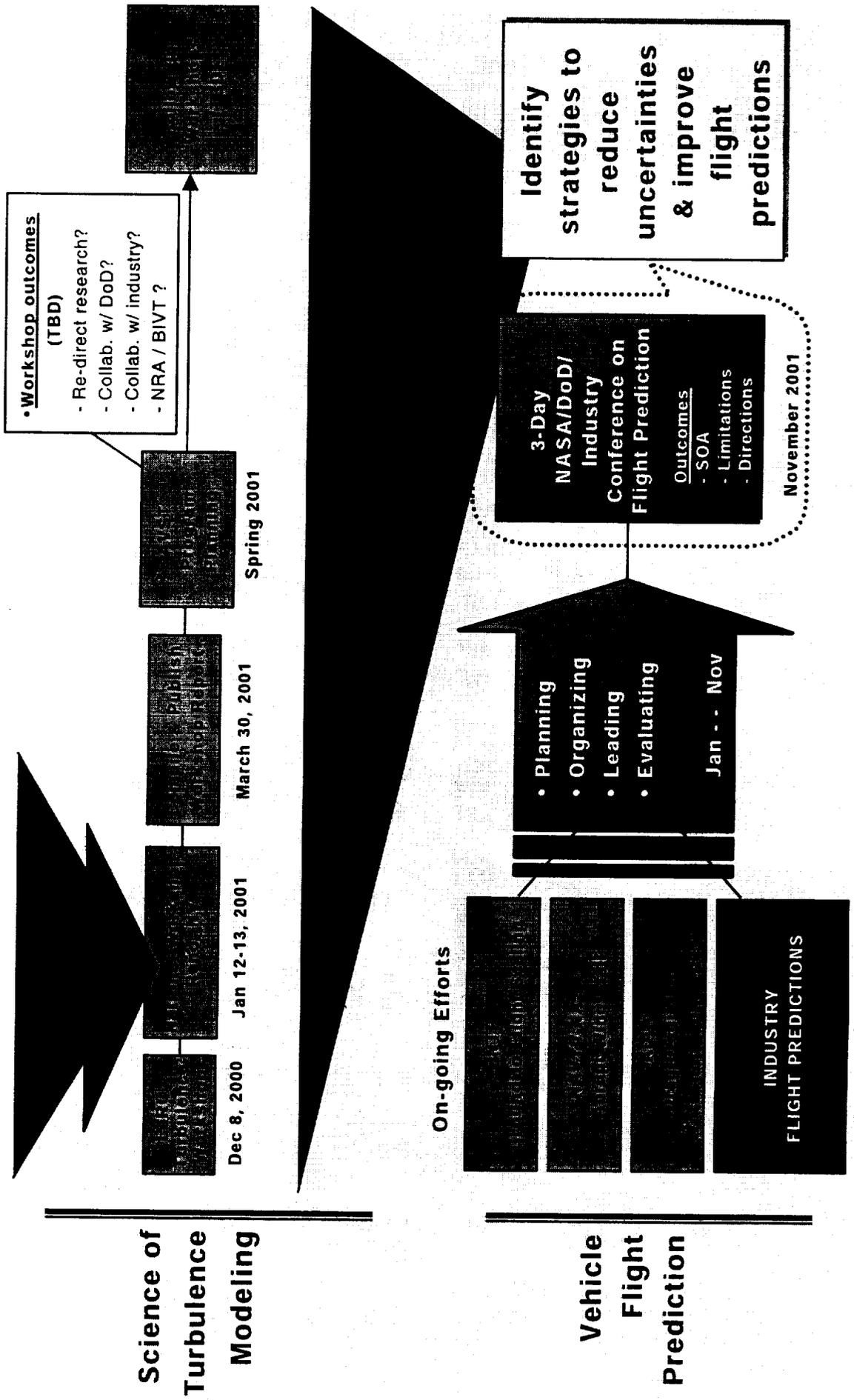


Pacing Items of Research in Computational Tools Development

	1970s	1980s	1990s	2000s
Numerics		██████████		
Grid			██████████	
Physical Modeling			██████████	██████████

**(SENSITIVE INFORMATION -
SLIDE NOT AVAILABLE)**

NASA Flight Prediction Roadmap (Near-Term)



Turbulence Modeling Workshop

Purpose

- **Identify significance of turbulence modeling in capturing various flow phenomena encountered during flight and in predicting flight performance**
- **Assess adequacy of current turbulence models and modeling approaches in addressing various flow interactions and identify shortfalls**
- **Identify possible research directions in turbulence modeling for next 3 to 5 years to meet our stated goal of flight performance prediction**

Turbulence Modeling Workshop

Expectations

A free and open discussion on

- **Adequacy and shortfalls of current turbulence models (or a hierarchy of models) in capturing dominant flow phenomena during flight**
- **Effects of compressibility, unsteadiness, transition, and Reynolds number on modeling**
- **Status of experimental data base necessary to develop/validate turbulence models**
- **Need of new approaches in turbulence modeling or even complete flow modeling (other than RANS approach)**
- **'Figures of Merits' to evaluate turbulence models, e.g. a unit problem, complex problem, robustness of the model, integration with computational codes, ease of use by a designer, etc.**

Workshop Structure and Outcome

- **Overview and technical presentations**
- **Three group discussions in parallel around preselected topics which will be rotated to capture thinking of all the participants on each topic**
- **Workshop report to be made available to all participants by March 30, 2001**

5/05

ASTAC Airframe Systems Subcommittee Perspective

**Presented to
ICASE / NASA Turbulence Modeling Workshop**

12 January 2001

Reno, Nevada

M. O. Anderson

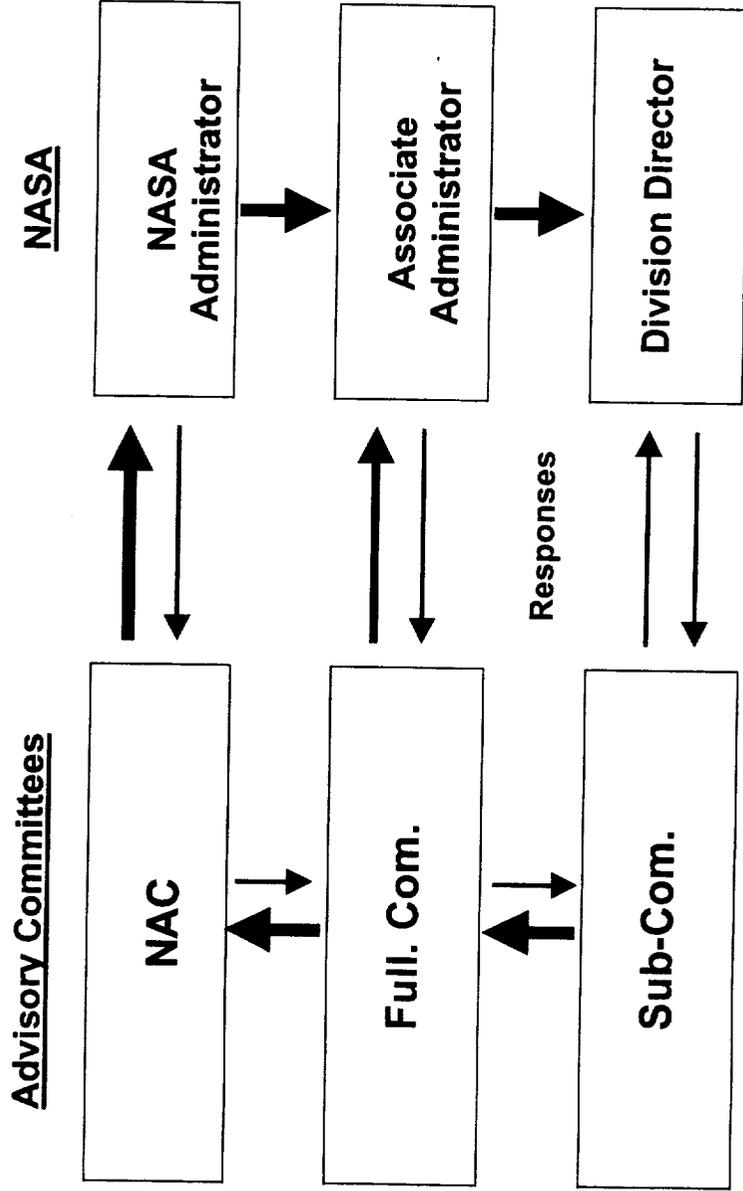
**NASA ASTAC Airframe Systems Subcommittee Perspective
12 January 2001 ICASE / NASA Turbulence Modeling Workshop**

Introduction

- Airframe Systems Subcommittee role in support of NASA Aerospace Technology Advisory Committee (ASTAC) and NASA Advisory Council (NAC).
- Relationship of turbulence modeling to strategic issues for NASA Aerospace Vehicle Systems Technology Program (AVSTP).
- Genesis of Subcommittee's interest in status of turbulence modeling.
 - Subcommittee recommendations for workshop format.
 - Assessment of today's status from Subcommittee perspective.

**NASA ASTAC Airframe Systems Subcommittee Perspective
12 January 2001 ICASE / NASA Turbulence Modeling Workshop**

NASA Advisory Council Structure



**NASA ASTAC Airframe Systems Subcommittee Perspective
12 January 2001 ICASE / NASA Turbulence Modeling Workshop**

Strategic R&D Issues for Subcommittee

- Nanotechnology vs. next generation composites for transports.
- Breadth / depth balance for revolutionary new aircraft concepts.
- Alternate CFD development approaches given external challenges.
- Reliability-Based Design vs. 'factor of safety' design philosophies.
 - Autonomous aircraft vs. next generation flight deck.
 - New design / current production retrofit balance for noise.
 - Ground-to-flight scaling.
- Next generation 'Design for Safety' / aging fleet balance for wiring.
- Speed regime balance (subsonic vs. supersonic vs. hypersonic).
- Aircraft capacity balance (regional / business aircraft vs. commercial transports).

**NASA ASTAC Airframe Systems Subcommittee Perspective
12 January 2001 ICASE / NASA Turbulence Modeling Workshop**

MD-11 Lift Levels (Boeing Sensitive Data)

(Sensitive Information - Chart Not Available)

NASA ASTAC Airframe Systems Subcommittee Perspective 12 January 2001 ICASE / NASA Turbulence Modeling Workshop

Airframe Systems Subcommittee Assessments

'Our major concern with current CFD turbulence modeling capabilities is the inability to reliably predict separation onset / progression characteristics (i.e., determining whether a flow is separated or not). This is the essence of most aerodynamic ...design problems and challenges. While great success has been achieved with CFD in accurately predicting attached flow conditions, and some promising techniques are emerging for dealing with massively separated flows, the reliable prediction of separation onset remains elusive. This is recognized... as the most difficult challenge for RANS....[T]he Subcommittee does urge the following actions:

- Accelerate the current effort to assess the capabilities of Reynolds stress turbulence models for cases where other models have failed.
 - Involve....all pertinent NASA research capabilities....
 - Move up the date for the Turbulence Modeling Workshop which is intended to assess results and identify strategies for further development from 4Q01 to sometime this calendar year (CY00). This assessment is needed earlier.'
- (Subcommittee report on AVSTP review held at NASA LaRC 7-9 December 1999)

'Current CFD (turbulence modeling) capabilities do not permit the reliable prediction of separation onset / progression characteristics. Efforts currently underway to address this deficiency, which is a critical path requirement if desired design cycle time reductions are to be achieved, need to be accelerated. Major advancements are needed.' (Letter to ASTAC Chair, 21 March 2000)

**NASA ASTAC Airframe Systems Subcommittee Perspective
12 January 2001 ICASE / NASA Turbulence Modeling Workshop**

Airframe Systems Subcommittee Assessments (concluded)

'[T]he inability of RANS methods reliably to predict separation onset and progression characteristics for the broad range of complex and different flow physics situations needed is well documented....[A]chieving reliable predictions of separation onset characteristics is the most difficult challenge facing RANS. In fact, there is a growing sentiment that it will not be achievable. The wide variety of flow physics types encountered with high lift configurations is a vivid example of the formidable challenge posed by having to find / develop a single turbulence model to represent adequately all pertinent physics. It is because of these identified (and very possibly fundamental) limitations of RANS methods that the Subcommittee has pushed for a workshop to be held to address current RANS limitations so that researchers from ...NASA..., government agencies, academia, and industry can come together to discuss and develop a plan for addressing and (hopefully) overcoming current limitations.'

(Subcommittee response to Action Item 9 tasked by ASTAC at 15-6 Aug 00 meeting)

"Turbulence Modeling suggestions:

- Address situations where we have known major disconnects.
 - Think 'flow physics.'
- Broaden the platform base (777, MD-11, C-17, C-5, C-141, regional / business aircraft).
 - Pursue error analysis for CFD and experiments."

(Subcommittee feedback on AVSTP review held at NASA LaRC 24-6 October 2000)

**NASA ASTAC Airframe Systems Subcommittee Perspective
12 January 2001 ICASE / NASA Turbulence Modeling Workshop**

Subcommittee Recommended Plan (16 October 2000) for Workshop

- Summarize historical configuration / flight condition / flow prediction problems.
- Explain selection of initial configuration / flight condition / flow for study.
- Disseminate 'lessons learned' (gridding, aeroelasticity, turbulence modeling, etc.)
- Present near term plans to expand scope of ongoing study beyond initial efforts.
- Assess prospects for Reynolds Averaged Navier Stokes (RANS) turbulence modeling vs. alternate approaches (DNS, LES, etc.)

**NASA ASTAC Airframe Systems Subcommittee Perspective
12 January 2001 ICASE / NASA Turbulence Modeling Workshop**

Summary

- **Airframe Systems Subcommittee offers advice. We should not (and can not) issue mandates to NASA regarding planning for activities such as this workshop.**
- **Aerospace Vehicle Systems Technology Program (AVSTP) will continue to be driven to undertake R&D with potential for strong contribution to NASA's goals.**
- **Ability of turbulence model refinements to contribute significantly to achievement of NASA goals is uncertain.**
- **Many issues (geometric fidelity, gridding, processes/tools for design loads determination, aeroelasticity, wind tunnel effects, transition prediction, flow unsteadiness, flight test techniques, etc.) can contribute to inadequate prediction of flight characteristics.**
- **Limitations of current (and future) turbulence models have not been resolved.**
- **NASA / Boeing CFD Buffet Onset Team has made significant progress. Much yet remains to be done.**
- **Outstanding Subcommittee concerns should be pursued vigorously within proposed 21st Century Vehicle Technology Program.**

**NASA ASTAC Airframe Systems Subcommittee Perspective
12 January 2001 ICASE / NASA Turbulence Modeling Workshop**

Expectations

- We must be willing to try new approaches. We can't continue doing what we know how to do today if it won't get us where we as a community need to go.
- We might need to accept fundamental limitations of our methods and align our expectations for fidelity of predictions accordingly.
- We must have healthy debates that cannot be seen merely as limit cycling.
- We need representation from all of NASA (LaRC, ARC, GRC, CTR, etc.), other government agencies (DOD, etc.), from throughout academia, and from the full the spectrum of industry (transports, regional / business aircraft, rotorcraft, etc.) We may have it this time. If so, we should keep it. If not, we should have it for our next steps.
- We must work together.

NASA-ICASE 2001 Workshop

High-Reynolds-Number Separated Flows

Philippe Spalart

Outline

- Ultimate expectations of the aerospace industry from CFD.
- On the nature of RANS turbulence modeling.
- Are unsteady, 3D, high-Re flows truly more challenging?
- Simple vs. elaborate RANS models.
- Detached-Eddy Simulation and related treatments:
no panacea, but quite promising for a class of flows.
- Outlook.

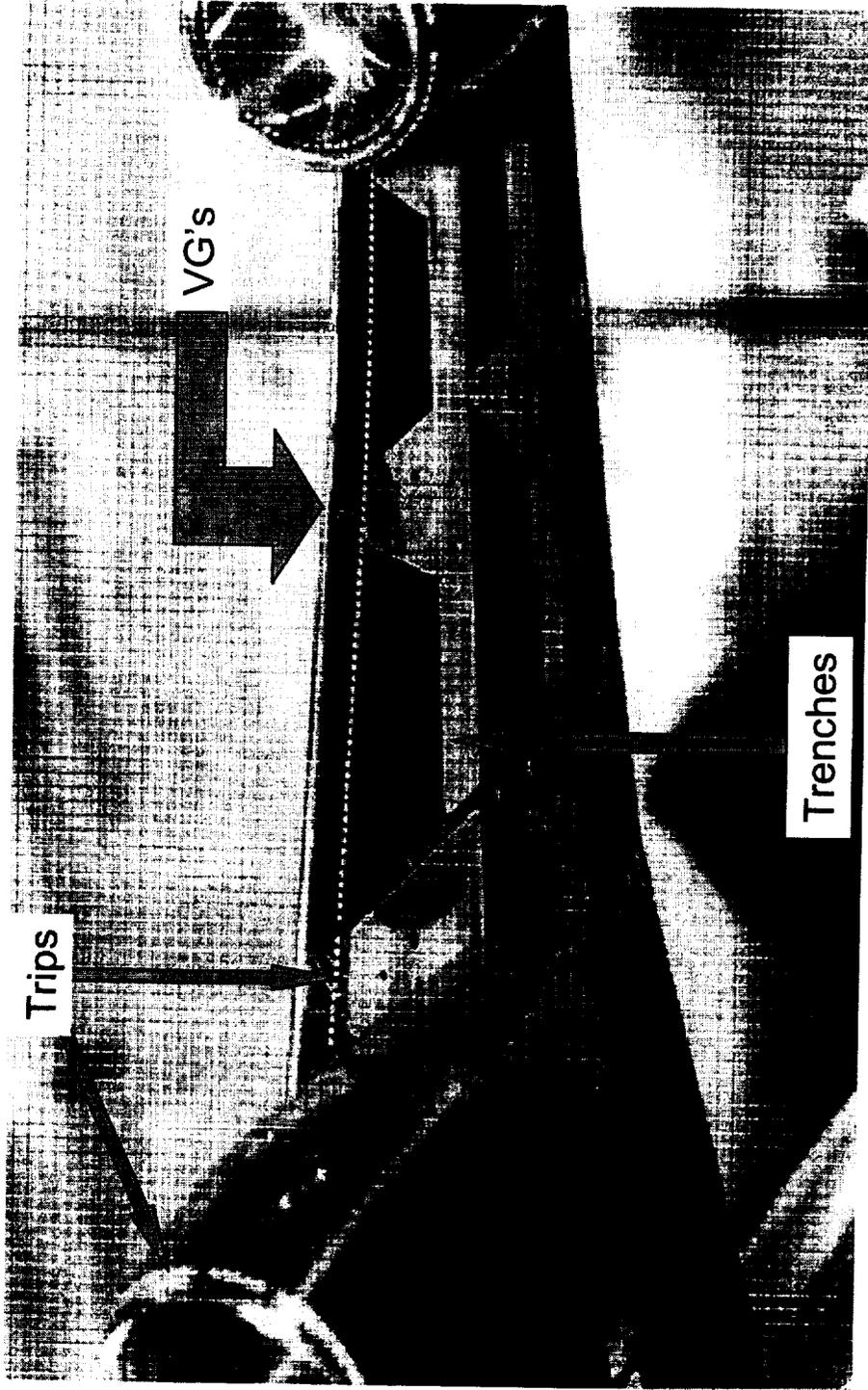


Ultimate Expectations from CFD

- Perfect predictions!
 - Errors in the 1% range for quantities such as total drag or buffet Mach number. 1dB of noise.
 - This is even though CFD is competing with imperfect wind tunnels.
 - Boundary-layer tripping is an art.
 - We are re-building the Boeing Transonic Wind Tunnel.
- The approach of choice:
 - can be applied or *extrapolated* to flight the best.
 - can be run *many* 1000 times in a matter of weeks.
 - CFD is essential for (attached-flow) design, of course.
- Either with tunnels or flight, aeroelastics is extremely important. We encounter new “issues” all the time.
- Separated flows for Stability & Control depend on small aerodynamic devices and flow features:
 - Nacelle chines, Kruger seals, spoilers, vortilons, vortex generators.
 - RANS modeling of free vortices is very poor (diffusive is far off).
 - For VG’s, treated collectively (“manipulated TBL”), it’s non-existent.



Testing Challenges at Flight Reynolds Numbers



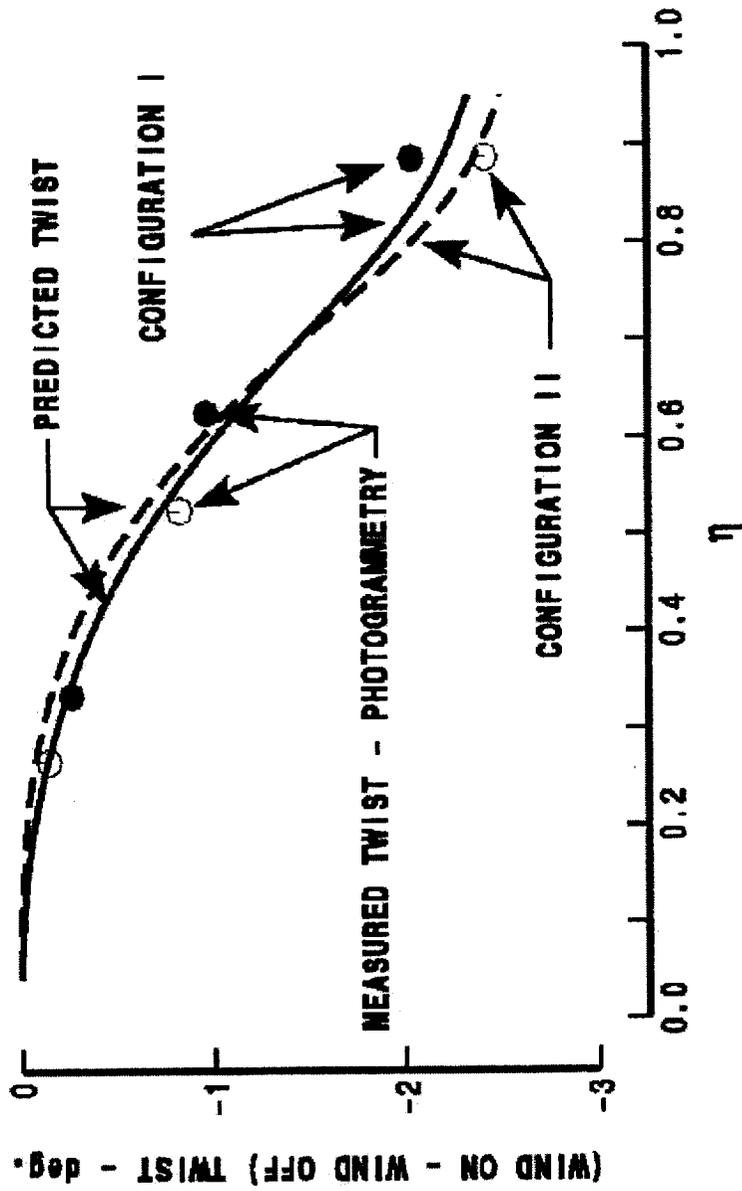
Test in the NASA NTF



Om et al., 2001-0909

Wing Twist in Cryogenic Tunnel

$Q=1900$ PSF, $M=.855$, $C_L = 0.5$

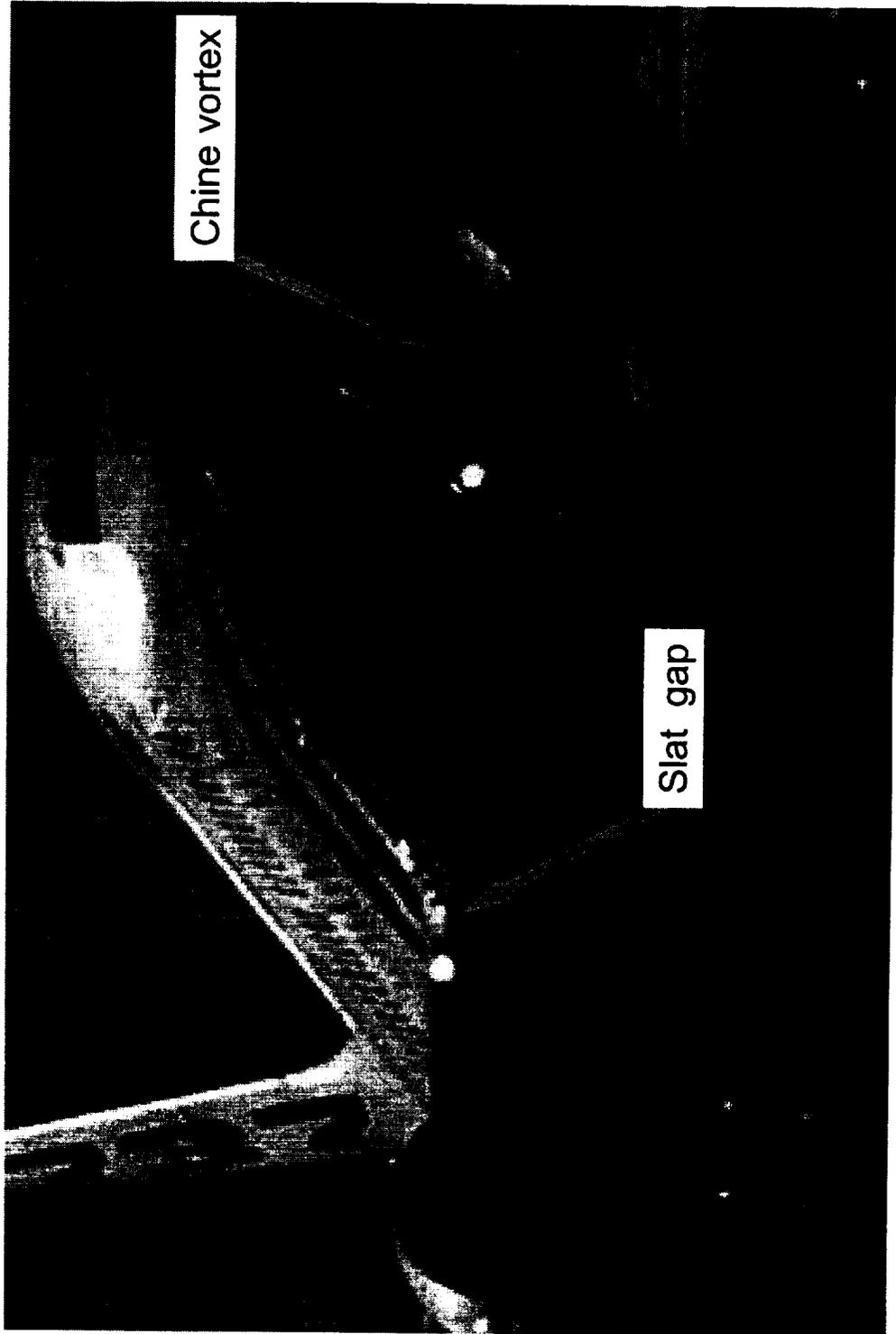


Test in the NASA NTF



Oh et al., 2001-0909

Small Flow Features Have Much Control



Chine vortex

Slat gap



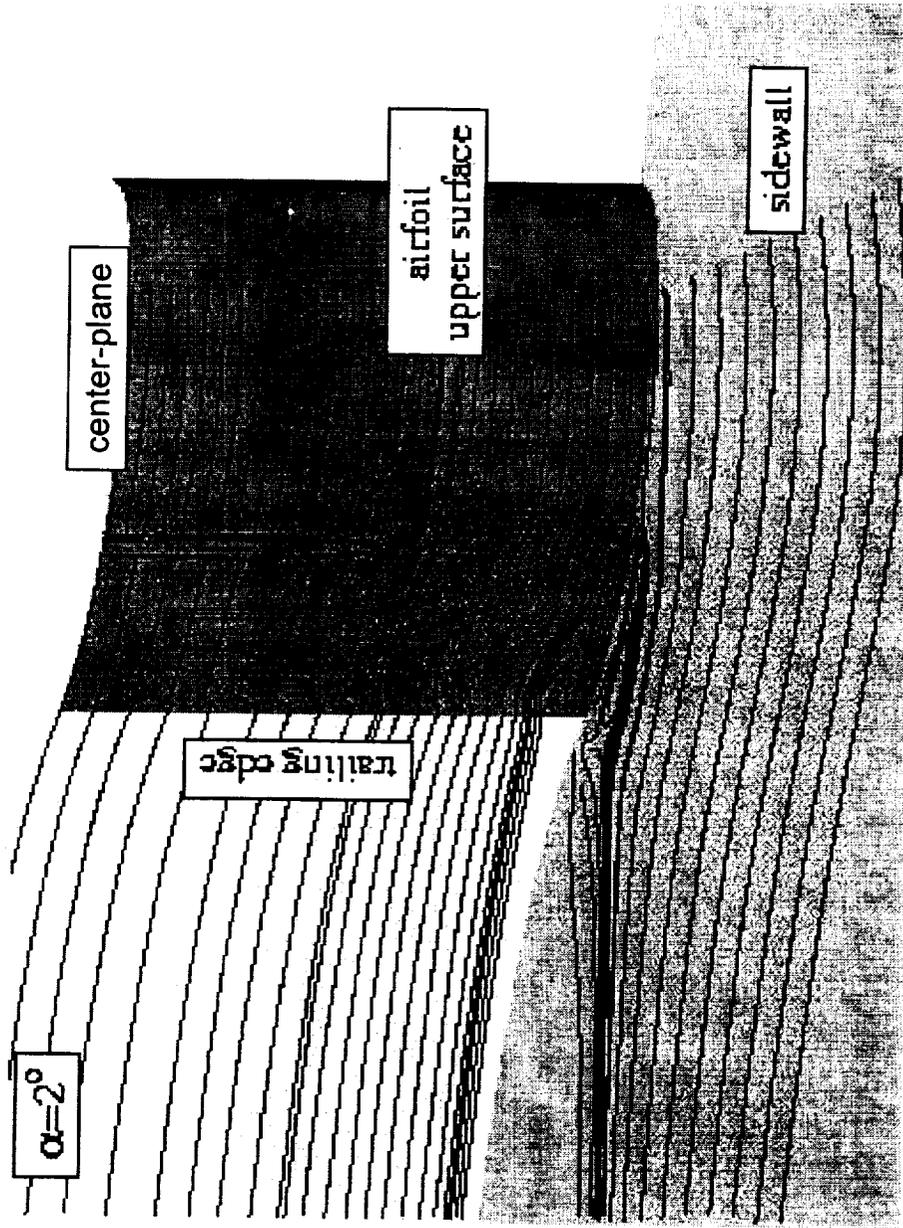
(who needs adaptive grids?)

The Nature of RANS Turbulence Modeling

- RANS modeling is fundamentally limited, of course. Turbulence does not exist at (x, y, z, t) , but CFD demands a “force” at (x, y, z, t) .
- The design of a model contains rigorous decisions:
 - Invariance, symmetry.
 - Exact terms if Reynolds-Stress Transport.
- However a model needs to be trained.
 - It has empirical content (all terms in S-A; ϵ_{ij} , pressure terms in RST).
 - It takes numbers from experiment or DNS.
- The calibration database is far from perfect
 - Data rarely is accurate to 1%.
 - 2D airfoil tests have become suspicious.
 - The Karman Constant is under attack, to the tune of a 2% skin-friction change at fuselage Reynolds numbers.
- We are not beyond “Stanford Olympics”-type work.
 - But we have better excuses for not matching.
- DNS comes just short of contributing.
- I know of no option besides RANS for boundary layers in practice.
 - LES is decades away.
 - Not to mention Quasi-DNS... (“LES” with viscous sublayer resolved)

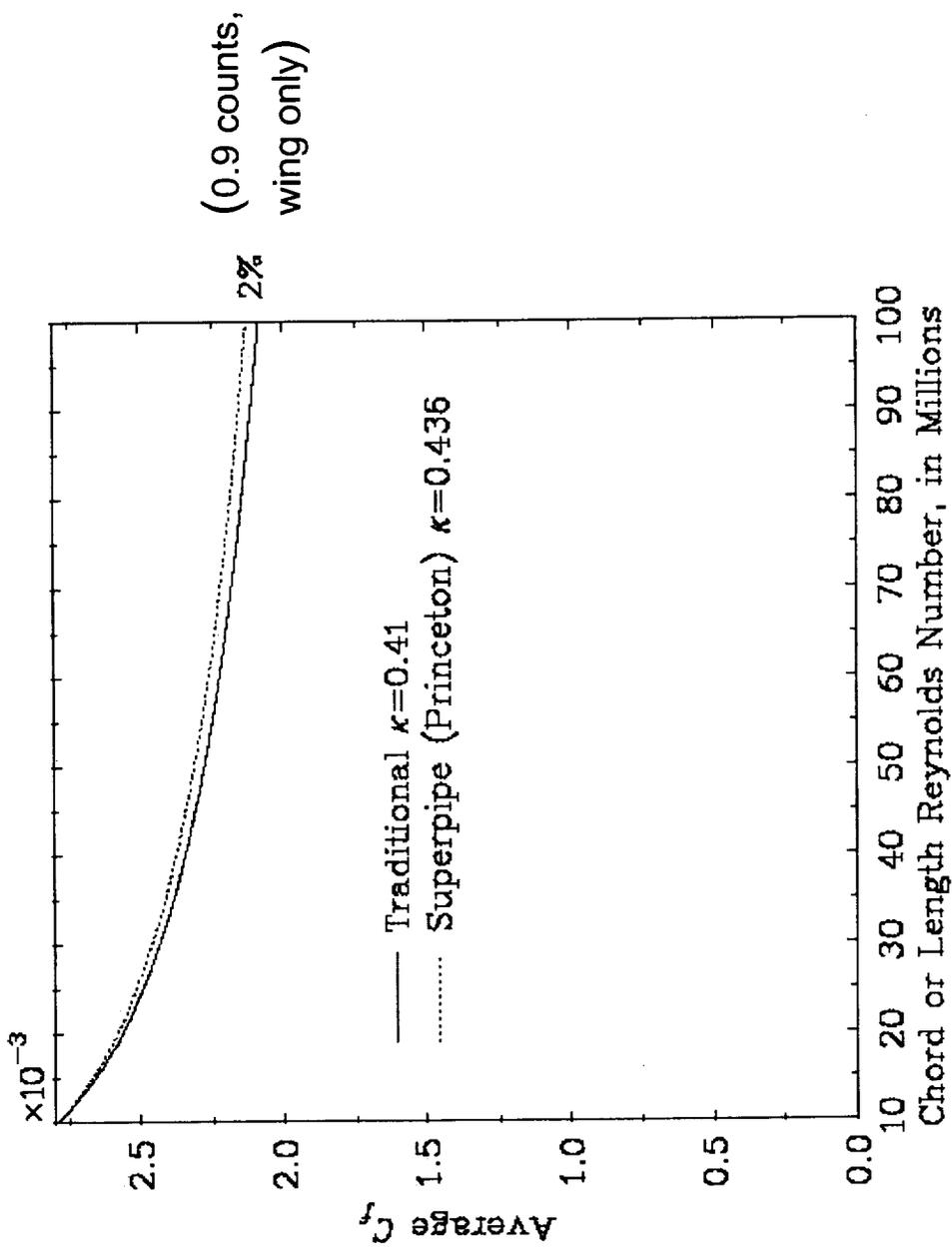


Effect of Side-Walls in Airfoil Testing



Low AR test *WITH* side-wall suction  **BOEING** Jiang, Long Beach, 2000-0510

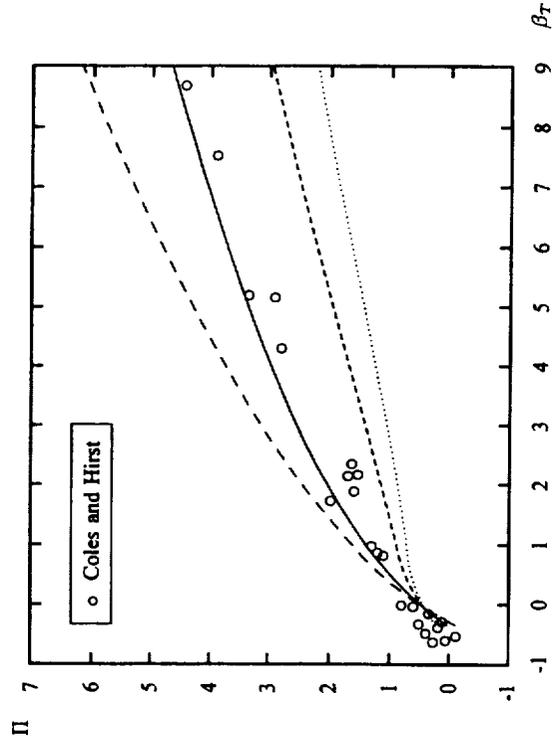
Effect of Karman Constant on Skin Friction



By Strelets group

The Challenge of 2D Boundary Layers

Shape parameter for self-similar BL

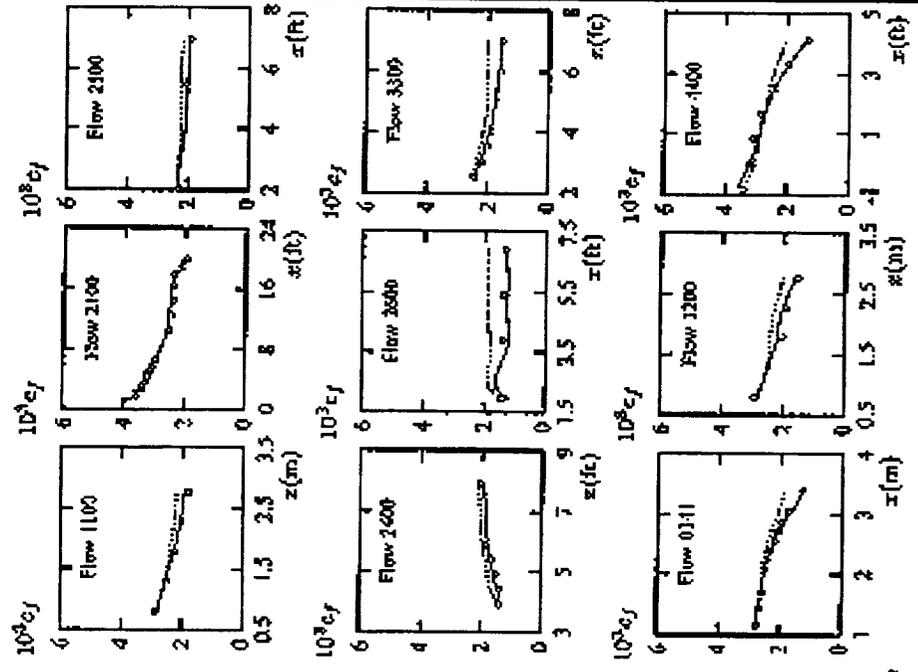


Adverse pressure gradient →

From Wilcox book



Skin friction with pressure histories



Unsteady, Three-Dimensional, High Reynolds. Truly more challenging?

- Sponsors like a new study to address a new difficulty.
- Of course, it is D/Dt that matters, not $\partial/\partial t$.
- Turbulence is deeply unsteady, therefore unsteadiness “of a new nature” is needed to claim a step in difficulty.
- A “steady” 2D boundary layer in adverse gradient is difficult enough, not to mention a “steady” vortex!
- Unsteady RANS is a very ambiguous approach for many flows, such as simple Karman shedding.
- 3D flows make eddy viscosity look wrong, but even in 2D:
 - $\langle u'^2 \rangle$ and $\langle v'^2 \rangle$ are off;
 - and play a role in adverse pressure gradient.
- On the other hand, 3D separation:
 - does not imply $u_t = 0$;
 - could leave the near-wall layer rather normal.
- The same for “high Reynolds number”: no mystery there.
 - K matters! 

Simple versus Elaborate RANS Models

- Reynolds-Stress Transport models:
 - are intrinsically more “correct” than few-equation models;
 - but their accurate range is not gratifyingly wider.
 - We read about “cautious optimism”.
 - Example: curvature effects. DO they come automatically?
 - RST models may not have vastly more adjustable constants; besides, optimizing many constants is difficult.
 - They still do “amusing” things (Apsley & Leschziner on the Obi diffuser: 2D separation better predicted with wall functions than with integration to the wall!).
- Complex models **will** “win”
 - because RANS will not be flushed out;
 - when reducing the remaining error is worth the extra cost;
 - but it could be only in boundary layers (*next slide*).



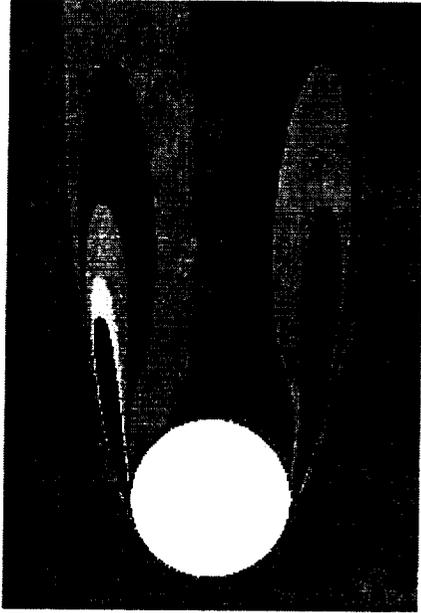
Detached-Eddy Simulation

- The words “demonstrable progress” in the invitation were mine.
- DES and related methods,
 - RANS in the boundary layers (initially S-A, now also SST),
 - LES after massive separation (IF it takes place),will “rule” in Aerodynamics.
- For some applications, resolving the unsteadiness would be needed even if SRANS gave a perfect mean flow. URANS is “stubborn”.
- In the LES region:
 - grid refinement provides a believable improvement in physics;
 - the model’s role vanishes;
 - we see a suggestion of grid convergence!
- However, RANS is not perfect even in boundary layers; separation prediction is as much of a concern in DES as in pure RANS.
- DES must be done well; grid design is a challenge. Education needed.
- DES should give us a step improvement over RANS in accuracy and in exploitability for a class of flows (trucks, cars, buildings, bridges, stall/spin, spoilers, landing gears, cavities, noise...).

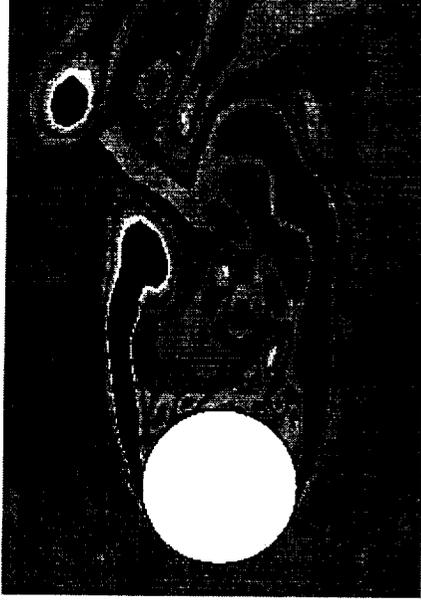


The Resolved Solution in Different Approaches

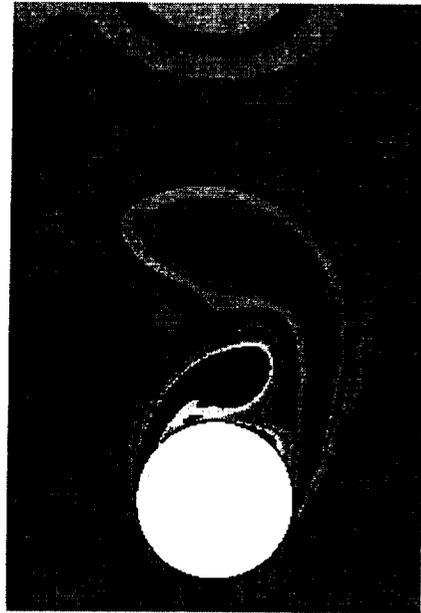
SRANS



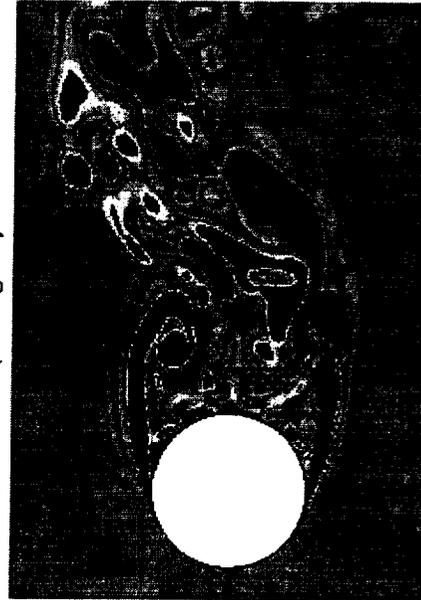
DES (coarse grid)



URANS



DES (fine grid)



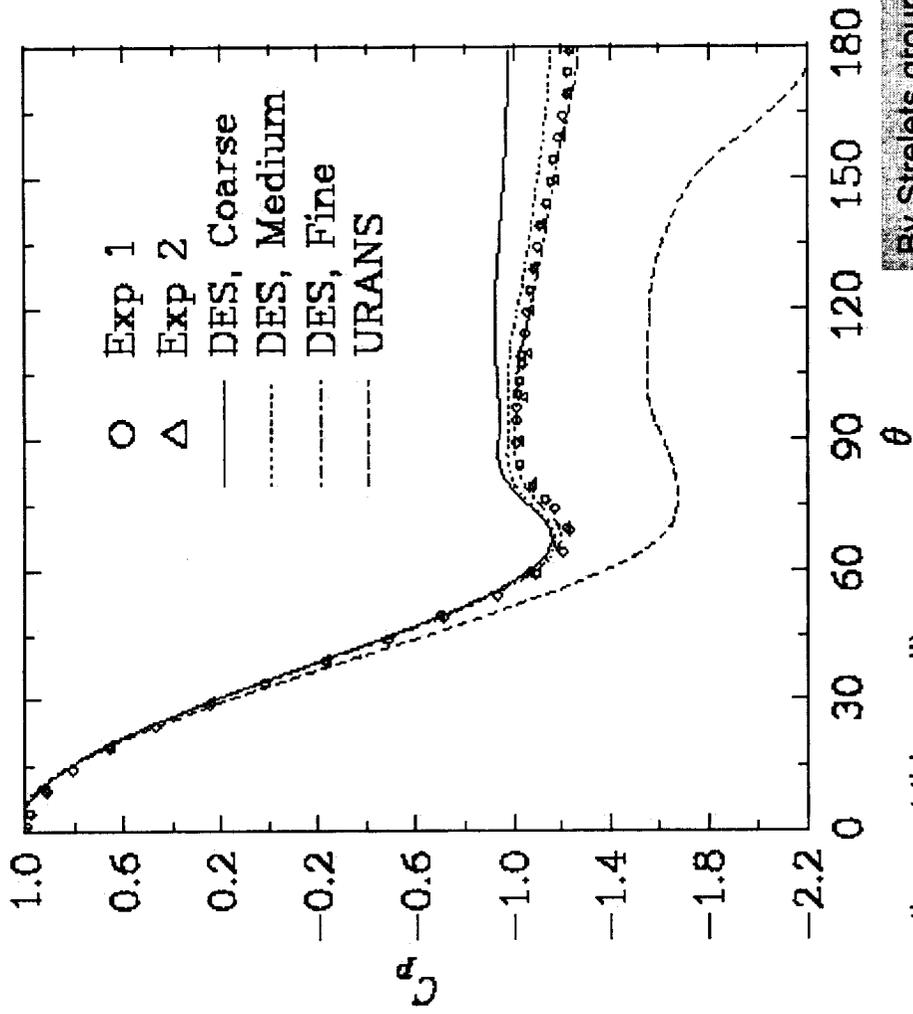
Cylinder, laminar separation, $1.e5$



By Strelets group

Circular Cylinder: Grid Convergence?!

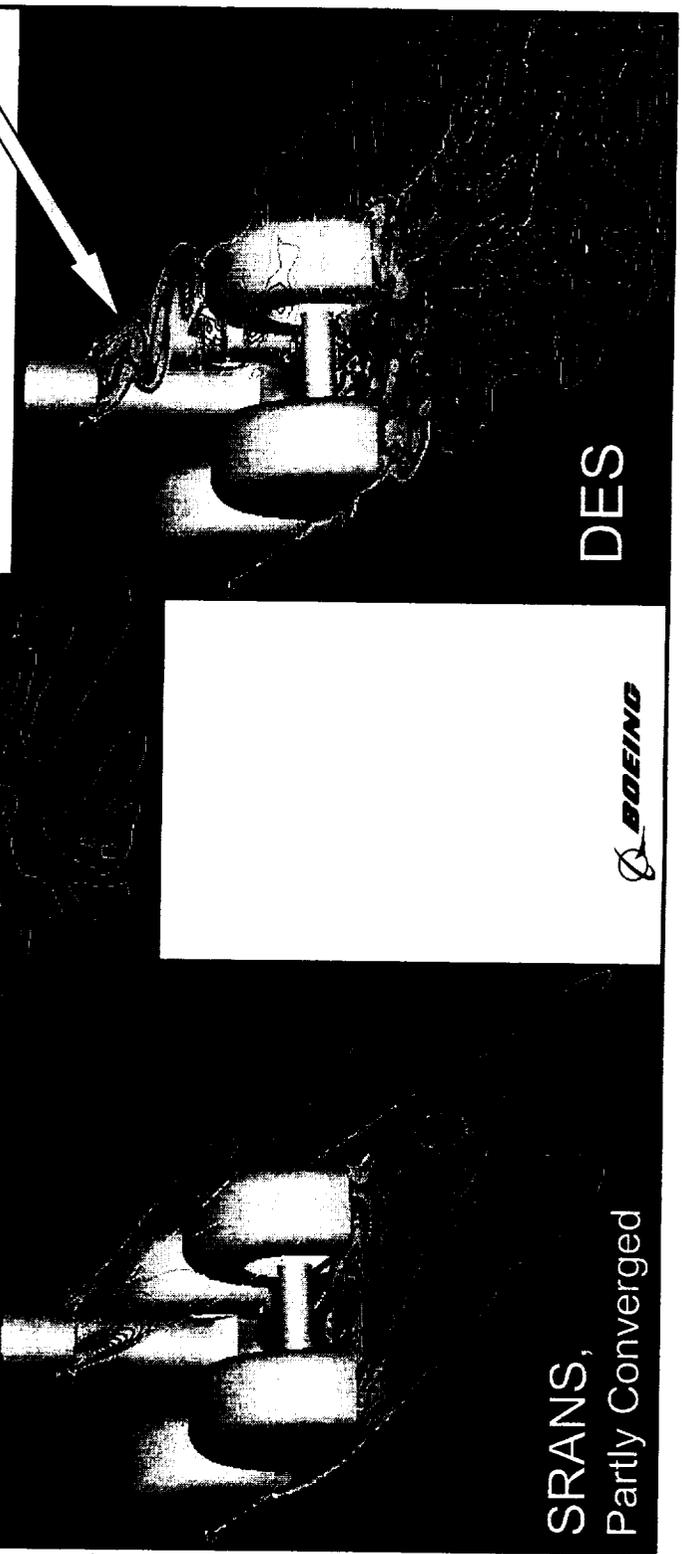
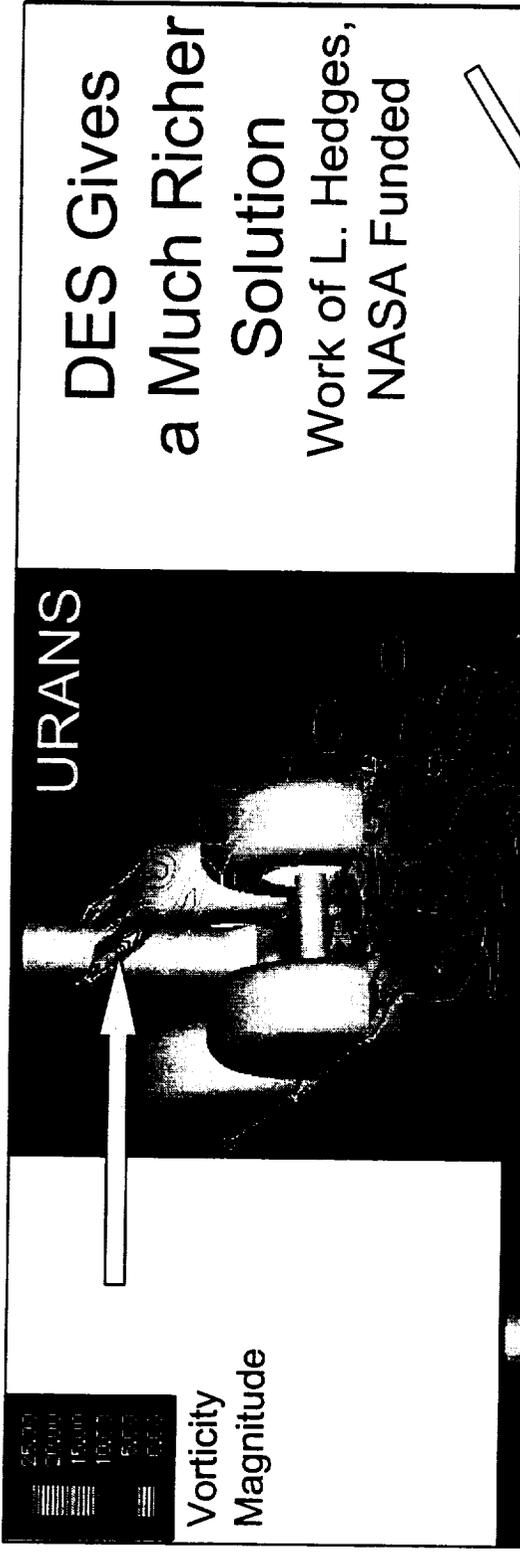
Laminar Separation, $Re \approx 10^5$



(turbulent separation: not this good!)



By Strelets group, FTAC, 2000

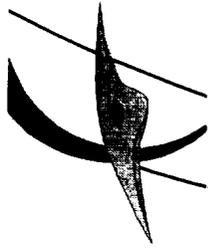


Outlook

- It is hard to be “bullish” about RANS when exquisite accuracy is needed, but I see no other option in the boundary layers.
- Some test-CFD conflicts were alleviated by better:
 - accounting for aeroelasticity;
 - grid convergence and geometry.
- We modelers still have “a place to hide”.
- CFD agreeing with NTF tunnel instead of flight is embarrassing.
- The cores of common models such as S-A and SST are not evolving (we have worked on curvature, compressibility, wall functions, roughness).
- It is hard to recommend between working on RANS “in the box” (EASM, RST?) and “out of the box” (Durbin’s f ? Perot’s potentials?).
- At flight conditions, checking for laminar regions on an “educated user” basis, as opposed to systematic close-coupled transition prediction, appears adequate.
- DES and other methods that are part-LES are worth a lot of exploration, but still rely on RANS for separation.



53/08



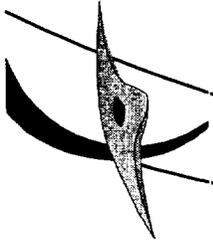
Turbulence Modeling Needs and Capabilities for Military Aircraft

Brian R. Smith

Lockheed Martin Aeronautics
Company

ICASE/LaRC Turbulence Workshop

January 12, 2001



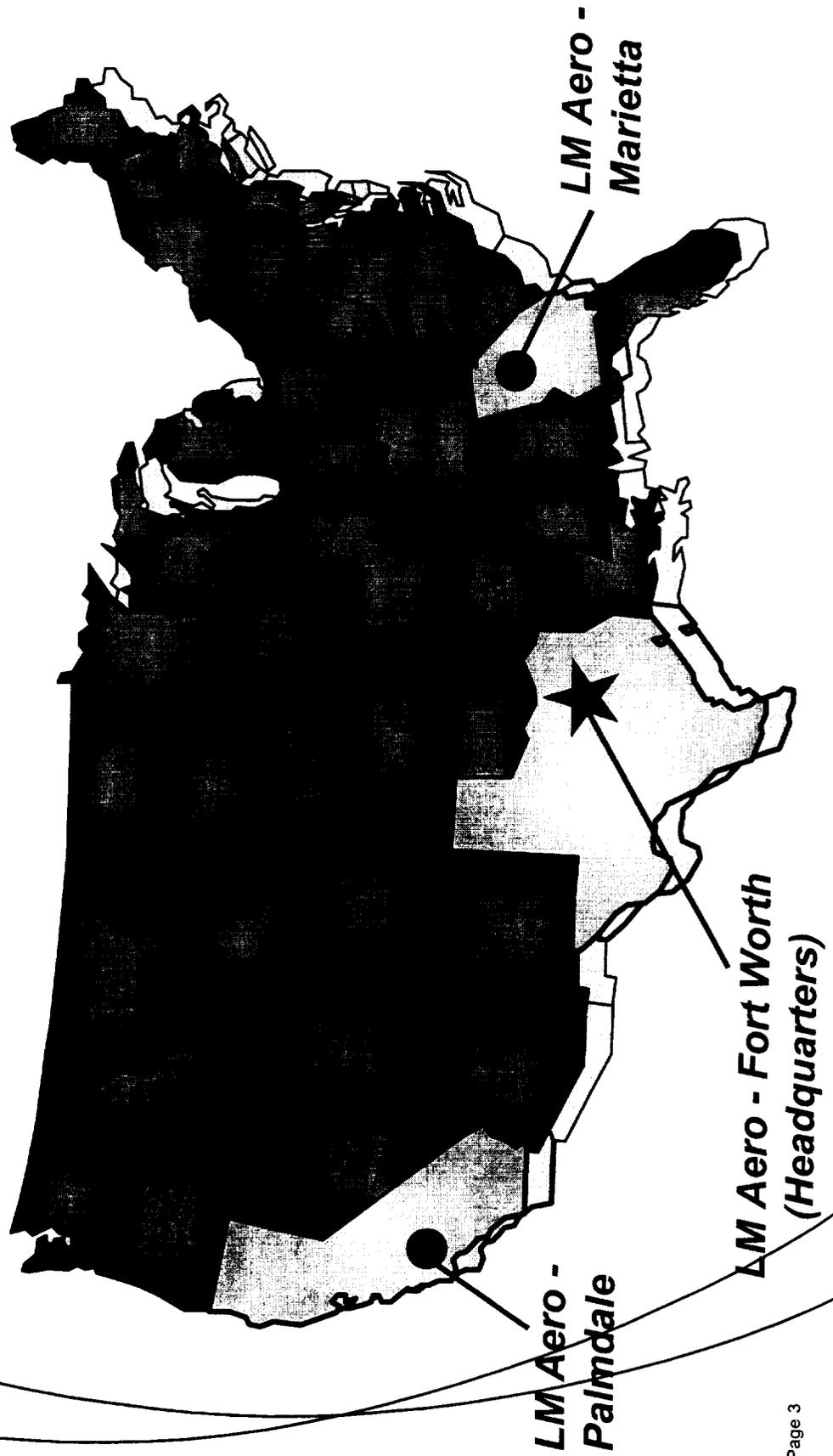
Outline

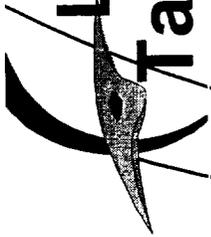


- Lockheed Martin Aeronautics product line
- Turbulence modeling application challenges
- Current modeling approaches (RANS)
- Turbulent flows with large scale unsteadiness (LES)
- Experimental accuracy and extrapolation to full scale
- Directions for future research

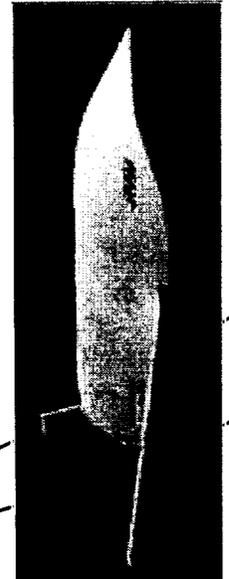
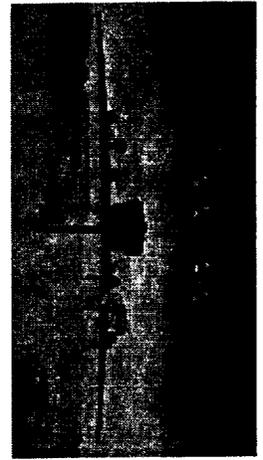
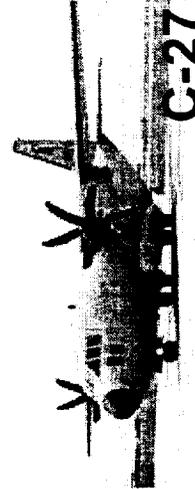
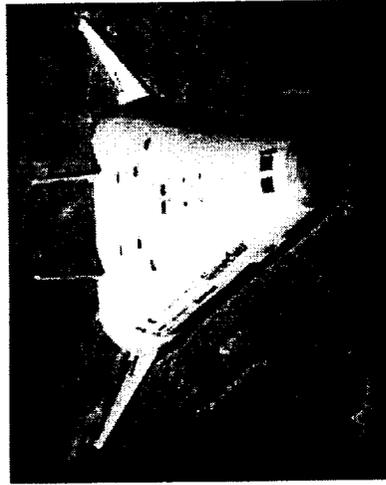
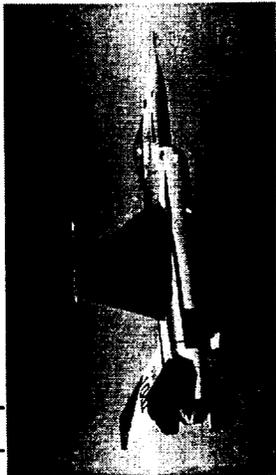
LM Aeronautics Transition

All LM Aeronautics business has been integrated into one single company - Lockheed Martin Aeronautics Company (LM Aero)





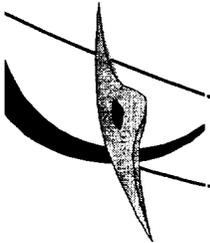
LM Aeronautics Lines of Business: TacAir, Air Mobility, & Special Projects



Pag

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Turbulence Modeling is a Major Source of Error in CFD Simulations

Magnitude of numerical errors has steadily decreased over past 10 years.

- Bigger, faster computers - better grid resolution
- Improved algorithms

Much less turbulence modeling R&D today than 10 years ago

Applications are more demanding

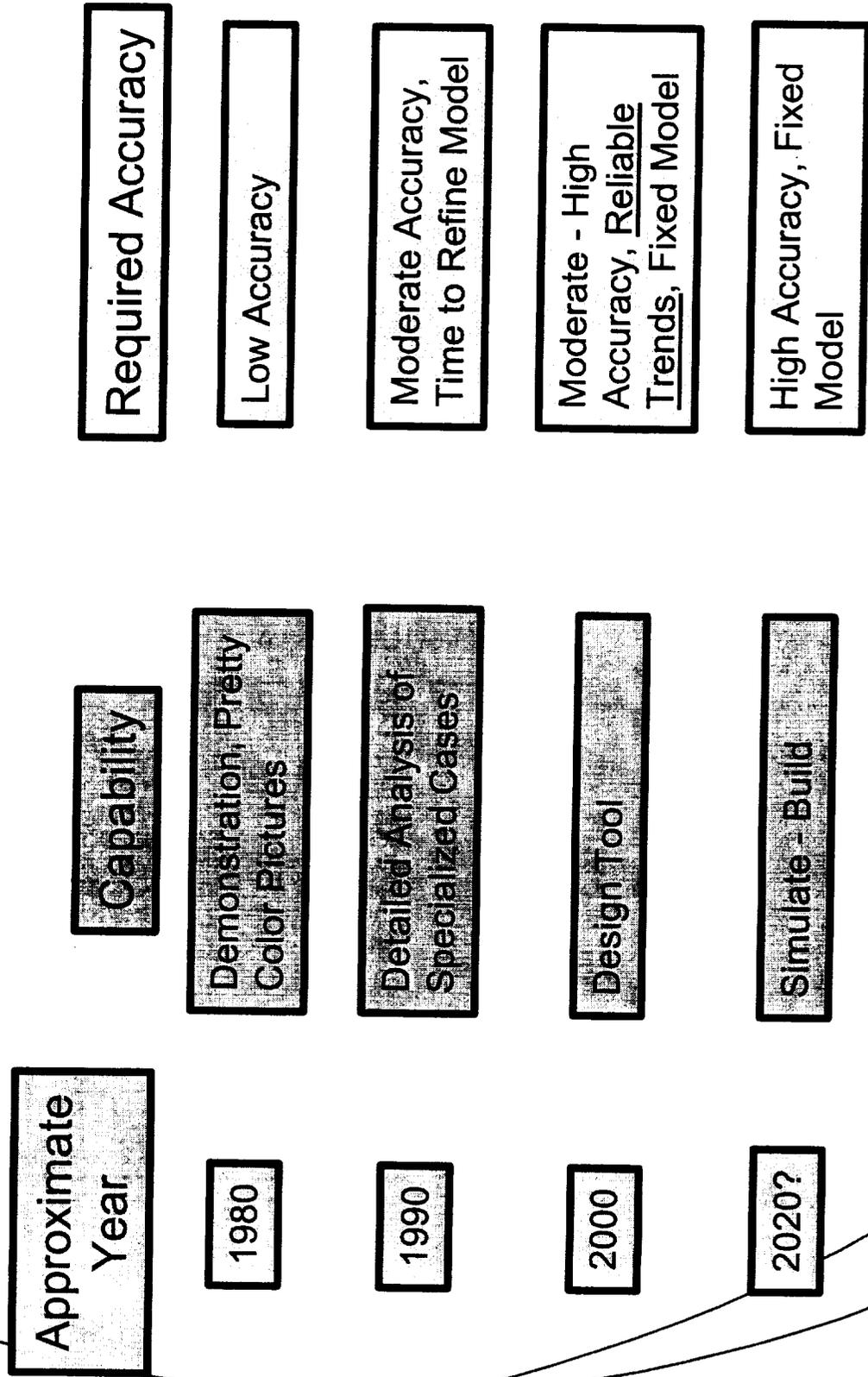
- LO considerations drive configuration - more separation
- Avionics integration results in non-aerodynamic shapes
- Flow control research - unsteady, small scale structures

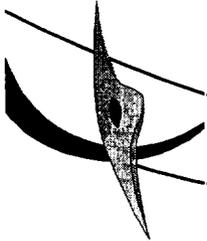
More reliance on CFD

- Reduced budgets for testing and development
- Compressed schedules - eg. compare JSF to F-22

Turbulence modeling errors are more visible and have more serious consequences today than they did 10 years ago.

Turbulence Modeling Accuracy Requirements:





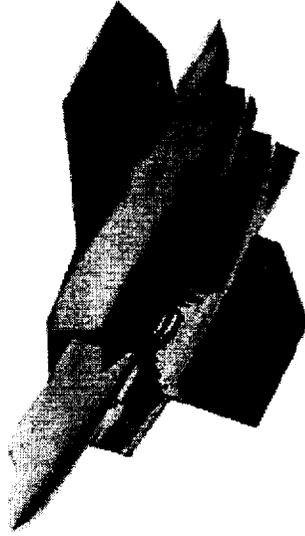
Fighter Aircraft Turbulent Environments Complex Geometries - Complex Flows



Fighter Aircraft External Aerodynamics Issues

- Pod and turrets - unsteady turbulent wakes
- Weapons bays - unsteady inviscid and turbulent flow mixing.
- STOVL - Jet impingement, entrainment
- Vortex flows over wings - vortex bursting
- High AOA - highly unsteady separation
- High speed flow - strong shock BL interactions

Weapons Bay Loads



STOVL Environment

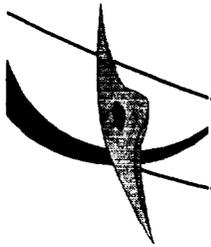


Avionic Pod Integration



Store Integration





Advanced Fighter Aircraft and UCAV Internal Flows - Radical Designs



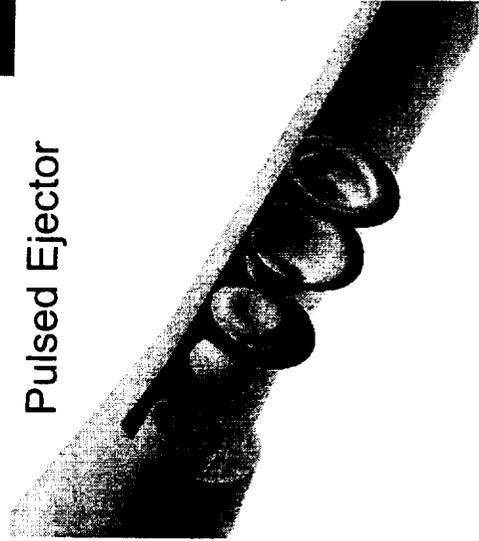
Turbulent phenomena key to effectiveness of innovative designs

- Diverterless inlet - 3-D turbulent boundary layer
- Pulsed Ejector - unsteady inviscid - viscous interactions
- Compact inlet - streamwise curvature
- Conformal Fluidic nozzle - compressible shear layer entrainment

Diverterless Supersonic Inlet



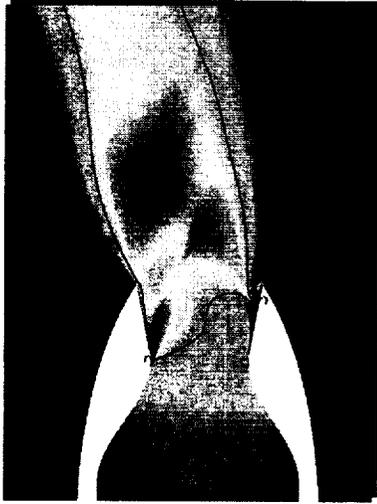
Pulsed Ejector



Compact Inlet

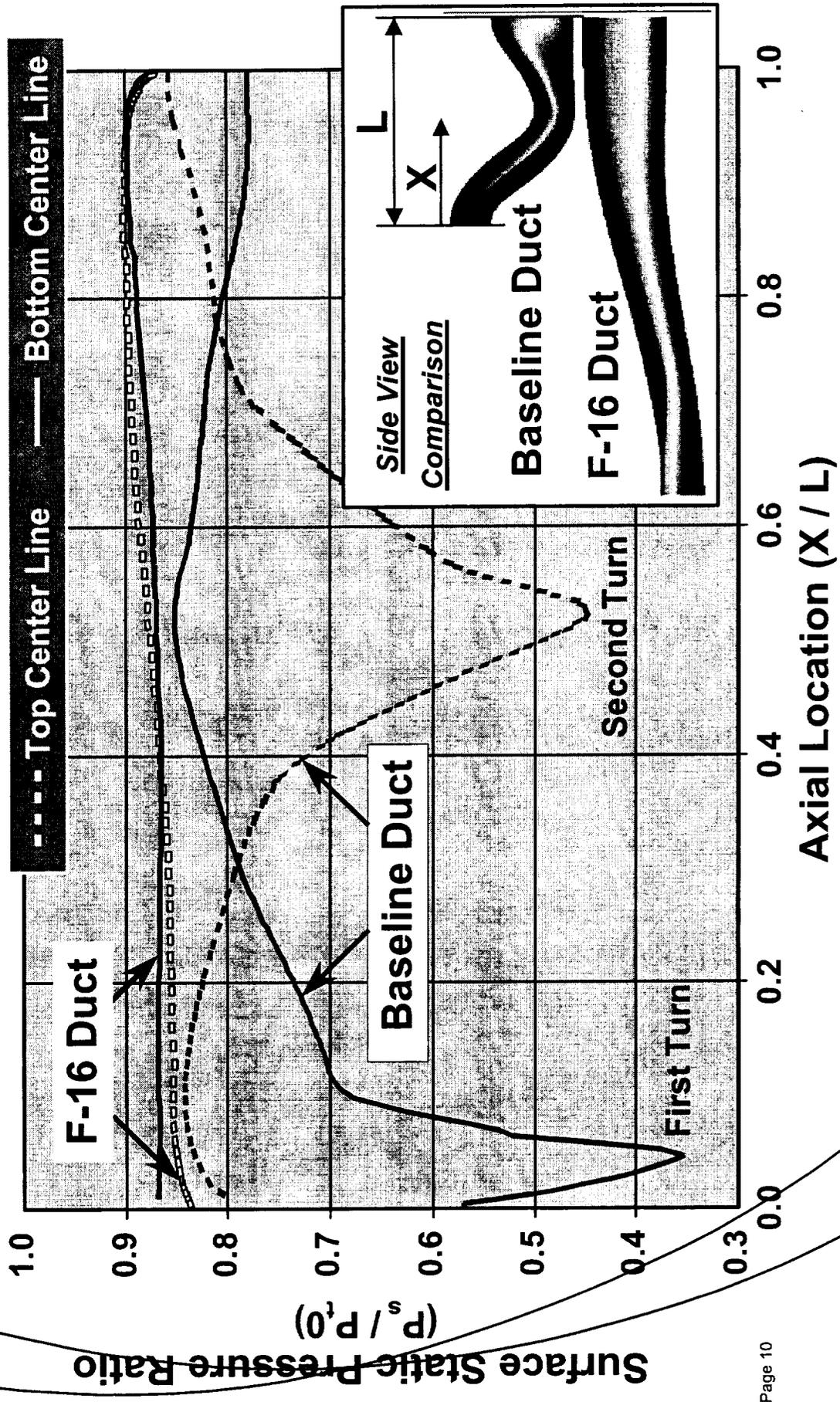


Conformal Fluidic Nozzle



Inlet Geometry Comparison

Baseline duct features extremely aggressive curvature which leads to unacceptable performance without technology advancement.





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Turbulence Modeling Practice in Aerospace Industry

Most turbulent flow applications use one or two transport equation models

- One equation - Spalart - Almaras
- Two equation
 - √ $k - \epsilon$ including wide range of variants
 - √ $k - \omega$ and SST
 - √ $k - \kappa l$

Why are more advanced models not used ?

- Cost of implementation and validation
- Inadequate validation - does model provide improvements over a wide range of flows?
- Computational robustness is absolutely critical - increases the cost of implementation greatly.
- Experience base and expectations with current models make change difficult.



Shortcomings of Two Equation Models for Aerospace Applications

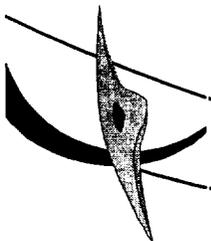


Primary shortcomings of one and two equation models

- Streamwise Curvature
- Reattached Boundary Layer
- Unsteady Separation
- Vortical Flows/Swirl
- Shock-Boundary Layer Interactions
- 3-D Boundary Layers - strong crossflow
- Compressible shear layer

In order to be useful improved models must not degrade accuracy of predictions in attached boundary layer flows

For near term implementation in the industrial environment, models that increase computational requirements by more than a factor of 2 or 3 would likely be useful only for special cases

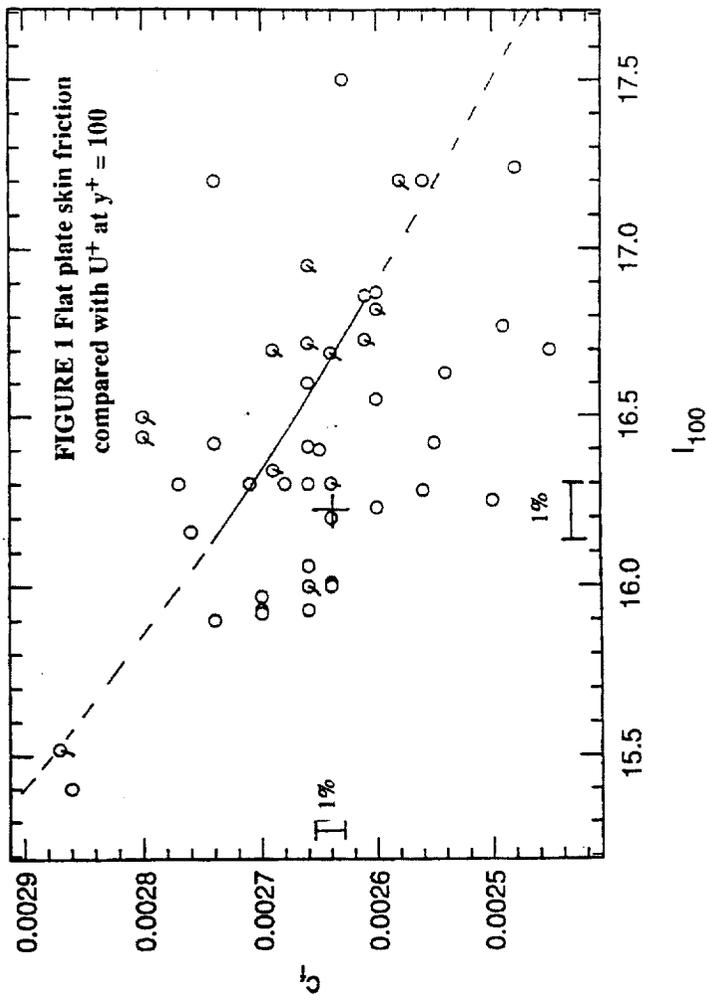


Turbulence Model Accuracy for Simple Flows is a Major Source of Concern



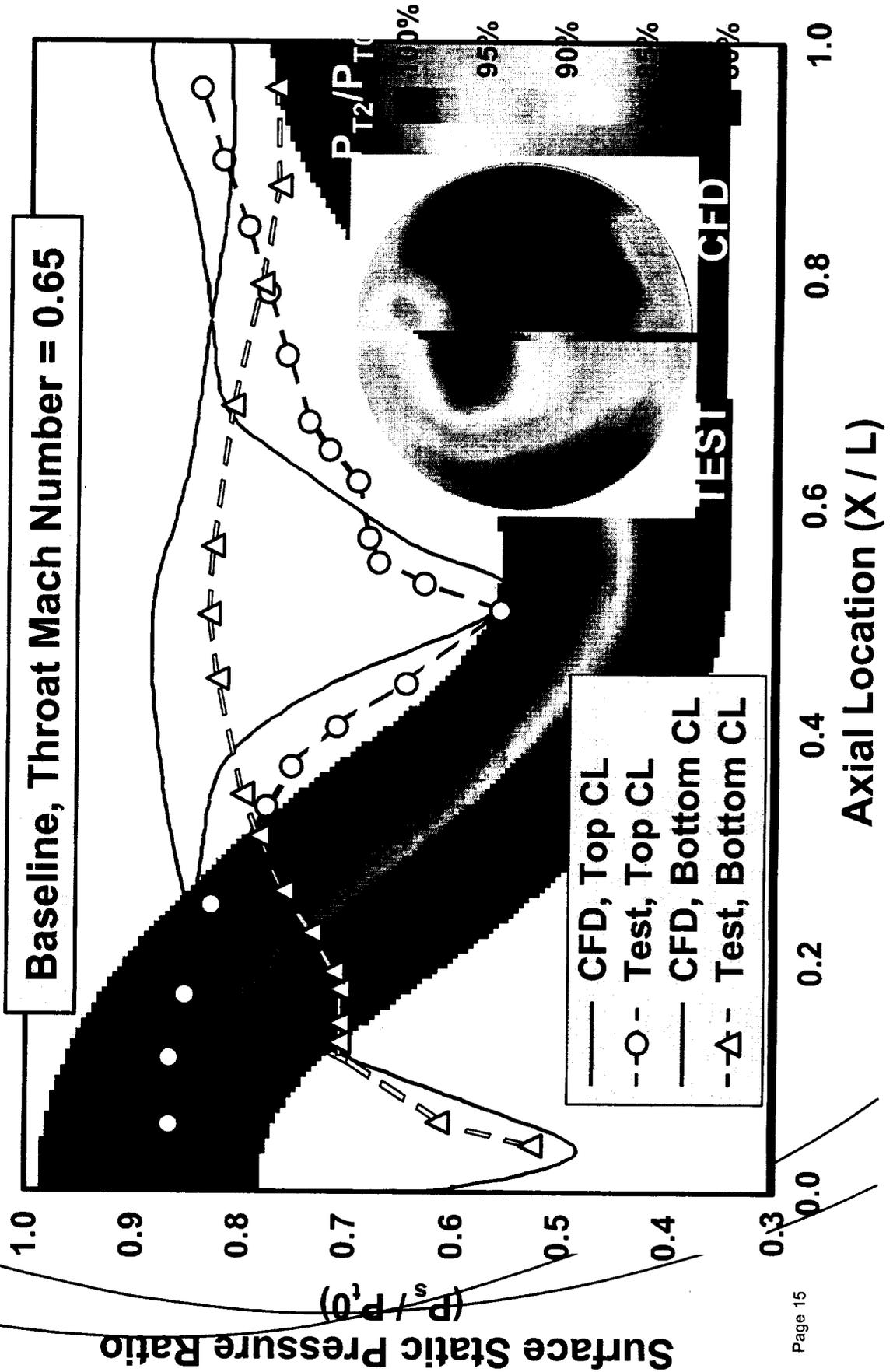
Results from Collaborative Testing of Turbulence Models Project - 1991
 Flat plate turbulent boundary layer
 Skin friction errors of $\pm 5\%$

Plot of U^+ vs C_f at $Re_\theta = 10000$



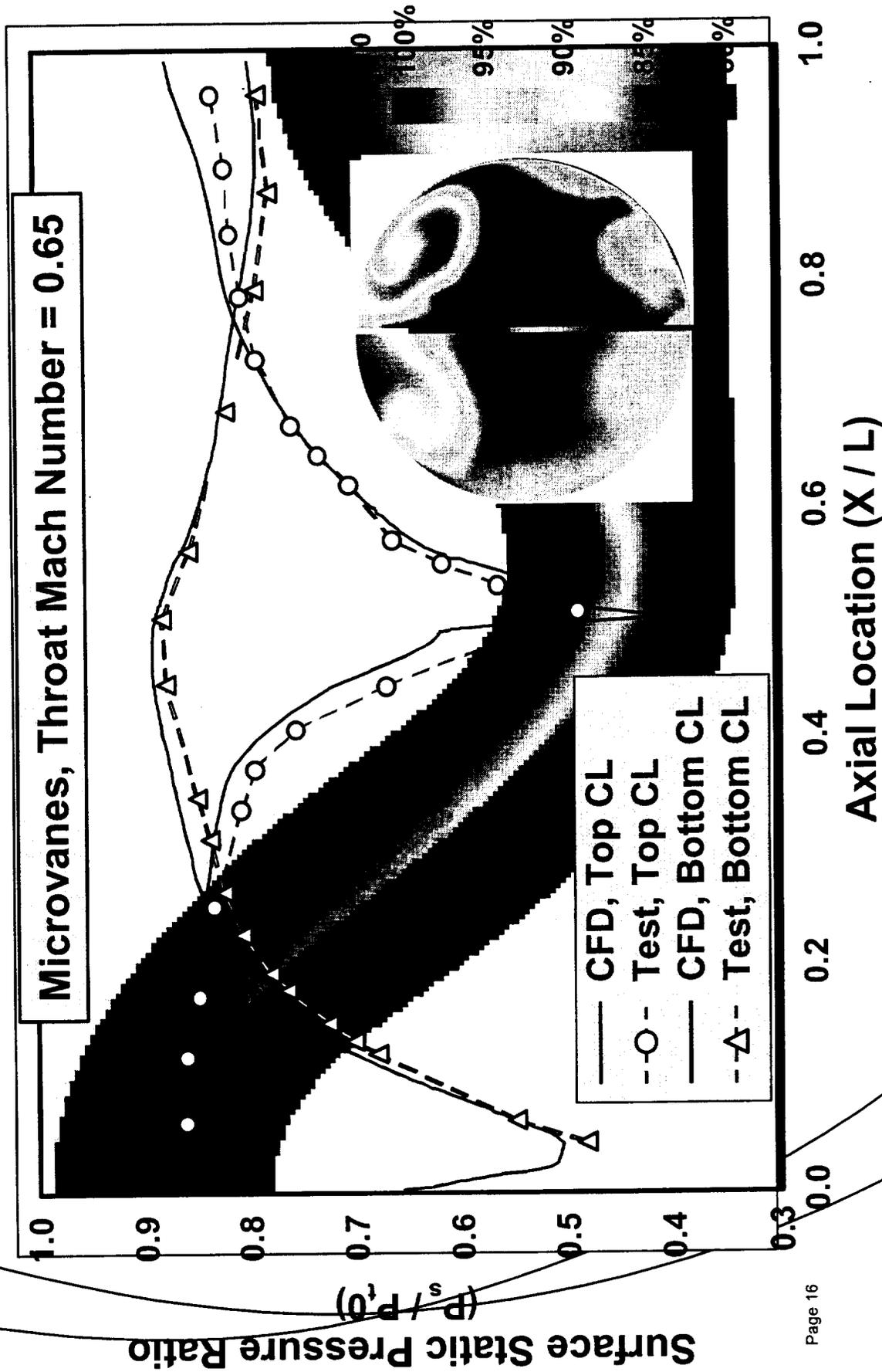
Baseline Test-to-CFD Comparison

Two equation model underpredicts losses in baseline duct.



Effector Test-to-CFD Comparison

Two equation model closely matches performance with flow control.



Improved RANS Models Can Account for Complex Turbulent Phenomena

Non-equilibrium two equation

- Simple implementation
- Modest improvements

Three equation

- Not applicable to highly complex geometries
- Good potential for curvature effects

Algebraic stress

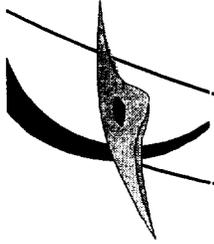
- Stress calculations can reduce diagonal dominance
- Curvature effects require accounting for shear stress convection

Reynolds Stress Closure

- Computational intensive
- Not Robust

Enstrophy model

- Complex
- Not mature



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Large Eddy Simulation Necessary for Some Aerospace Applications

LES is extremely computationally intensive and it is not used unless RANS is not suitable
LES is less accurate than RANS for attached and mildly separated flows
LES is at the "analysis" rather than "design tool" level of maturity

Where is LES required?

Unsteady pressures or loads are needed

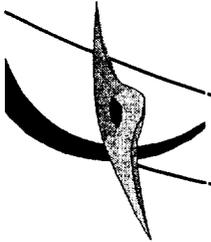
- Weapons Bays
- Wakes of pods and turrets

Scales of inviscid structures and turbulent eddies are similar

- Weapons Bays
- Unsteady, small scale actuation for active flow control

Unsteady separated flows

- Wakes of pods and turrets
- High angle of attack and large control surface deflections

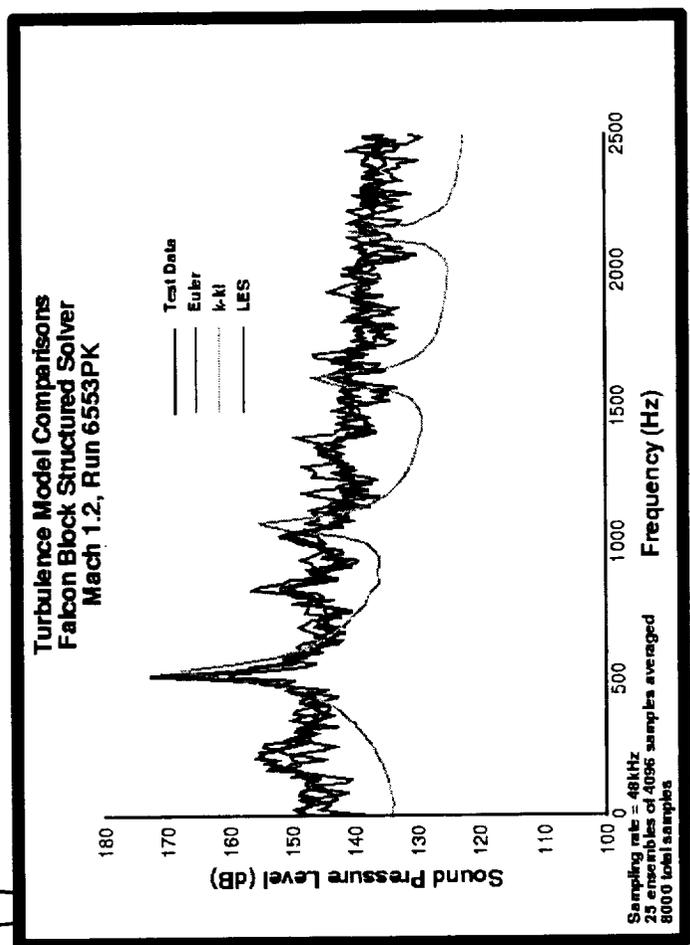


Simulation of Weapons Bay for Structural Loads Requires Unsteady Analysis

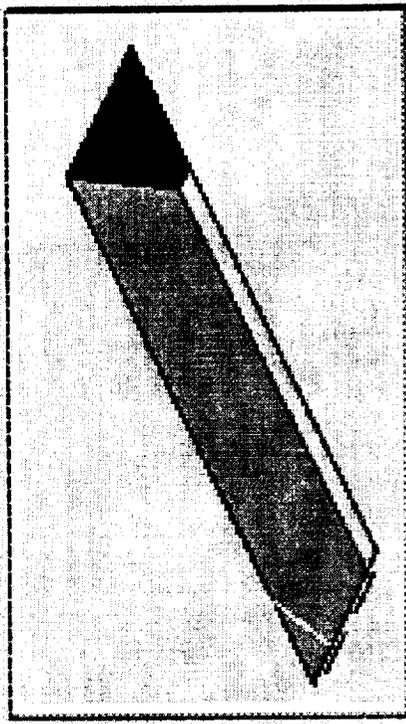


Unsteady pressures needed for structural analysis
RANS solution damps unsteady structures
Unsteady Euler simulation is primitive LES

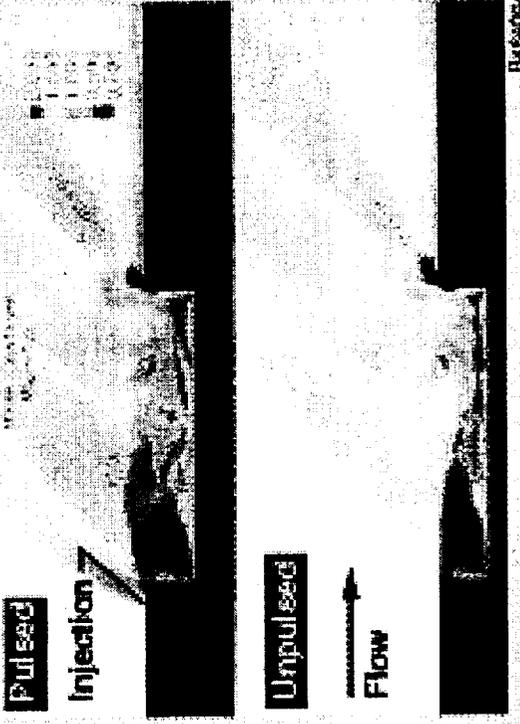
WICS Bay, Mach = 1.2

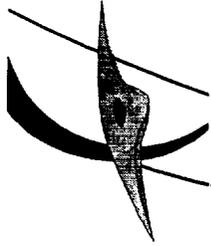


Symmetry plane Mach contours show resolved unsteady structures in flowfield



3D Euler with and without pulsed injection



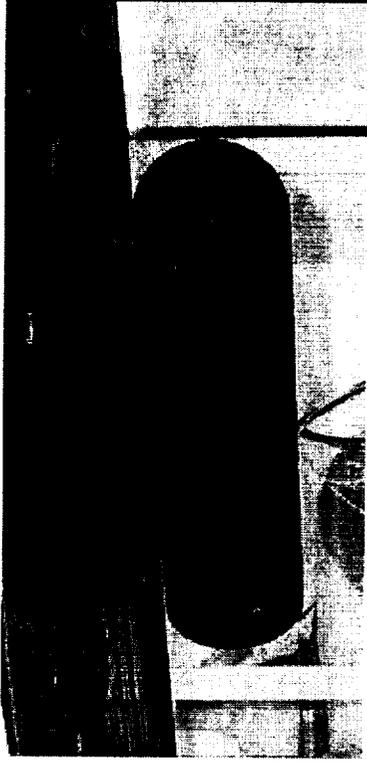


Pod Flow Field Characterization



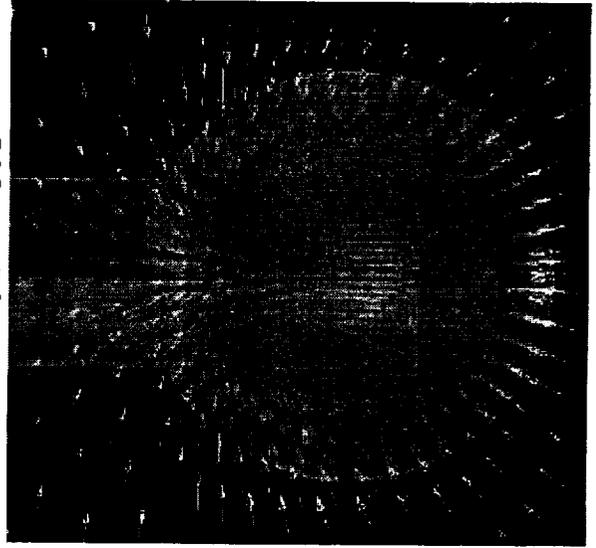
- Generic Pod Modeled after LANTIRN
- Identified pair of vortical structures in downstream wake
- Wake Vortex Structure is Unstable Dynamically

Wind Tunnel Installation



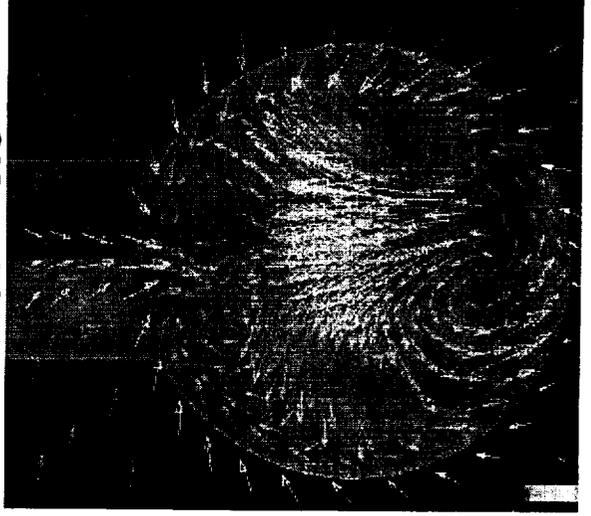
RANS

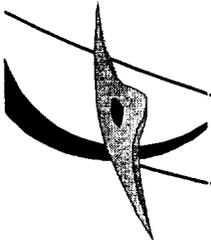
at $x/D = 0.5$



Instantaneous LES

at $x/D = 0.5$



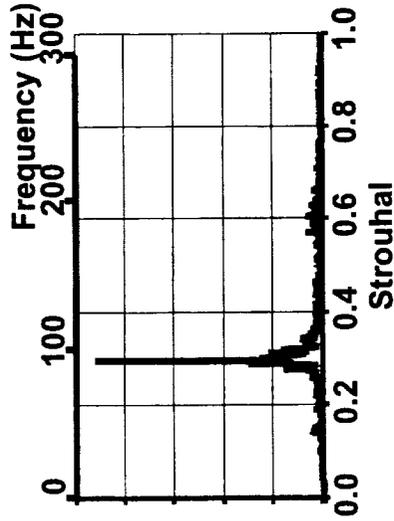


Pod Wake Acoustic Signature



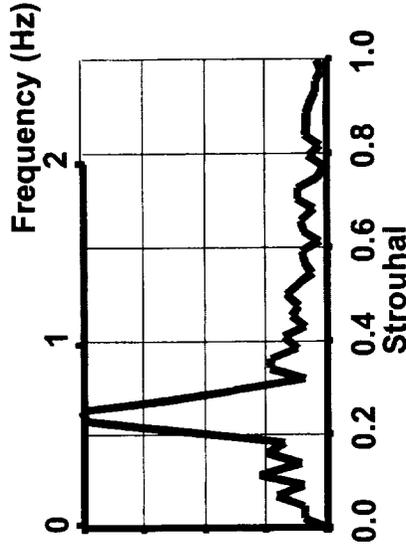
ADF Pressure Data

U_{inf} = 118 ft/sec
 x/D = 3.86, y/D = 0.04,
 z/D = 0.45



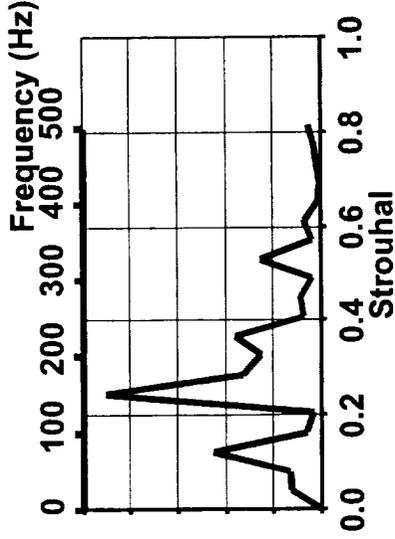
PIV Water Tunnel

U_{inf} = 1 ft/sec
 x/D = 2.06, y/D = -0.12,
 z/D = 0.40

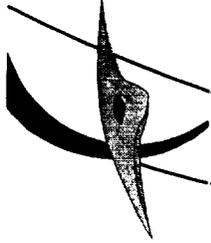


LES Simulation

U_{inf} = 224 ft/sec
 x/D = 2.06, y/D = -0.12,
 z/D = 0.395



Data Source	Primary Mode (Hz)	U _{inf} (ft/sec)	Strouhal No.
Low Speed Wind Tunnel	91	118	0.292
Water Tunnel PIV	0.65	0.92	0.268
Time Accurate CFD:LES	150	223	0.248



LES Modeling Development

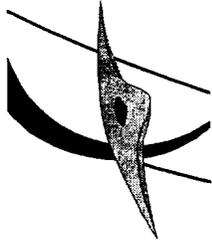


LES simulations will not replace RANS in next 10-15 years (at least!)

- Cost and turnaround time for LES is prohibitive for design
- Accuracy for wall bounded flows grid dependent
- Cost to obtain full scale Re solutions is very high

LES development has absorbed a disproportionate share of turbulence modeling research effort over past 5 years

Hybrid RANS/LES methods should continue to be explored, but this is not a trivial development effort

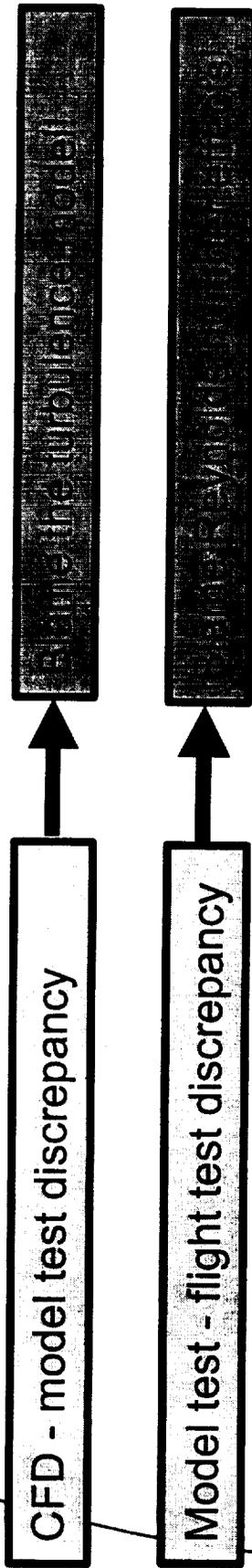


Outline

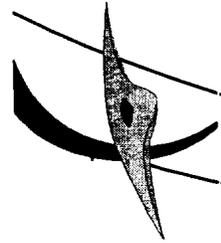


- Lockheed Martin Aeronautics product line
- Turbulence modeling application challenges
- Current modeling approaches (RANS)
- Turbulent flows with large scale unsteadiness (LES)
- Experimental accuracy and extrapolation to full scale
- Directions for future research

Experimental Accuracy Considerations



"No one believes CFD data except for the guy who ran it. Everyone believes wind tunnel data except for the guy who took it." R.G. Bradley



Sources of Error in Test Data



One turbulence modeler's list of experimental errors

- Model geometry
- Trip location
- Transitional boundary layer due to tripping
- Sting effects
- Strut effects
- Integration of discrete instrumentation
- Balance errors
- Data reduction
- Probe influence
- Instrumentation accuracy
- Aeroelastic effects
- WT blockage
- Turbulence levels



Outline

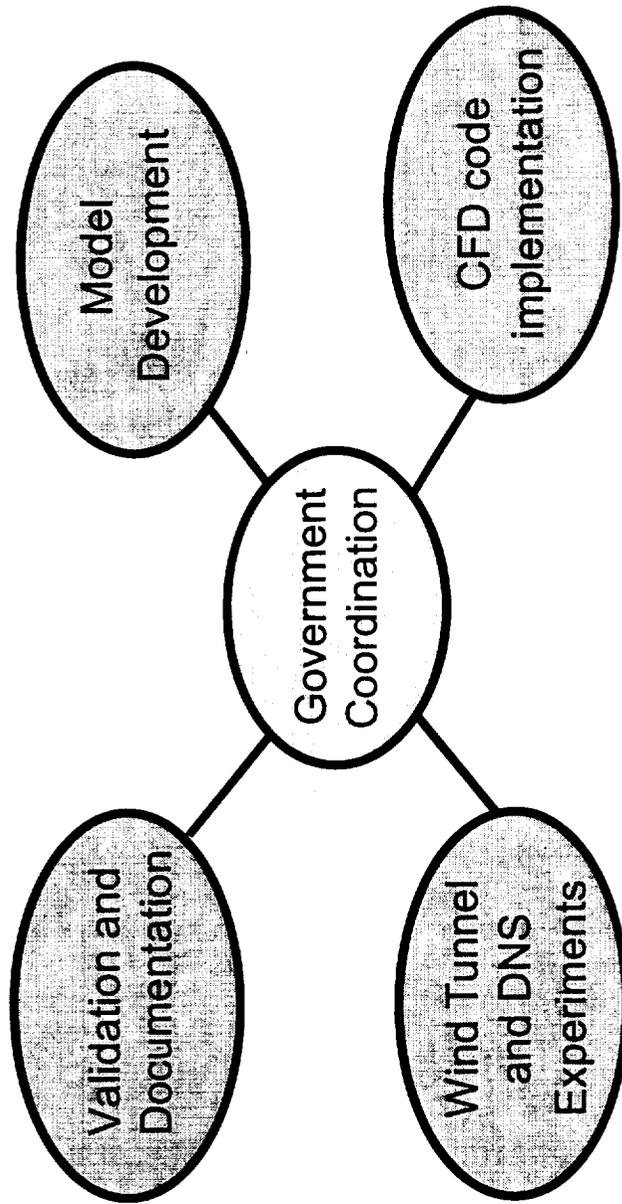


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- Experimental accuracy and extrapolation to full scale
- Directions for future research

Directions for Improved Turbulence Modeling

Establish accuracy of current models across a range of simple flows that isolate fundamental phenomena.

Need an integrated development effort with NASA and/or AF the focal point.



Validation and Documentation

“Competitions”, (Stanford 1968, 1981) are useful, but results become dated quickly

Support Collaborative Testing of Turbulence Models (CTTM) approach

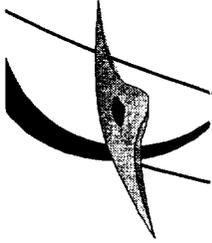
- Establish permanent and constantly evolving database of turbulence models and test cases
- Include numerical sensitivity and robustness.

Benefits

- Eliminates redundant validation and assessment efforts
- Provides clear metrics to assess progress in field
- Ensures models maintain accuracy on simple flows

Disadvantage

- Requires long term commitment of budget and resources to maintain database



Model Development

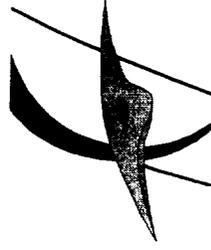


A hierarchy of RANS models is desirable

- Small number of models - preferably related.
- Simple, computationally efficient models will be used where applicable.
- Analytically derived models that have not been demonstrated for wall bounded flows in a compressible flow solver are of limited value.
- Not enough attention is paid to the length scale equation in modeling development.
- Less models, more complete development and implementation.

Development of LES models should continue, but not to the exclusion of RANS modeling development.

Hybrid models, LES where unsteadiness dominates, RANS where appropriate is desirable but non-trivial.



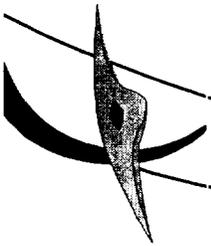
Wind Tunnel and DNS Data



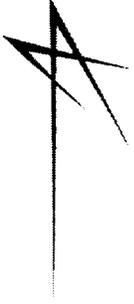
Coordinated effort allows shortcomings in experimental database to be addressed.

Where questions exist, wind tunnel models should be tested in multiple facilities, with different instrumentation to achieve reliable data.

DNS results are useful, but coordination with turbulence modeling efforts are needed.

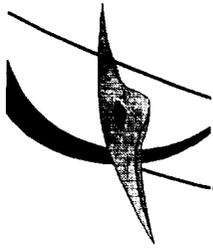


Model Implementation



Models need to be implemented in compressible CFD solvers and tested for numerical robustness.

Funding for research into efficient implementation of turbulence models should be considered.



Conclusion



Consequences of continuation of current research level and approach:

- Aerospace industry will miss significant opportunities to use CFD to reduce development costs because of inaccuracies in simulation capability.
- US aerospace leadership position will be adversely affected

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**TURBULENCE MODELING:
A NASA PERSPECTIVE**

T. B. Gatski

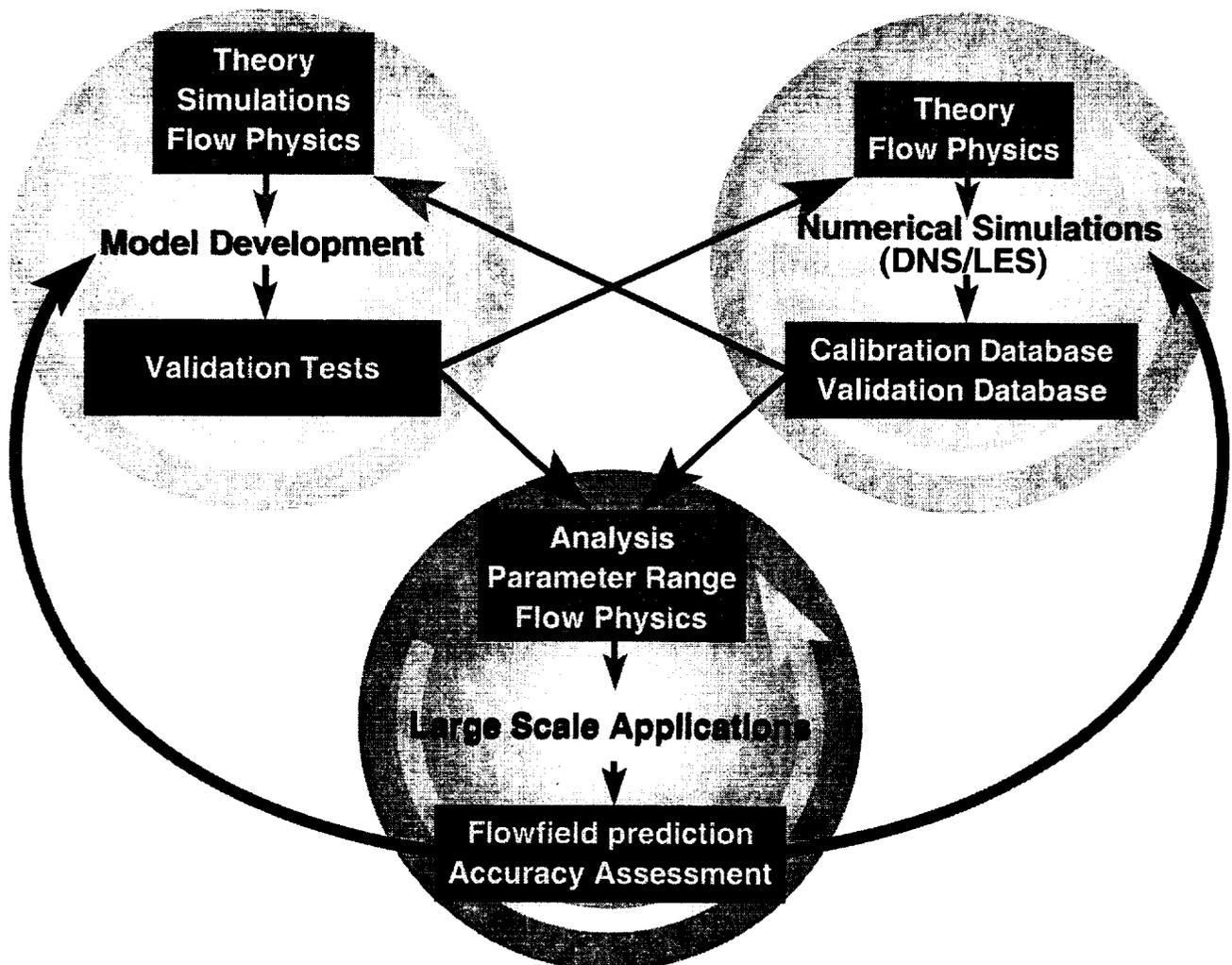
**Computational Modeling & Simulation Branch
NASA Langley Research Center
Hampton, VA 23681, USA**

**Turbulence Modeling Workshop
January 12 – 13, 2000
Reno, Nevada**

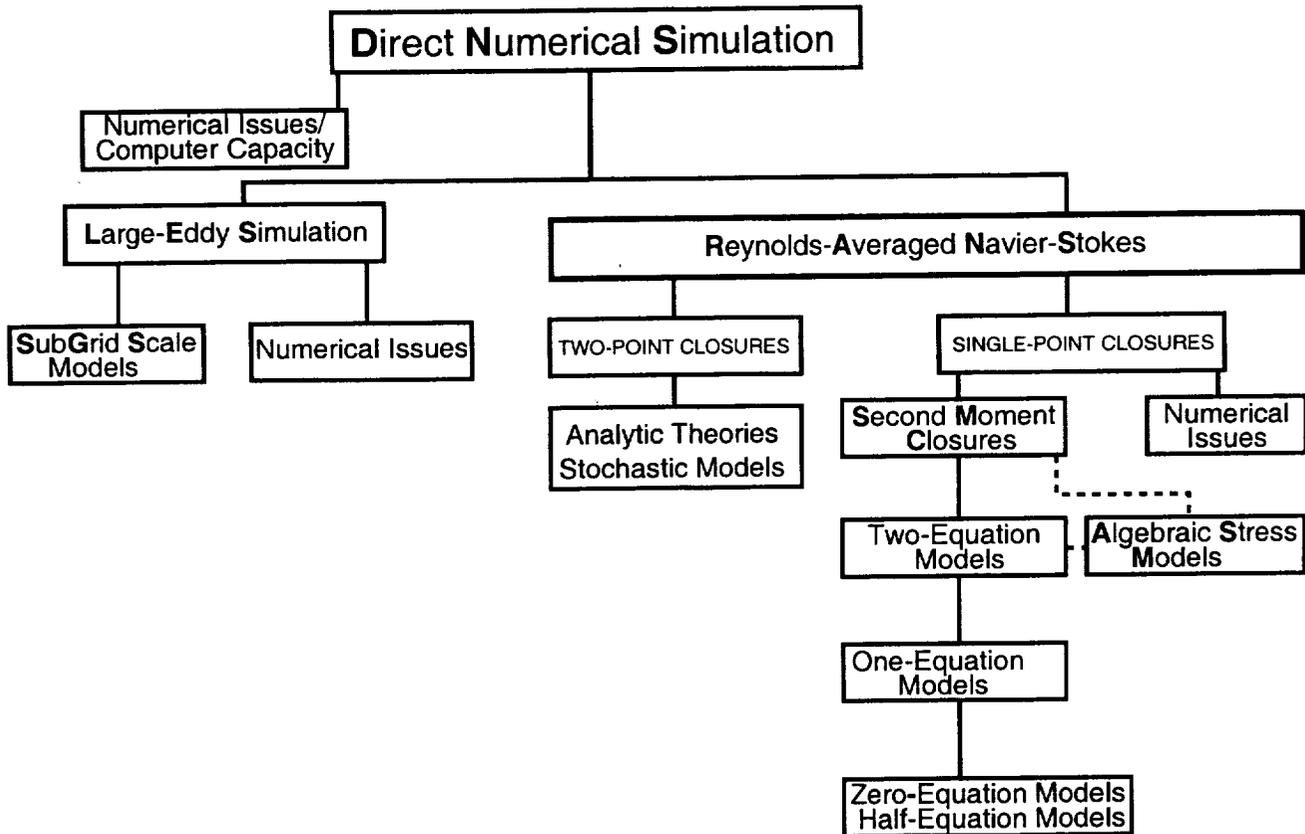
OBJECTIVE

- Identify deficiencies in predictive capabilities
- Develop improved/new models
 - * Capable of more accurate predictions of flows currently of interest
 - * Capable of solving more complex flows which become of interest

APPROACH



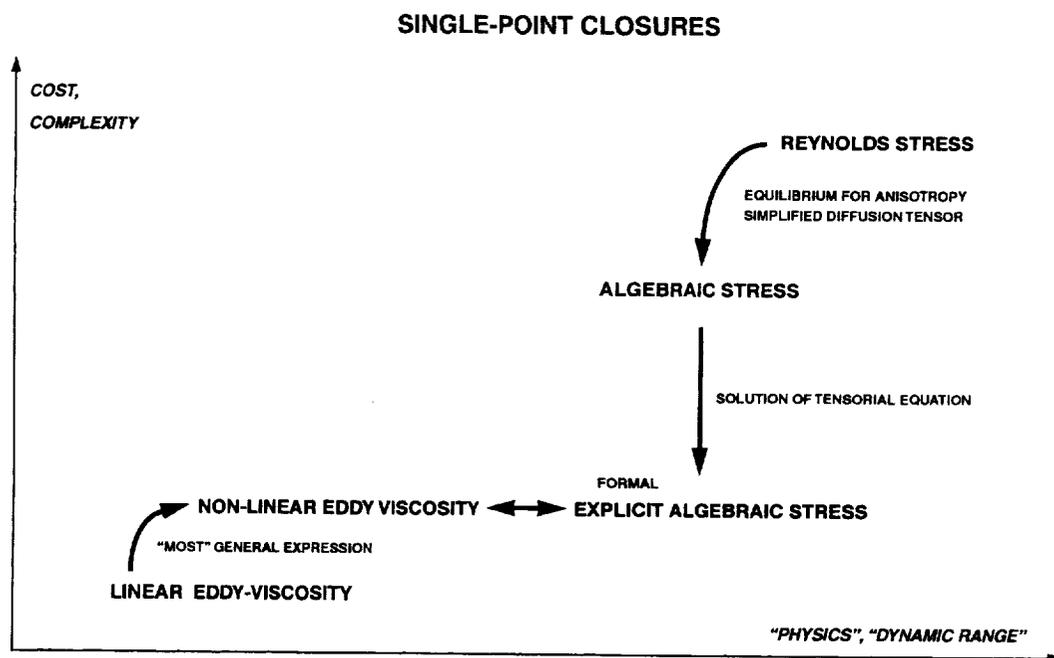
HIERARCHY OF SOLUTION METHODS



- RANS approach currently most common methodology for calculating turbulent (aerodynamic) flow fields
- RANS formulations inherently susceptible to the closure problem
 - * As statistical moment equations are derived, higher-order moments appear that require closure
- Within RANS framework, level of sophistication used in developing the turbulent closures varies widely
- A *separate* though *related* issue is the numerical solution of the closed set of equations needed in RANS formulation
 - * CFD issues associated with accuracy and efficiency of solution of RANS equations depend on closure level

TURBULENCE MODELING FOCUS

- Single-point (space and time) correlations
 - * Linear eddy viscosity model (LEVM)
 - * Nonlinear eddy viscosity model (NLEVM)
 - § Algebraic stress model (E)ASM
 - * Second moment closure (SMC)
 - § Reynolds stress model (RSM)



- Closure model development focused in incompressible regime
- Mean variable density extensions used mainly in compressible flows
 - * Role of compressible correlations uncertain
 - * Direct numerical simulation of supersonic flow (Ames, Langley)

LINEAR EDDY VISCOSITY MODELS

- The momentum equation is

$$\bar{\rho} \frac{D\bar{u}_i}{Dt} = -\frac{\partial \bar{p}}{\partial x_i} + \frac{\partial}{\partial x_j} \left[(\mu + \mu_t) \frac{\partial \bar{u}_i}{\partial x_j} \right]$$

- Turbulent closure model is taken as

$$\bar{\rho} \tau_{ij} = \frac{2}{3} \bar{\rho} K \delta_{ij} - 2\mu_t S_{ij}$$

$$b_{ij} = \frac{\tau_{ij}}{2K} - \frac{\delta_{ij}}{3} = -C_\mu \tau S_{ij}$$

- * μ_t is the turbulent eddy viscosity
- * τ is a turbulent time scale
- * b_{ij} is the Reynolds stress anisotropy tensor
- * Term proportional to the kinetic energy K is (formally) absorbed into the pressure term for \bar{p}
- Coupling between mean flow and turbulence is through μ_t

TWO-EQUATION MODEL

- Many two-equation models
 - * $K - \varepsilon$ model
 - * $K - \omega$ model
 - * **Shear Stress Transport** model (Ames)
 - * More

ONE-EQUATION MODEL

- Transport equation for the turbulent eddy viscosity
- Popular among industrial users due to its ease of implementation, relatively inexpensive cost, and good performance

HALF-EQUATION MODEL

- Outer eddy viscosity is modified to account for the effect of streamwise evolution of the flow on the turbulence
 - * Ordinary differential equation is solved for the streamwise evolution of the maximum shear stress (Ames)

ZERO-EQUATION (ALGEBRAIC) MODEL

- Based on Prandtl's (1925) mixing length theory
- Isotropic eddy viscosity

LIMITATIONS AND ALTERNATIVES TO LEVMs

- LEVM are a proven tool in turbulent flow-field predictions
 - * Inherent in the formulation are several deficiencies
 - § Isotropy of the eddy viscosity
 - Consequence of Boussinesq approximation which assumes direct proportionality between τ_{ij} and S_{ij}
 - Precludes prediction of turbulent secondary motions in ducts
 - § Material-frame indifference of the models
 - Consequence of sole dependence on (frame-indifferent) S_{ij}
 - Insensitivity of turbulence to noninertial effects
 - Need dependence on rotation rate tensor W_{ij}
 - * Such defects cannot be fixed in a rigorous manner
- Nonlinear eddy viscosity models (NLEVMs) and their subset algebraic stress models (ASMs) extend the range of applicability of LEVMs
 - * Replace the Boussinesq approximation $\tau_{ij} = \tau_{ij}(S_{ij}, \tau)$ with $\tau_{ij} = \tau_{ij}(S_{kl}, W_{kl}, \tau)$
 - * Need for transport equations for the characteristic turbulent scales
 - * NLEVM and EASM formulations based on a two-equation closure
 - § Any other (lower) closure (zero-, half-, one-, or two-equation) could be connected to a NLEVM or ASM.

NONLINEAR EDDY VISCOSITY/ ALGEBRAIC STRESS MODELS

- Class of nonlinear eddy viscosity models that extend the one-term tensor representation in terms of S_{ij} used in LEVMs to

$$\tau_{ij} = \frac{2}{3}K\delta_{ij} + \sum_{n=1}^N \alpha'_n T_{ij}^{(n)}$$

- * $T_{ij}^{(n)}$ ($n = 1 \dots N$) is a given tensor basis, N finite
- * α'_n expansion coefficients which need to be determined
- For general Reynolds stress representations, coupling to mean flow can be either through the direct use of τ_{ij} in momentum equation or through a modified form given by

$$\bar{\rho} \frac{D\bar{u}_i}{Dt} = -\frac{\partial \bar{p}}{\partial x_i} + \frac{\partial}{\partial x_j} \left[(\mu + \mu_t) \frac{\partial \bar{u}_i}{\partial x_j} \right] + \mathcal{S}$$

- * \mathcal{S} represents nonlinear (source) terms from the tensor representation
- Generally assumed in developing closures for Reynolds stresses
 - * Functional dependency on the characteristic turbulent scales
 - * Functional dependency on the mean velocity gradient

$$b_{ij} = b_{ij}(S_{kl}, W_{kl}, \tau)$$

- Tensor representations basis also assumed to be functions of \mathbf{S} and \mathbf{W}

- For $\mathbf{b}(\mathbf{S}, \mathbf{W}, \tau)$ this basis consists of the elements

$$\begin{aligned}
 \mathbf{T}^{(1)} &= \mathbf{S} & \mathbf{T}^{(6)} &= \mathbf{W}^2\mathbf{S} + \mathbf{S}\mathbf{W}^2 - \frac{2}{3}\{\mathbf{S}\mathbf{W}^2\}\mathbf{I} \\
 \mathbf{T}^{(2)} &= \mathbf{S}\mathbf{W} - \mathbf{W}\mathbf{S} & \mathbf{T}^{(7)} &= \mathbf{W}\mathbf{S}\mathbf{W}^2 - \mathbf{W}^2\mathbf{S}\mathbf{W} \\
 \mathbf{T}^{(3)} &= \mathbf{S}^2 - \frac{1}{3}\{\mathbf{S}^2\}\mathbf{I} & \mathbf{T}^{(8)} &= \mathbf{S}\mathbf{W}\mathbf{S}^2 - \mathbf{S}^2\mathbf{W}\mathbf{S} \\
 \mathbf{T}^{(4)} &= \mathbf{W}^2 - \frac{1}{3}\{\mathbf{W}^2\}\mathbf{I} & \mathbf{T}^{(9)} &= \mathbf{W}^2\mathbf{S}^2 + \mathbf{S}^2\mathbf{W}^2 - \frac{2}{3}\{\mathbf{S}^2\mathbf{W}^2\}\mathbf{I} \\
 \mathbf{T}^{(5)} &= \mathbf{W}\mathbf{S}^2 - \mathbf{S}^2\mathbf{W} & \mathbf{T}^{(10)} &= \mathbf{W}\mathbf{S}^2\mathbf{W}^2 - \mathbf{W}^2\mathbf{S}^2\mathbf{W}.
 \end{aligned}$$

- Nonlinear eddy viscosity models (NLEVMs)

- * Expansion coefficients determined from

- § Calibrations with experimental or numerical data
- § Some physical consistency constraints

- Explicit algebraic stress models (EASMs)

- * Expansion coefficients derived consistent with the results of tensor representations from the full differential RSM

- In both models

- * Explicit tensor representation for \mathbf{b} is obtained
- § Subset of full representation basis

SOME EXAMPLES

- Quadratic NLEVM (Glenn)
 - * RDT (rapid distortion theory) result for rapidly rotating turbulence (no shear) used
 - * α_i coefficients determined by applying realizability constraints to the cases of axisymmetric expansion and contraction
 - * Coefficients optimized by comparison with experiment and numerical simulation
- Quadratic EASM (Langley)
 - * Extracted form from RSM with SSG pressure-strain rate correlation model
- Enhancements to improve predictive capability
 - * Rotational and curvature effects (CTR, Langley)
 - * Wall proximity effects (CTR, Langley)

LIMITATIONS AND ALTERNATIVES TO NLEVM/EASMs

- NLEVM/EASMs are now being used in many applications
- Inherent in the formulation are two (possible) deficiencies
 - * Weak equilibrium assumption ($Db_{ij}/Dt = 0$)
 - * Assumed form of turbulent transport and viscous diffusion model
- Such defects can be addressed in a rigorous manner with EASMs
 - * Improving frame-invariance property of formulation (Langley)
 - * Modifying assumed form for turbulent transport model
- Close linkage between the (E)ASMs and the Reynolds stress equations
 - * Directly incorporate models for the pressure strain rate correlation and anisotropic dissipation rate
- Unfortunately not all features of differential SMC retained
 - * Relaxation effects of individual stress components precluded
 - * Turbulent transport effects only partially taken into account

SECOND MOMENT CLOSURES (SMCs)

- Reynolds stress model (RSM) most common SMC at this time
 - * Structure based models account for dimensionality of turbulence
- Calibrations extensively based on homogeneous flows
 - * Applied to inhomogeneous flows

Incompressible Flow

- $\tau_{ij} = \overline{u'_i u'_j}$

$$\frac{D\tau_{ij}}{Dt} = \bar{P}_{ij} + \Pi_{ij} + D_{ij} - \varepsilon_{ij}$$

$$\bar{P}_{ij} = -\tau_{ik} \frac{\partial \bar{u}_j}{\partial x_k} - \tau_{jk} \frac{\partial \bar{u}_i}{\partial x_k}$$

$$\Pi_{ij} = \overline{p' \left(\frac{\partial u'_i}{\partial x_j} + \frac{\partial u'_j}{\partial x_i} \right)}$$

$$D_{ij} = -\frac{\partial}{\partial x_k} \left[\underbrace{\overline{u'_i u'_j u'_k} + \overline{p' (u'_i \delta_{jk} + u'_j \delta_{ik})}}_{\text{turbulent transport}} - \underbrace{\overline{(\sigma'_{ik} u'_j + \sigma'_{jk} u'_i)}}_{\text{viscous diffusion}} \right]$$

$$\varepsilon_{ij} = \frac{2}{3} \varepsilon \delta_{ij} + 2\varepsilon d_{ij} = \overline{\sigma'_{ik} \frac{\partial u'_j}{\partial x_k}} + \overline{\sigma'_{jk} \frac{\partial u'_i}{\partial x_k}} \approx 2\nu \frac{\partial u'_i}{\partial x_k} \frac{\partial u'_j}{\partial x_k}$$

- * Development of improved closure models for
 - § Pressure-strain rate correlation (Langley, Glenn)
 - § Anisotropic dissipation rate (Langley)
 - § Turbulent transport term (Langley)
 - § Wall proximity effects (CTR)

Compressible Flow

- $\bar{\rho}\tau_{ij} = \overline{\rho u_i'' u_j''}$ (Favre variables)

$$\bar{\rho} \frac{D\tau_{ij}}{Dt} = \bar{\rho} \tilde{P}_{ij} + \bar{\rho} \Pi_{ij} + \bar{\rho} D_{ij} - \bar{\rho} \epsilon_{ij} + \bar{\rho} M_{ij}$$

$$\bar{\rho} \tilde{P}_{ij} = -\bar{\rho} \tau_{ik} \frac{\partial \bar{u}_j}{\partial x_k} - \bar{\rho} \tau_{jk} \frac{\partial \bar{u}_i}{\partial x_k}$$

$$\bar{\rho} \Pi_{ij} = \bar{\rho} \Pi_{ij}^{dl} + \bar{\rho} \Pi_{ij}^d = \overline{p' \left(\frac{\partial u_i'}{\partial x_j} + \frac{\partial u_j'}{\partial x_i} \right)}$$

$$\bar{\rho} \Pi_{ij}^{dl} = \frac{2}{3} \overline{p' \frac{\partial u_k'}{\partial x_k}} \delta_{ij}$$

$$\bar{\rho} D_{ij} = -\frac{\partial}{\partial x_k} \left[\underbrace{\overline{\rho u_i'' u_j'' u_k''}}_{\text{turbulent transport}} + \overline{p' (u_i' \delta_{jk} + u_j' \delta_{ik})} - \underbrace{\overline{(\sigma_{ik}' u_j' + \sigma_{jk}' u_i')}}_{\text{viscous diffusion}} \right]$$

$$\bar{\rho} \epsilon_{ij} = \frac{2}{3} \bar{\rho} \epsilon \delta_{ij} + 2 \bar{\rho} \epsilon d_{ij} = \overline{\sigma_{ik}' \frac{\partial u_j'}{\partial x_k}} + \overline{\sigma_{jk}' \frac{\partial u_i'}{\partial x_k}}$$

$$\bar{\rho} M_{ij} = \overline{\rho u_i''} \left(\frac{\partial \bar{\sigma}_{jk}}{\partial x_k} - \frac{\partial \bar{p}}{\partial x_j} \right) + \overline{\rho u_j''} \left(\frac{\partial \bar{\sigma}_{ik}}{\partial x_k} - \frac{\partial \bar{p}}{\partial x_i} \right)$$

- Development of improved closure models for
 - * Dilatation dissipation
 - * Pressure dilatation
 - * Mass flux model
 - * Wall proximity effects

SUMMARY OF CURRENT ACTIVITIES

Theoretical Approaches

- Half-equation and two-equation model improvements
 - * Eliminate coordinate dependence in required “switching function” for SST model (Ames)
 - * Extend range of applicability of turbulence models to transition regime (Glenn, Langley)
 - * Improve predictive capability in APG and free shear flows (Ames)
- Improve explicit algebraic stress formulations (Langley, CTR)
 - * Improve frame-invariance properties of model (Langley)
 - * Improve sensitivity to rotation and curvature (CTR, Langley)
 - * Formulate to account for compressible terms (Langley)
- Some selective modeling of current RSM closures
 - * Turbulent transport terms (Langley)
 - * Improve wall proximity effects (CTR)
- Structure function modeling (Ames)
- Length-scale equation from multi-point analysis (Glenn)
- Generalized wall functions (Glenn)

SUMMARY OF CURRENT ACTIVITIES

Applications

- Variety of aerodynamic flows
 - * High-lift flow field prediction (Ames, Langley)
 - * Transonic buffet onset analysis (Langley)
 - * Trap-wing CFD validation (Ames, Langley)
 - * Transonic vortex flow over delta wing
 - * Ramjet/scramjet flowpath analysis (Glenn, Langley)
 - * Variety of separated flow studies
- Variety of unit problems (Ames, Langley)
 - * Wakes in pressure gradient
 - * Flows with curvature
- Deficiencies in model performance cycled back into improved model development

Other RANS Modeling Areas

- Multi-scale turbulence models
- Non-equilibrium effects
- Dynamic zonal modeling
 - * Linkage between LES and non-stationary RANS-type closures
- Heat transfer and reacting flow modeling

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STANFORD UNIVERSITY
Thermosciences Division, M.E. Dept
Stanford, CA 94305-3030

ICASE/LaRC Turbulence modeling workshop

**Turbulence Modeling for
High Reynolds Number Separated Flows**

Peter Bradshaw
bradshaw@vk.stanford.edu

12 Jan. 2001
(no oral presentation)

MY TAKE ON SEPARATED FLOWS-I

- (I) Virtually all Reynolds-averaged turbulence models (or SGS models) are calibrated in flows dominated by shear layers (in suitable axes)
- (II) There is no guarantee that any model will be “universal” (i.e. reliable in flows very different from those used for calibration)
- (III) (important parts of) Separated flows are not dominated by shear layers
- (IV) Therefore Reynolds-averaged models cannot be guaranteed in separated flows. Ever.

MY TAKE ON SEPARATED FLOWS-II

- The problem of predicting separated flows has two parts:–
- (A) predicting the separation line* with a more-or-less given pressure distribution
- (B) predicting the separated region with a more-or-less given separation line

... “more or less” because there is strong upstream influence – but initial tests of a model could and should be divided into (A) and (B)

* “line” not “point” : all real-life separated flows are three-dimensional, some with very strong streamwise vorticity

TEST CASES FOR SEPARATED FLOWS

- Predicting reversed-flow skin friction in the 2D backstep flow is still a useful test. . .

. . .because it goes as $Re^{-0.5}$ approx. ($0.5 \neq 1/2$) and this should be reproduced by a low-Re (wall-layer) model

- The largely-neglected flow over a cone at zero incidence is a severe test of models for the separated region because that is so far from "still air". (Calvert, JFM **27**, 273 (1967): probably only the base pressure is reliable).
- In both these cases separation is forced at a sharp edge. There are several "boat tail" test cases (mainly axisymmetric) with separation from a smooth surface, generally with small separation regions.

WHY MODEL TURBULENCE?

...because, of course, we are too cheap to solve the exact equations like the structures people do

- "Turbulence modeling is the pacing item of CFD" – the late Jack Nielsen and many others
- Stan Birch of Boeing said – "what limits you is computing power, not turbulence models"
- Rightly or wrongly, industrial users stick with eddy-viscosity models

"BEST BUY" \equiv WHAT I HAVE NOW

- Correct – remembering that even testing of existing models can be limited by available/affordable computing
- There is an urge to say "if my model does thin shear layers and my pet N-S case (even the backstep) it must be OK".
- Large eddy simulation just models the smallest (sub-grid-scale) eddies which do not carry much stress or momentum
- But near a solid surface *all* eddies are small

EDDY VISCOSITY-I

“Glushko uses the TKE equation only to calculate the turbulent intensity $\overline{q^2}$ and then makes the highly questionable assumption that the eddy viscosity ν_T is given by $(\overline{q^2})^{1/2}L/\nu_T = \text{constant}$ ”
PB et al. JFM **28**, 593 (1967)

...(Glushko was implementing Prandtl-Wieghardt (1945))

- Eddy viscosity is easy to define (and measure). It is the ratio of a turbulence quantity to a mean-flow quantity,

(Reynolds stress)/(Mean strain rate)

- Therefore it should not be treated as a pure turbulence quantity (like TKE say)

EDDY VISCOSITY-II

- It *may* be better behaved / easier to correlate than Reynolds stress – but no guarantees
- In self-similar flows with one velocity scale and one length scale (e.g. u_τ and δ) eddy viscosity must scale as

$$\nu_t = u_\tau \delta f(y/\delta)$$

(and in slowly-changing flows near a solid surface $f(y/\delta) = \kappa y/\delta$ so $\nu_t = \kappa u_\tau y$)

- In such flows, (*production / dissipation*) = $g(y/\delta)$ and near a solid surface $g = 1$

UNSTEADINESS – I

- Reynolds averaging does not and cannot distinguish between unsteadiness and turbulence
- Neither can any other sort of averaging unless the unsteadiness is periodic or otherwise structured AND occupies a different frequency, or wavelength, range from the turbulence.
- Unsteadiness in a separated flow can very sensitive to boundary, or initial, conditions.
- This makes me pessimistic about the reliability of (Reynolds-) averaged models in separated flow...

UNSTEADINESS – II

...and of course we often want to predict the unsteadiness, to estimate structural buffeting or low-frequency noise

- Flows which are very sensitive to boundary or initial conditions are ill-posed problems, and there's an end of it!
- Better-posed problems need 3D time-dependent simulations, DNS, LES, DES or whatever
- DES, fed by a Reynolds-averaged model is likely to be reliable only if the boundary layers at separation are so thin that details of the turbulence don't matter

MY TAKE ON REYNOLDS NUMBER

- (1) Direct effects of viscosity on Reynolds stress in *fully-turbulent* flow are small for $u_\tau y / \nu < N$ where N is a function of space and time. $N \approx 200$ at IIT and KTH (at present!).
- (2) However, the surface of the “viscous superlayer” has a dimension much greater than 2 and its volume occupies a large fraction of the intermittent outer layer at low (i.e. laboratory) Re , leading to “direct viscous effects”.
- (3) Indirect effects of viscosity can enter (e.g. flat-plate boundary layers) via $d\delta/dx$ or du_τ/dx
- At “high” Re , (1) and (2) are not a concern. The received wisdom is that neither is (3)...

MY TWO CENTS ON THE LOG LAW-I...

- The bare-bones derivation of the log law, due to Landau, is that

$$\text{if } u = f(u_\tau, y, \nu)$$

$$\text{then } \frac{du}{dy} = \frac{u_\tau}{y} f\left(\frac{u_\tau y}{\nu}\right)$$

... and we expect $f \rightarrow 1/\kappa$ (say) as its argument tends to infinity.

- Obviously a necessary, but maybe not sufficient, condition for the "if" to be true is $y \ll \delta$
- Any other derivation is just the addition of bells and whistles to this dimensional argument.

MY TWO CENTS ON THE LOG LAW-II...

- The power laws of Barenblatt and colleagues imply that f does not tend to a constant but continues to vary as an *analytic* function of $u_\tau y/\nu$
- (i) I find it very difficult to believe that a second approximation to the log law will be another simple analytic function!
- (ii) Also, **direct** effects of viscosity must be small for large enough $u_\tau y/\nu$.
- (iii) However (earlier slide) the effect of streamwise gradients of δ and u_τ (indirect effects of viscosity) **may** extend to quite large Re (consider the uncertainty over the “exquisitely sensitive” wake parameter Π).

MY TWO CENTS ON THE LOG LAW-3...

- Panton has rightly pointed out that the regions of claimed validity of the log law and the Barenblatt et al. power law are not the same (though the power law is supposed to overlap part of the log law)...

...but this does not change the above discussion of *possible* indirect Re effects

- My advice to all concerned:- don't do second-order math. on first-order physics!

CONCLUSIONS

- The “High Reynolds Number” part of our title is hopefully just a warning to beware of low-Re effects in our test cases...

...but the “Separated Flows” part of the title is a reminder that such flow combine unsteadiness and turbulence

- (Reynolds-)averaged models can't distinguish the two in general
- If we want to predict the unsteadiness with any confidence we need (x, y, z, t) simulations

REWRITING HISTORY

- Surgeon-General's warning... I added this after the meeting – which I unfortunately missed so I couldn't give my views in discussion

- I didn't say so explicitly, above, but my pessimistic views about the (un)reliability of Reynolds-averaged models imply the general conclusion of the Workshop...

...that these models need very careful **validation**

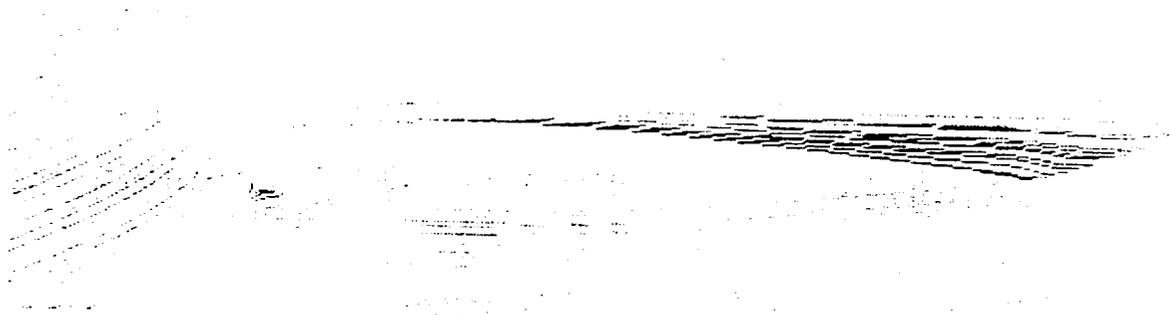
- A model user needs validation *in the type of flow that he/she wants to calculate* (since a model with fixed coefficients is unlikely to give results in all flows).

- If this implies using different coefficients in different flows, that's bad science but may be good engineering

2000-10
P. 1

K. SREENIVASAN
YALE UNIVERSITY

Some physical aspects of separated flows
(separation on flat-plate-like objects)

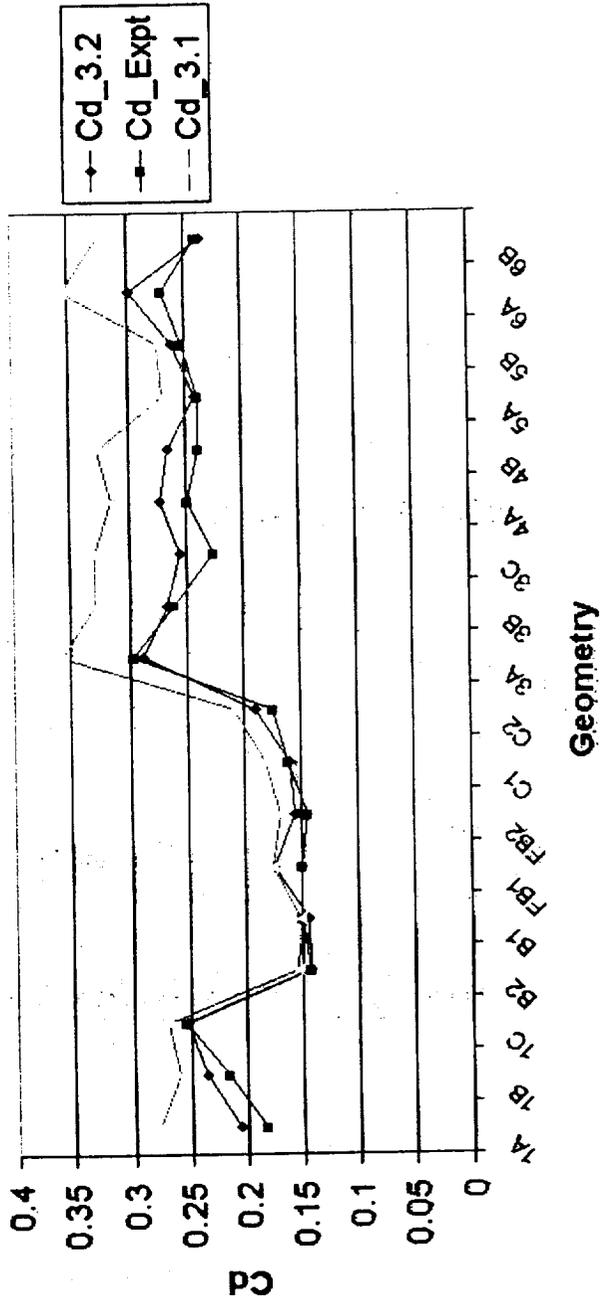


“In the spirit of a speculative research proposal”

Preliminary remarks on:

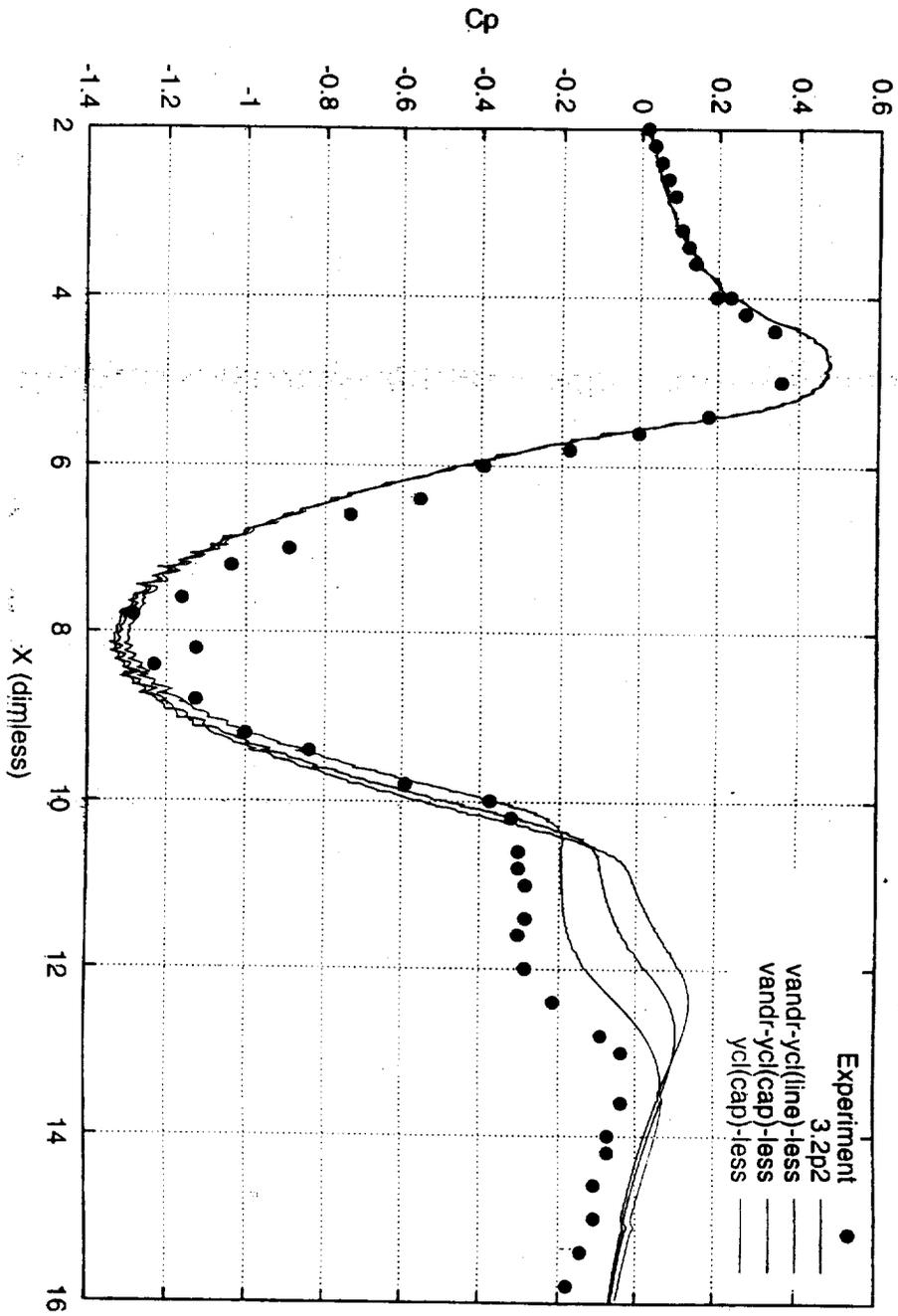
- LB methods
- Physics of turbulence modeling
- Vortex dynamics

Drag Coefficient over multiple bodies (PowerFLOW 3.1+3.2 v. Expt)



Courtesy of Hudong Chen
EXA corporation

Cp Vs X for the 2D Bump



NASA/CR-2000-210550
ICASE Report No. 2000-40

100-70
page 156
Duplicate



Evaluation of the Lattice-Boltzmann Equation Solver PowerFLOW for Aerodynamic Applications

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NASA Langley Research Center
Hampton, Virginia
Operated by Universities Space Research Association



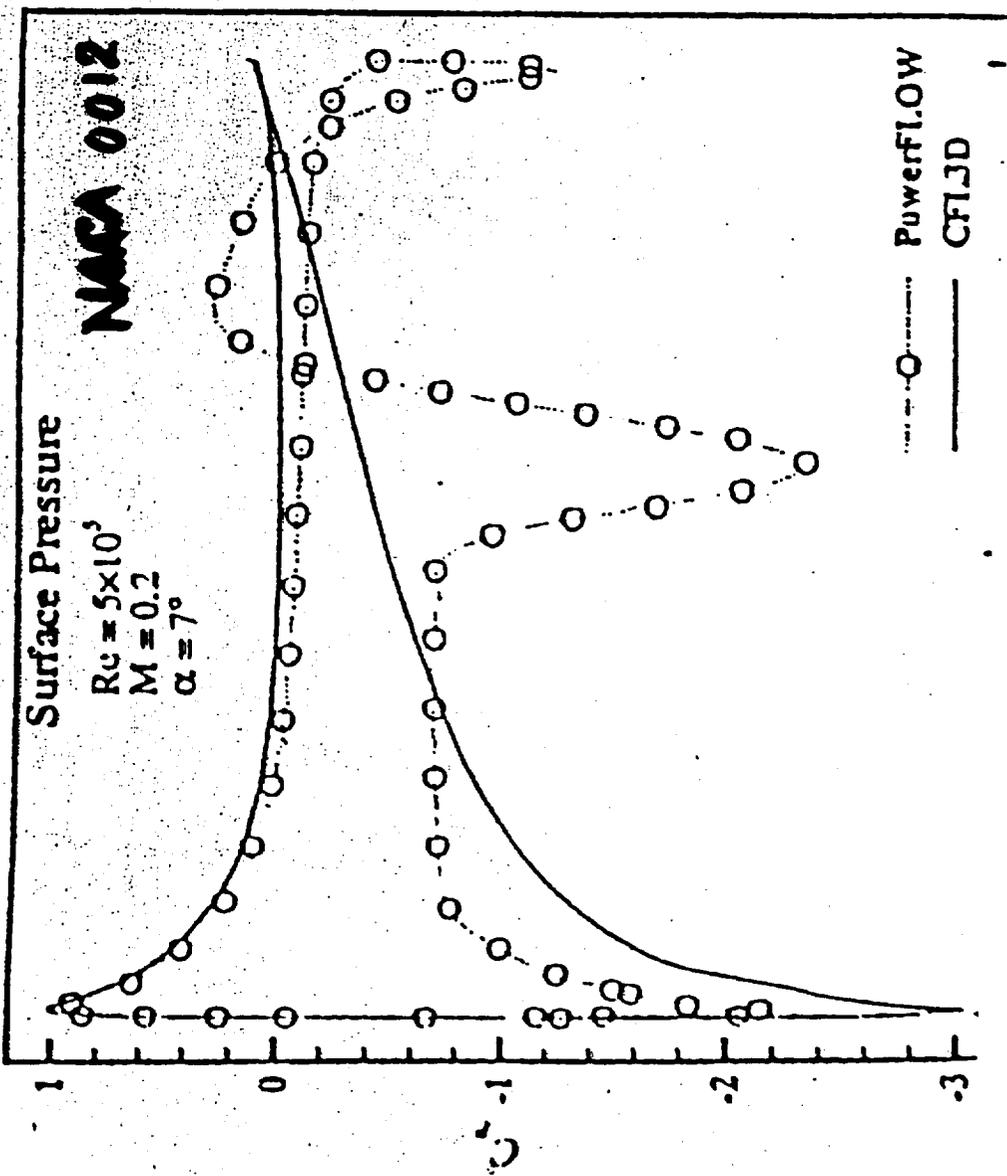
National Aeronautics and
Space Administration

Langley Research Center
Hampton, Virginia 23681-2199

Prepared for Langley Research Center
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October 2000

From ICASE 2000-00



Three basic ingredients of the calculations

1. Discrete Boltzmann systems

$$\partial_t f(\mathbf{x}; \mathbf{v}; t) + \mathbf{V} \cdot \nabla f(\mathbf{x}; \mathbf{v}; t) = C$$

Lattice gas reduces the phase space tremendously
BC simpler, mesh refinement easy to implement

2. Turbulence models

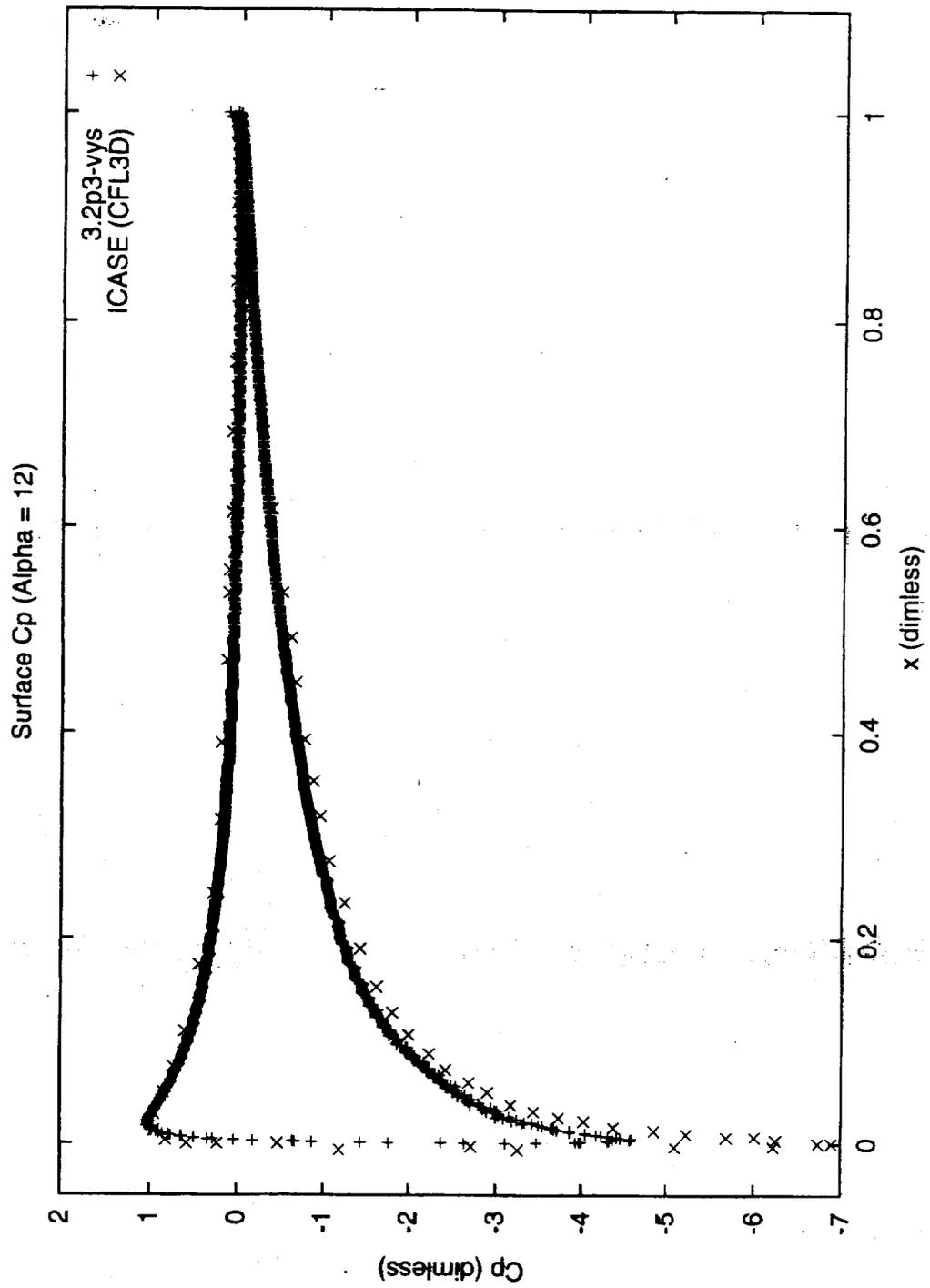
k- ϵ models: relaxation time in C varies locally to
model “subgrid” dynamics

3. Treatment near the wall

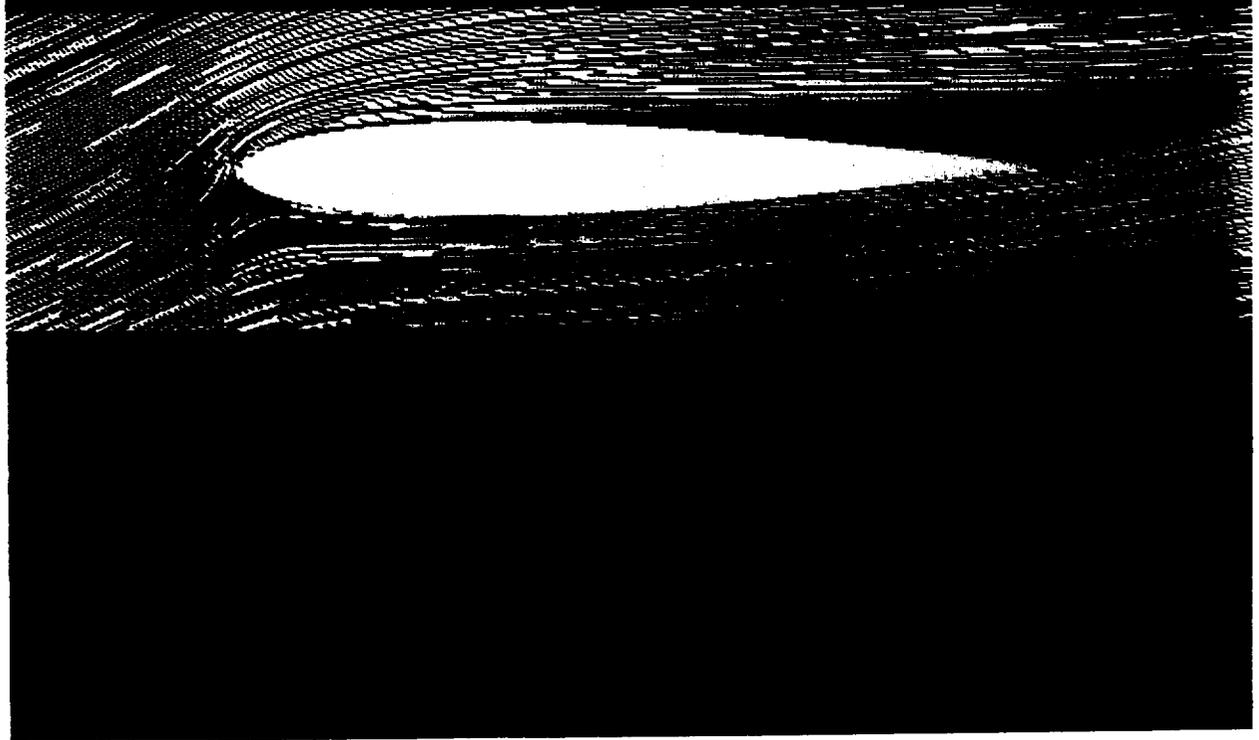
First point is patched to a modified log-law:

$$U_s^+ = A \log (y^+ / \xi(\nabla p)) + B.$$

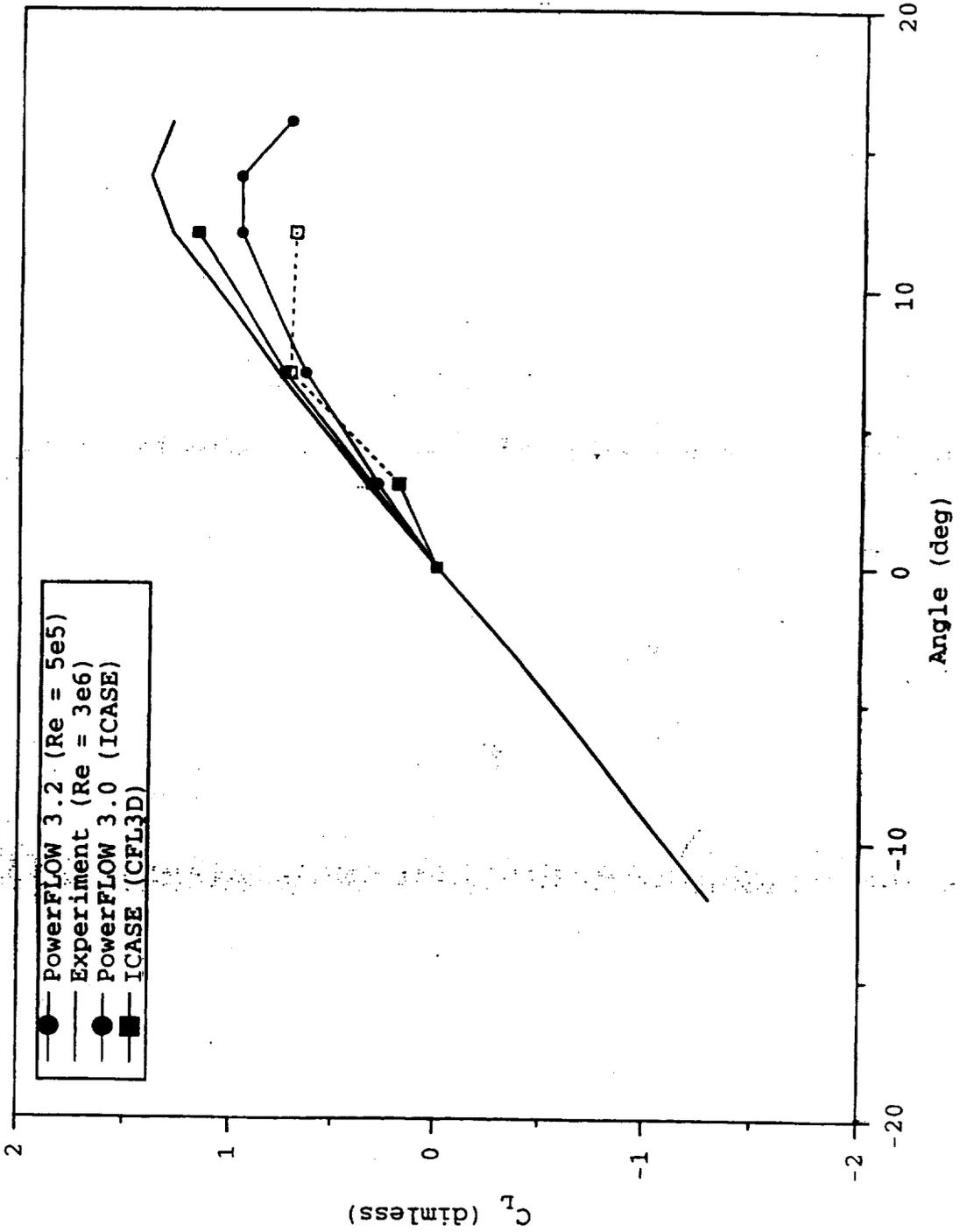
$$\xi(\nabla p) = 1 + a (\hat{\mathbf{u}} \cdot \nabla p)$$

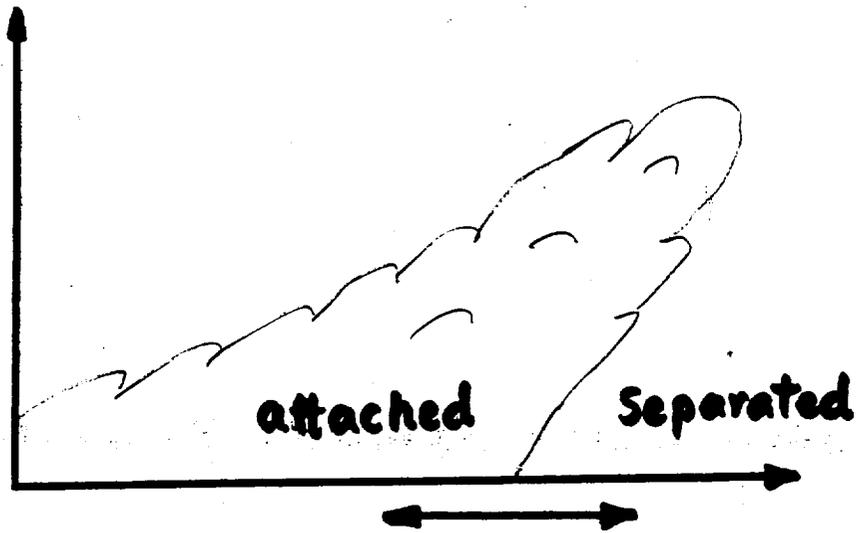


CA-0012 Alpha-14 EXA Corp

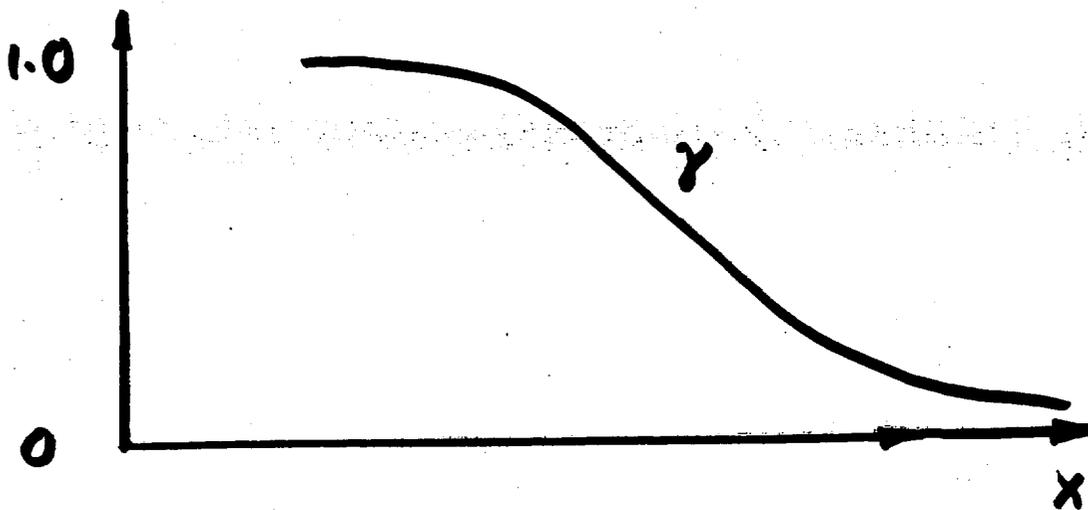


Exa Corp. Coefficient of Lift vs. Angle of Attack
 NACA 0012 Foil





$\gamma(x,y)$ = upstream-downstream intermittency factor
 = fraction of time that an observation point stays
 inside the attached region



A lowest order hypothesis

$$\pi = \gamma \pi_a + (1 - \gamma) \pi_s$$

$$k = \gamma k_a + (1 - \gamma) k_s, \quad \varepsilon = \gamma \varepsilon_a + (1 - \gamma) \varepsilon_s$$

Working forms of k and ε are known for the attached case

For instance, in the overlap region

$$k_a = u_\tau^2 / C_\mu^{1/2}, \quad \varepsilon_a = u_\tau^3 / \kappa y$$

What is the form in the separated region?

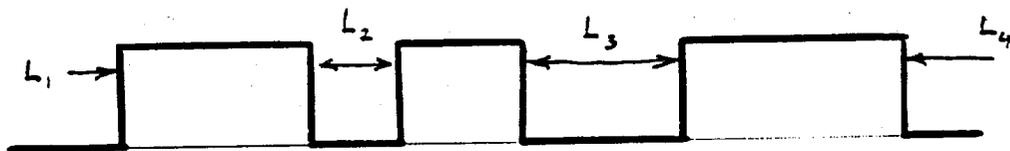
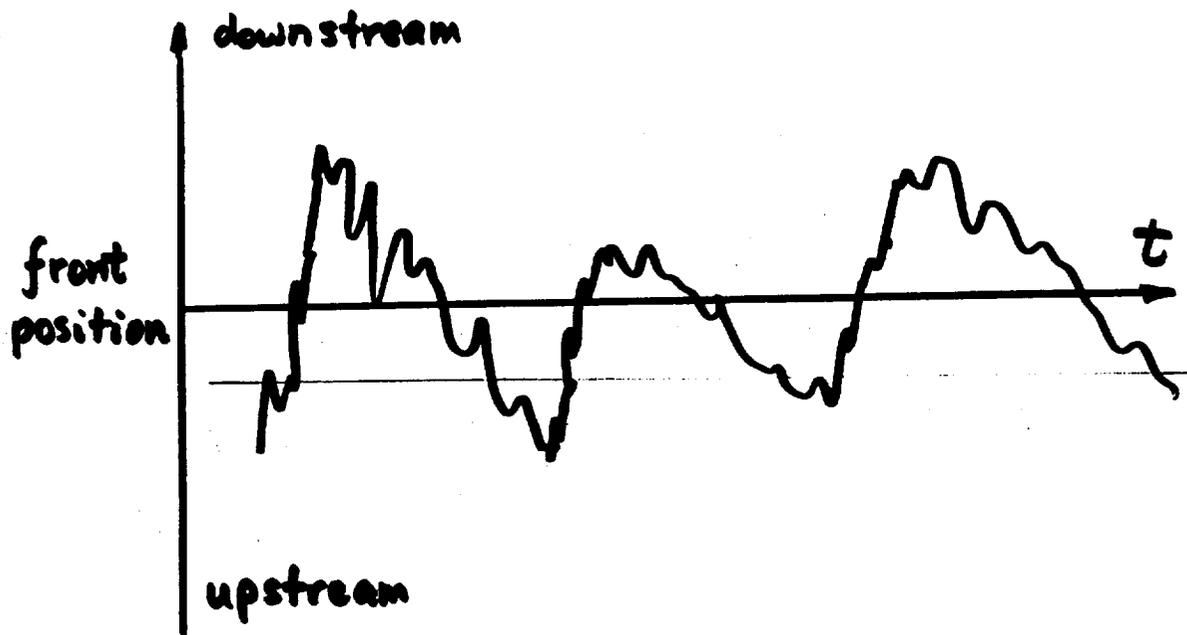
$$k_s \propto l^2 (\partial U / \partial y)^2, \quad \varepsilon_s = v_t (\partial U / \partial y)^2$$

l is most likely obtained through the mean velocity

Two things are needed:

- *Characterization of the separated region
- *The intermittency factor

Low-dimensional dynamics may be possible.
 What sort of low dimensional dynamics?



$$L = \exp -(L - \langle L \rangle), \langle L \rangle = \gamma$$

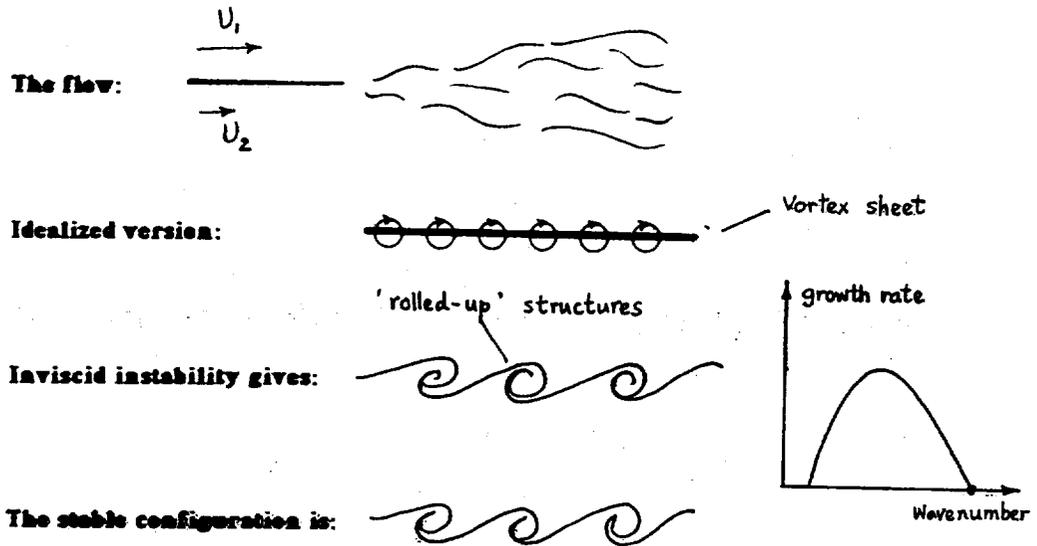
Intermittency factor:

$$\Lambda \equiv p' \delta / \tau_w, \Lambda \sim (\gamma - \gamma_0)^{-\lambda}$$

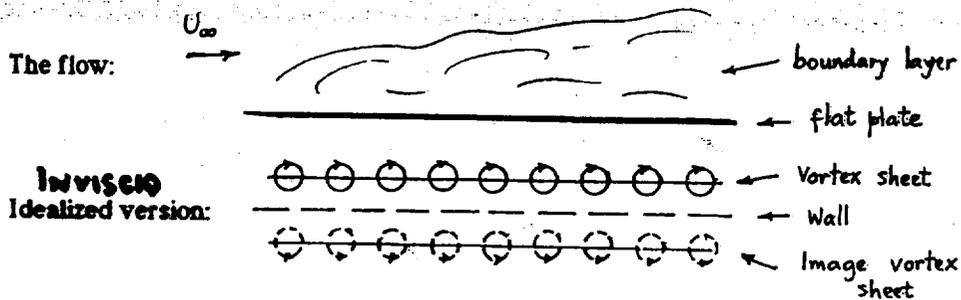
AN IMPORTANT LESSON TO BE LEARNT FROM THE PLANE MIXING LAYER STUDIES

(Only a very rough statement!)

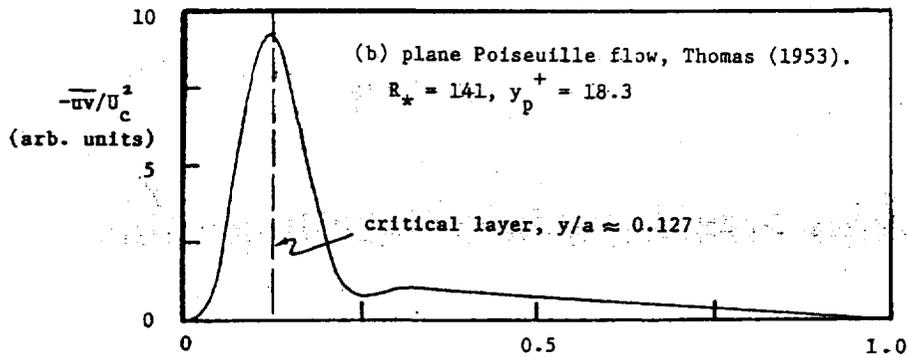
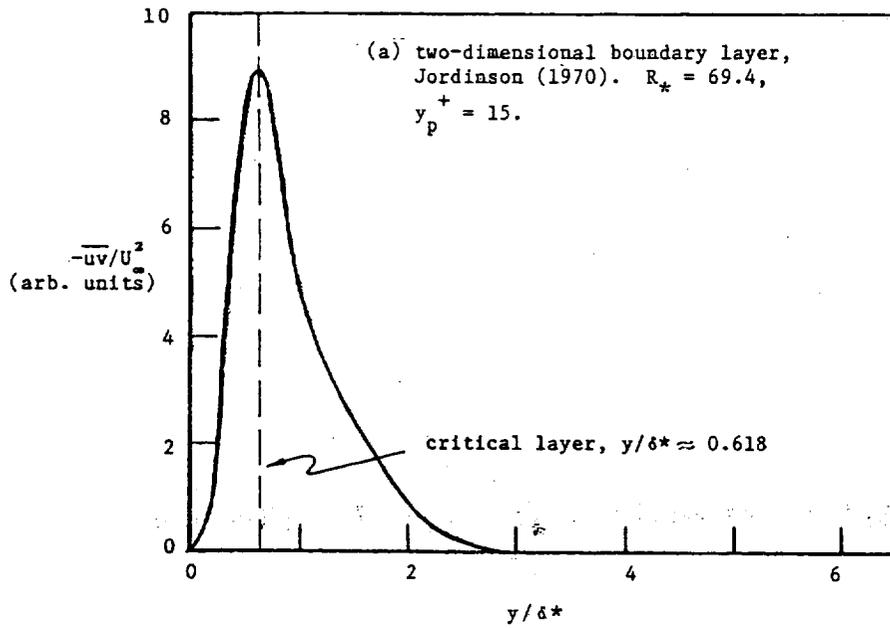
The **dominant structure** - the **stable configuration** resulting from the **inviscid instability** of a **suitably idealized version** of the flow



Similar statements (with less experimental backing) can be made about other free shear flows (e.g., wakes). Here, want to explore the consequences of extending this point of view to the turbulent boundary layer



Inviscid instability, viscous effects and the stable configuration: ??



The distribution of the Reynolds shear stress in (a) boundary layer and (b) channel (plane Poiseuille) flows, evaluated from the numerically computed eigensolutions. The eigensolution data in (a) were from Jordinson (1970), and in (b) from Thomas (1953).

$$y_p^+ \approx 1.87 R_*^{\frac{1}{2}} \quad (\text{Long \& Chen})$$

$$y_p^+ \approx 2 R_*^{\frac{1}{2}} \quad (\text{Sreenivasan})$$

$$y_p^+ = \lambda R_*^{\frac{1}{2}}$$

$$\lambda \approx 1.8 \pm 0.2$$

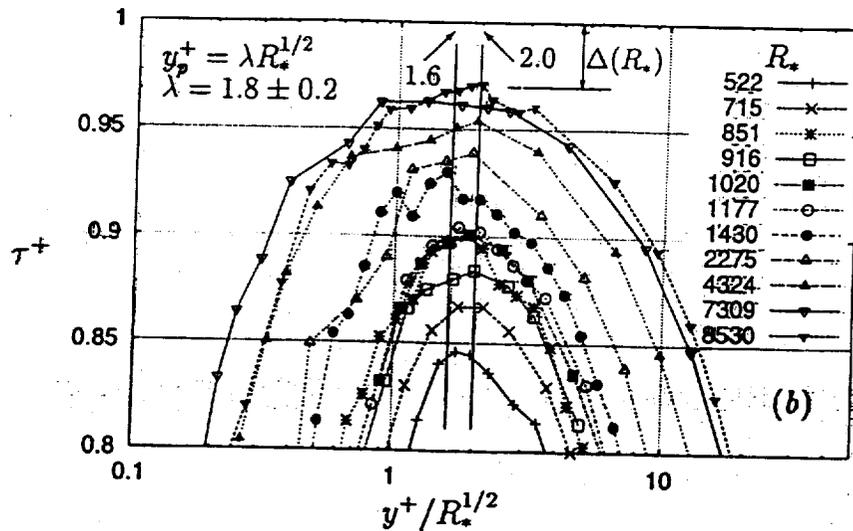


Figure 2: Plots of the turbulent shear stress τ^+ as a function of $y^+/R_*^{1/2}$ (a) across a channel and (b) near its peak for high Reynolds number experiments. The sources for the experimental data are Antonia *et al.* 1992 (channel, $R_* = 256, 916$), Comte-Bellot 1963 (channel, $R_* = 4324, 7309$), Kim *et al.* 1987 (channel DNS, $R_* = 180$), Laufer 1950 (channel, $R_* = 522, 1177, 2275$), Laufer 1954 (pipe, $R_* = 8530$), Sirovich *et al.* 1991 (channel DNS, $R_* = 125$), Wei & Willmarth 1989 (channel, $R_* = 715, 1020$), and Zagarola 1996 (pipe, $R_* = 851, 1430$). The shear stress has been obtained by the numerical differentiation of the measured velocity profile using Eq. (6) of section 3. Zagarola's data for higher Reynolds numbers could not be used because the mean velocity data have not been measured close enough to the wall.

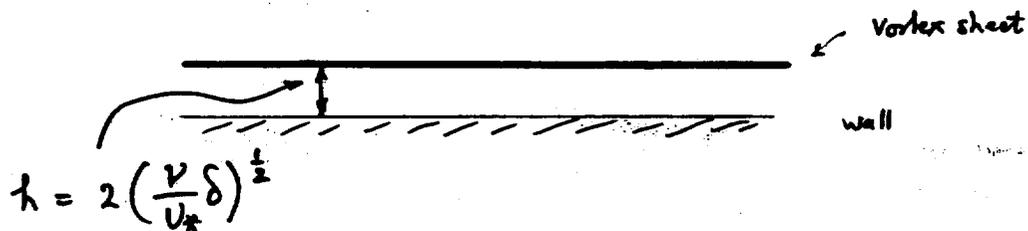
1. PEAK REYNOLDS STRESS LOCATION IS LIKE A CRITICAL LAYER

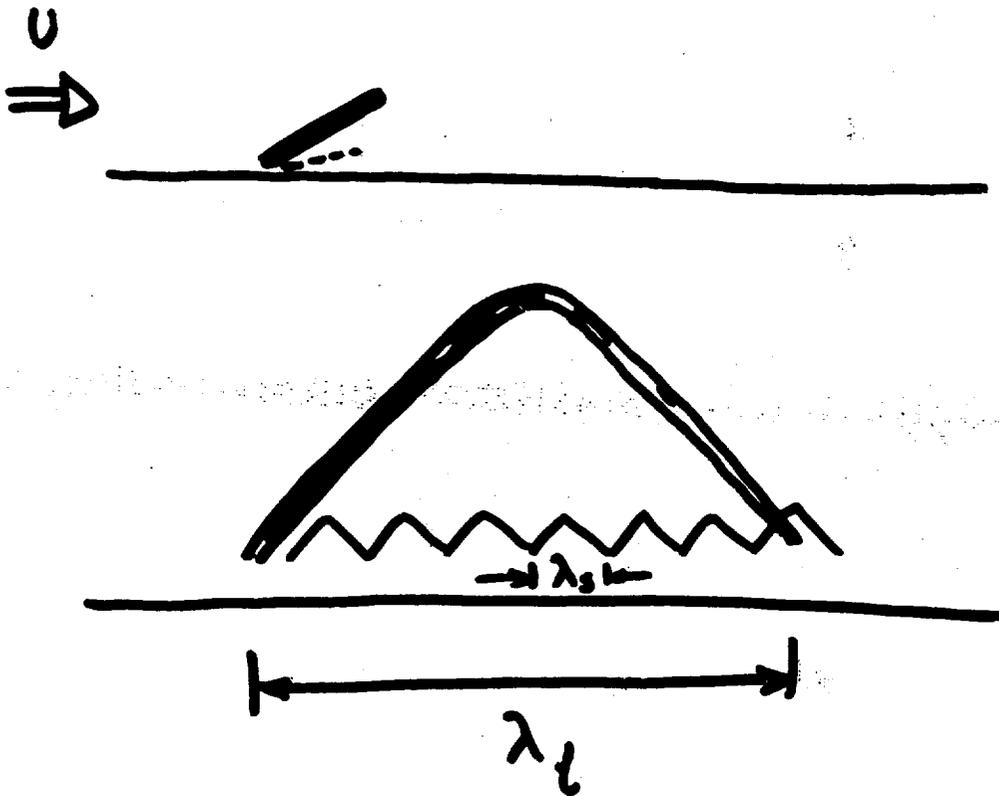
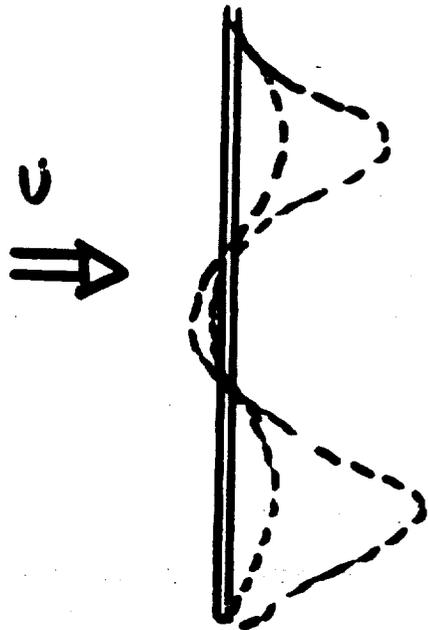
$$y_p^+ = 2 R_{\tau}^{\frac{1}{2}}$$

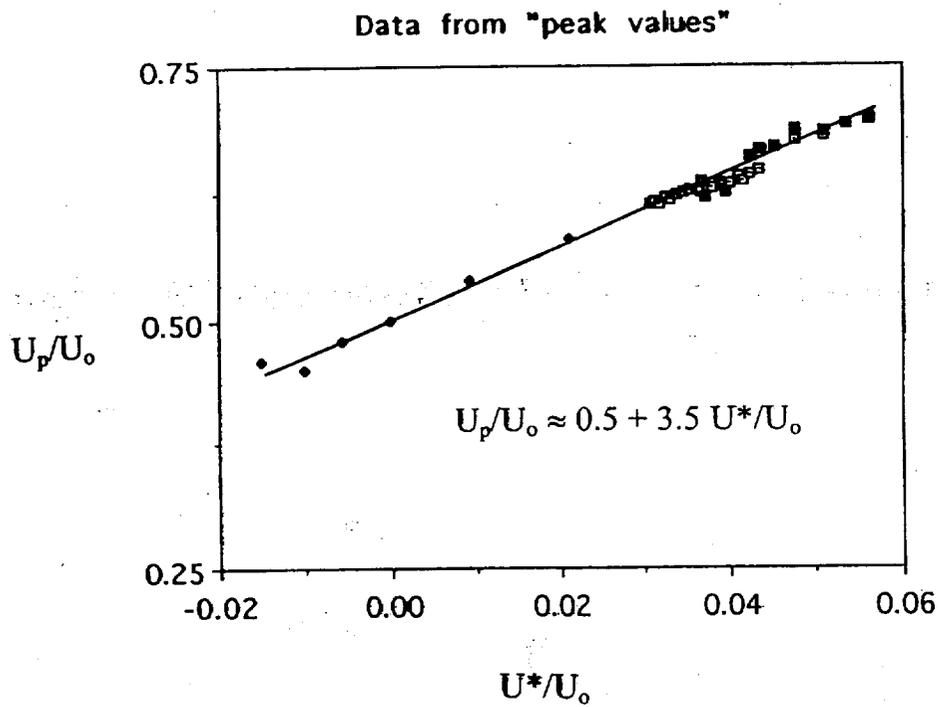
OR

$$h \equiv y_p = 2 \left(\frac{\nu \delta}{U_{\tau}} \right)^{\frac{1}{2}}$$

2. THE CRITICAL LAYER IS ESSENTIALLY A VORTEX SHEET







◆ Simpson's boundary layer in adverse pressure gradient
(all states of separation)

Other symbols: Constant pressure boundary layers, pipes
and channel flows

56/34

EXPERIMENTAL ISSUES RELATED TO TURBULENT HIGH REYNOLDS NUMBER SEPARATED FLOWS

Roger Simpson
Virginia Tech

QUESTIONS

What do we know?

What are the problems with the data?

What data are needed?

NATURE OF SEPARATED FLOWS

Nominal 2-D mean flows have highly 3-D instantaneous flows

SOME COMMON MEAN 3-D FLOWS

Juncture flows
Cross-flow separation
Vortical Separations
Swept wing separations

Some 3-D mean flows are complex and are difficult to calculate,
even for lower Reynolds number cases.

DATA THAT WE NEED

CASES WITH COMPLETE DOCUMENTATION

- Detailed free-stream conditions
- Surface pressure distributions
- Skin friction magnitude and direction
- Simultaneous 3-velocity component measurements with high sufficiently high spatial resolution for smallest turbulent scales; produces mean velocities, Reynolds stresses, and triple products
- Temporal and spatial correlations for time and length scales (multipoint data)
- Surface pressure fluctuations for vibrations/noise issues
- Rate of strain tensor, vorticity tensor, dissipation rate

Separated Flow over airfoil

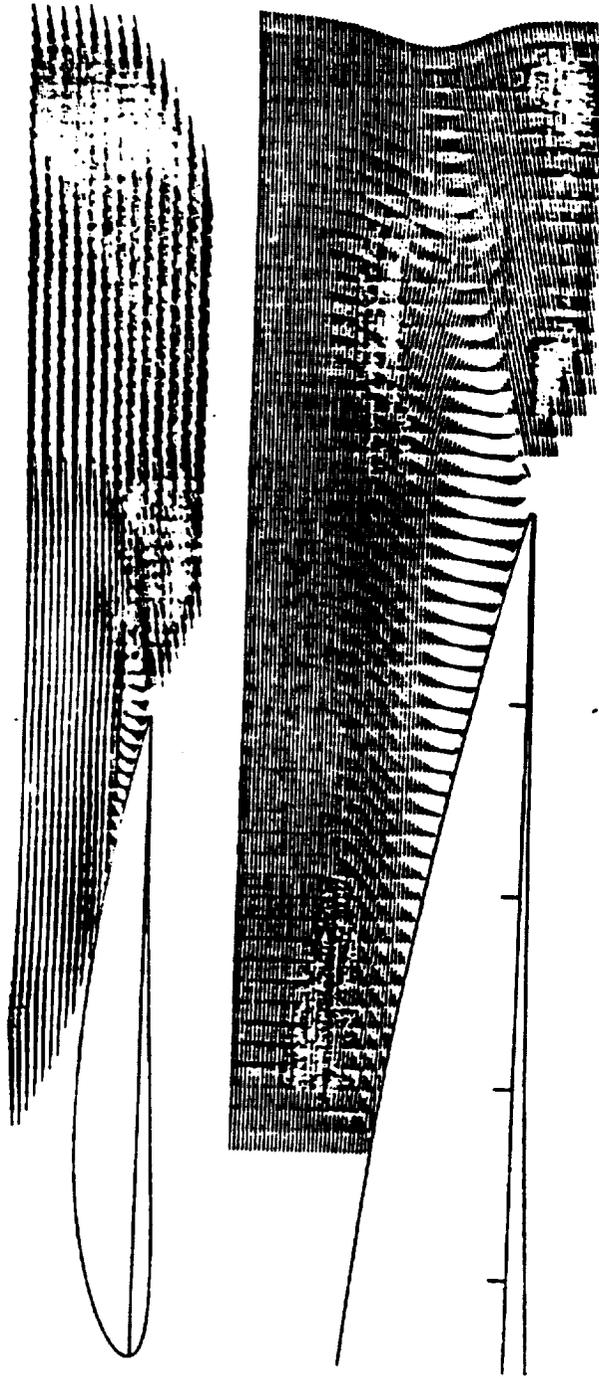


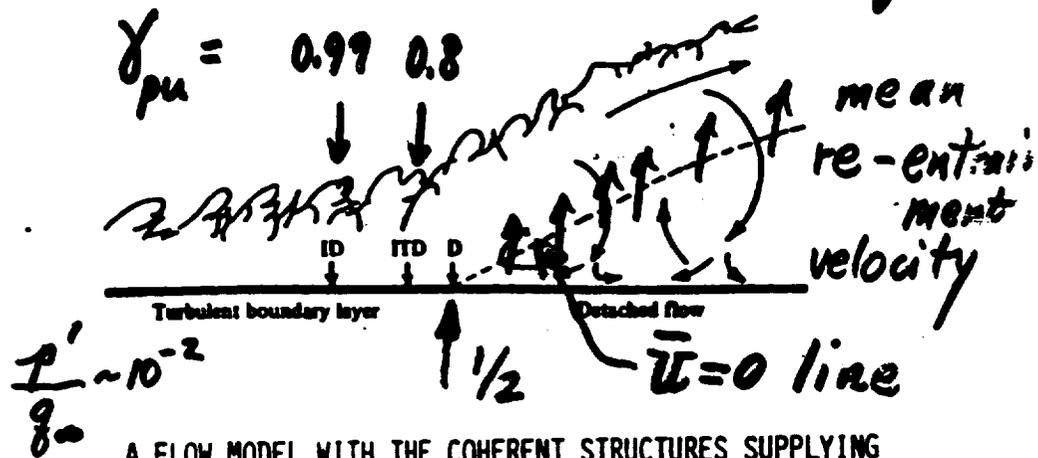
Figure 6C Partial display of vector field of mean velocity. Top: same scale as Figures 10 and 11. Bottom: close-up view of separated region. Tick marks on chord line are at intervals of 0.1 in x/c .

From Coles and Wadcock (1979)

reattachment: $\frac{P'}{\rho_0} \sim 10^{-1}$

NATURE OF A SEPARATING TURBULENT BOUNDARY LAYER

$\frac{L_E}{\delta} \approx 0.3$



A FLOW MODEL WITH THE COHERENT STRUCTURES SUPPLYING THE SMALL MEAN BACKFLOW. ID DENOTES INCIPIENT DETACHMENT; ITD DENOTES INTERMITTENT TRANSITORY DETACHMENT; D DENOTES DETACHMENT. THE DASHED LINE DENOTES $U = 0$ LOCATIONS. FROM SIMPSON ET AL. (1981b).

1. LARGE EDDIES GROW DURING DETACHMENT; large spanwise fluct.
2. LARGE EDDIES SUPPLY TURBULENCE ENERGY TO BACKFLOW AND CONTROL OUTER REGION ENTRAINMENT RATE
3. LARGE EDDY BEHAVIOR SCALES ON MAXIMUM SHEAR STRESS.
4. DIFFUSION AND DISSIPATION OF TURBULENCE ENERGY IN BACKFLOW.
5. SMALL $-\overline{uv}$ IN BACKFLOW; COLES "LAW-OF-THE-WALL" DOES NOT APPLY.

Simpson (1985) Two-dimensional turbulent separated flow AGARDograph 287.

Simpson (1996) Prog. Aerospace Sci, Vol. 32, p. 457.

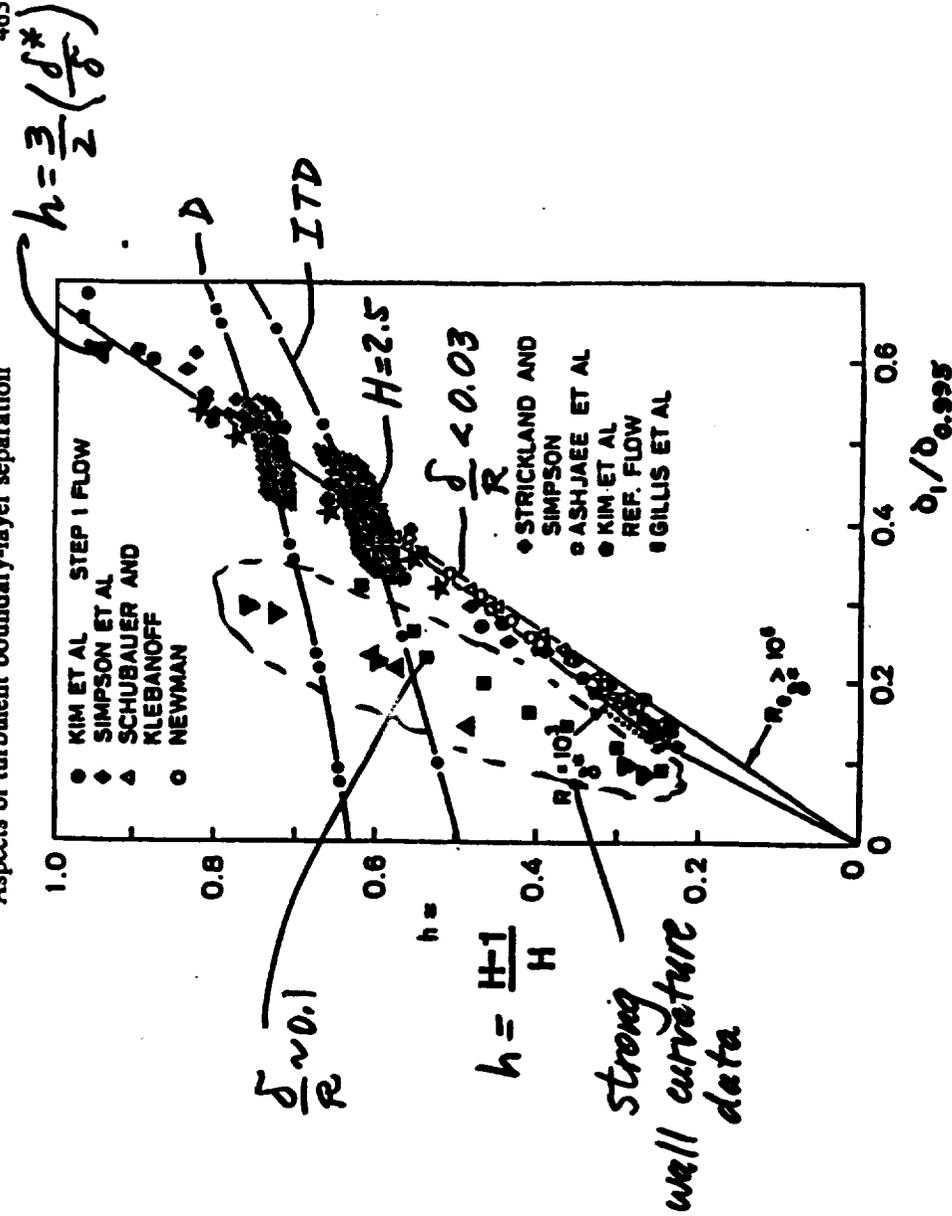


Fig. 4. A plot of h vs $\delta_1/\delta_{0.995}$ data for detaching and reattaching flows. Shaded regions—data reviewed by Sandborn and Kline⁽¹⁴⁶⁾ for intermittent backflow and for detachment. Intermittent transitory detachment (ITD) location given by Eq. (4a) and - - -; detachment (D) given by Eqs (4b) and (4c) and - · - · -; path for detaching flows over low curvature surfaces given by Eq. (4d) and solid line. Curved wall data: ■, data of Chou and Sandborn,⁽¹³⁴⁾ ▲, data of Sandborn and Liu,⁽¹⁴⁷⁾ ★, data of So and Mellor⁽¹³³⁾ (zero pressure gradient); ▼ data of Gersten et al.⁽¹³⁵⁾ Plot from Simpson.⁽¹³³⁾ (1996)

Separated profiles
 $\frac{u}{u_e} = f(H)$
 u_e
 not Re_θ .

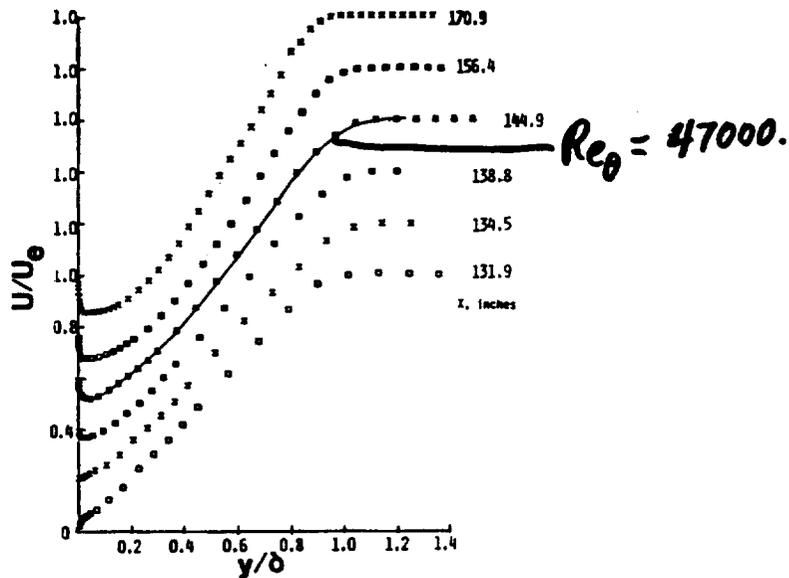


Fig. 22 Detaching flow mean velocity profiles (Simpson et al., 1981a) - $Re_\theta \sim 16000$
 from laser and hot-wire anemometer data. Note displaced ordinates. Solid line denotes $Re_\theta = 47000$, $H = 5.38$ data of Hastings and Moreton (1982).

Mean Backflow
 Similarity

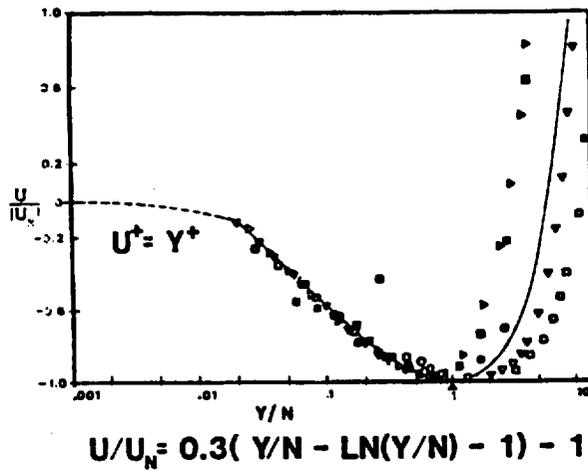
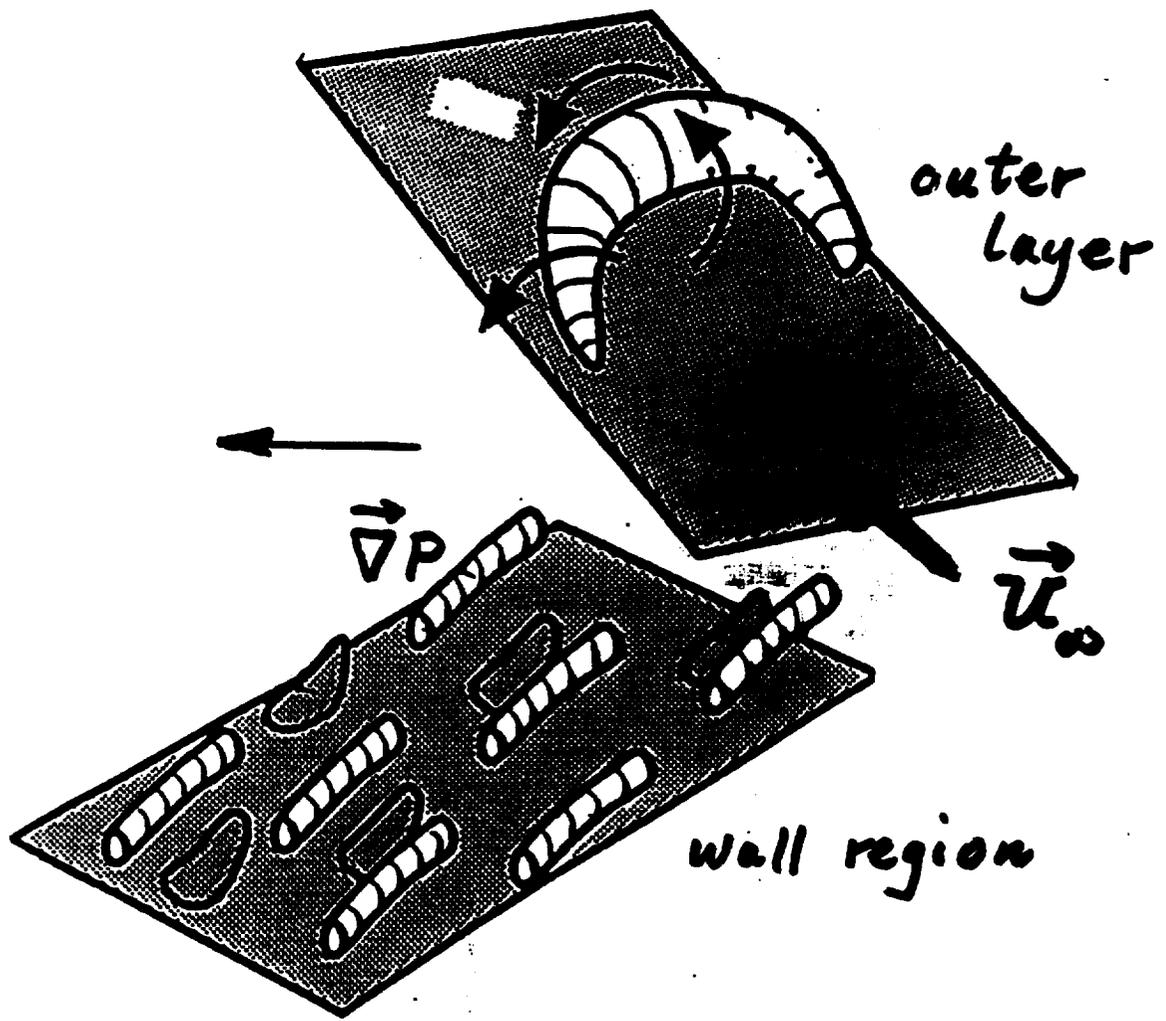


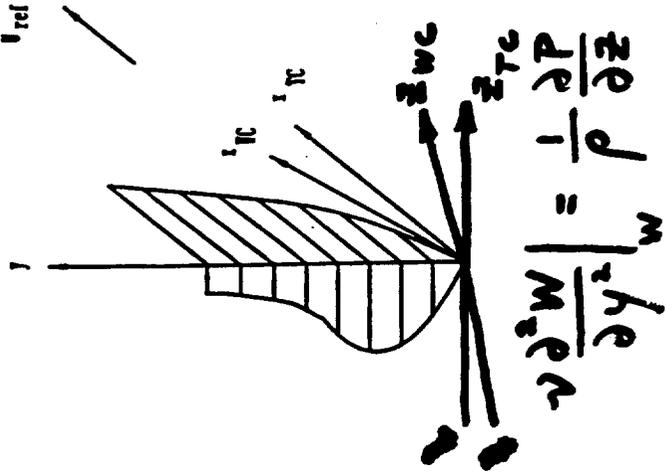
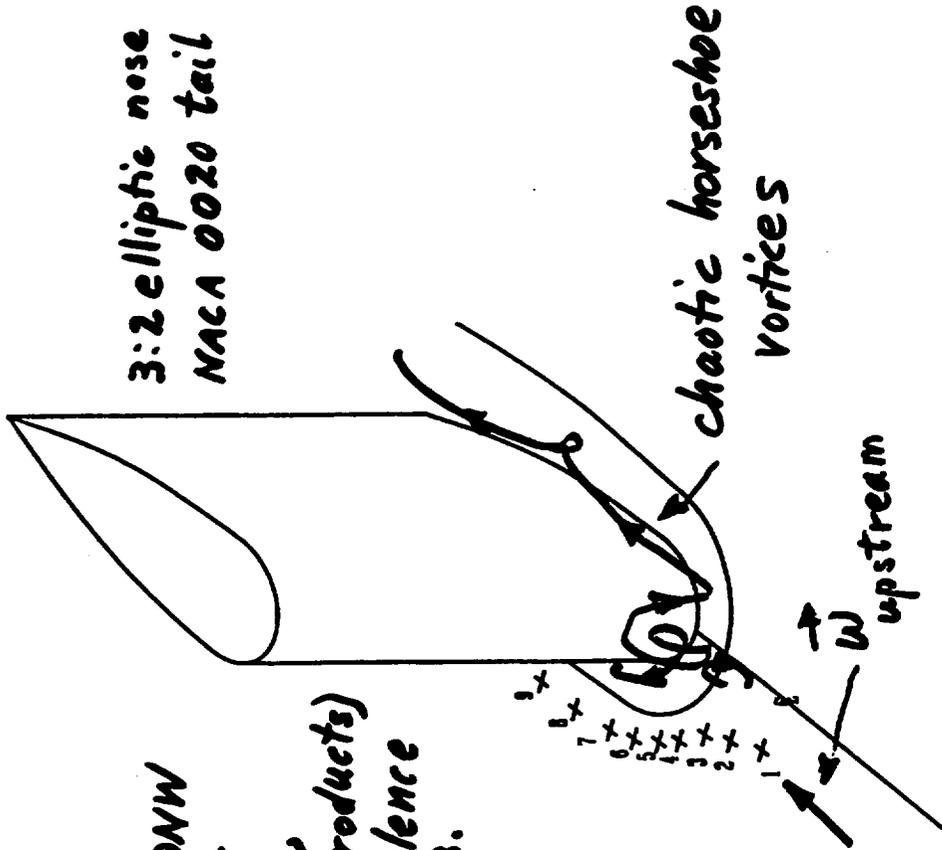
Fig. 23 Normalized backflow mean velocity profiles. Simpson et al. (1981a). LDV: \square , 3.53 m.; \blacktriangleright , 3.68 m.; \blacksquare , 3.97 m.; \blacktriangledown , 4.34 m. Hastings and Moreton (1982): LDV \circ . Westphal pulsed-wire \bullet . Solid line, equation (IV.11). Dashed line, equation (IV.12). From Simpson (1983).



Coherent Structures in 3-D Flow

$Re_\theta = 23,000$
 2-D approach flow
 agrees closely with DNW
 hot-wire data in outer
 layer (mean, stresses,
 available DNW triple products)
 No DNW near-wall turbulence
 data. AIAA-99-0553.

3:2 elliptic nose
 NACA 0020 tail



see Simpson (2001) "Juncture
 Flows," Annual Reviews of Fluid
 Mechanics.

bimodal in w

Print II 10 May 1995 II

Velocity magnitude contours and secondary flow streamlines

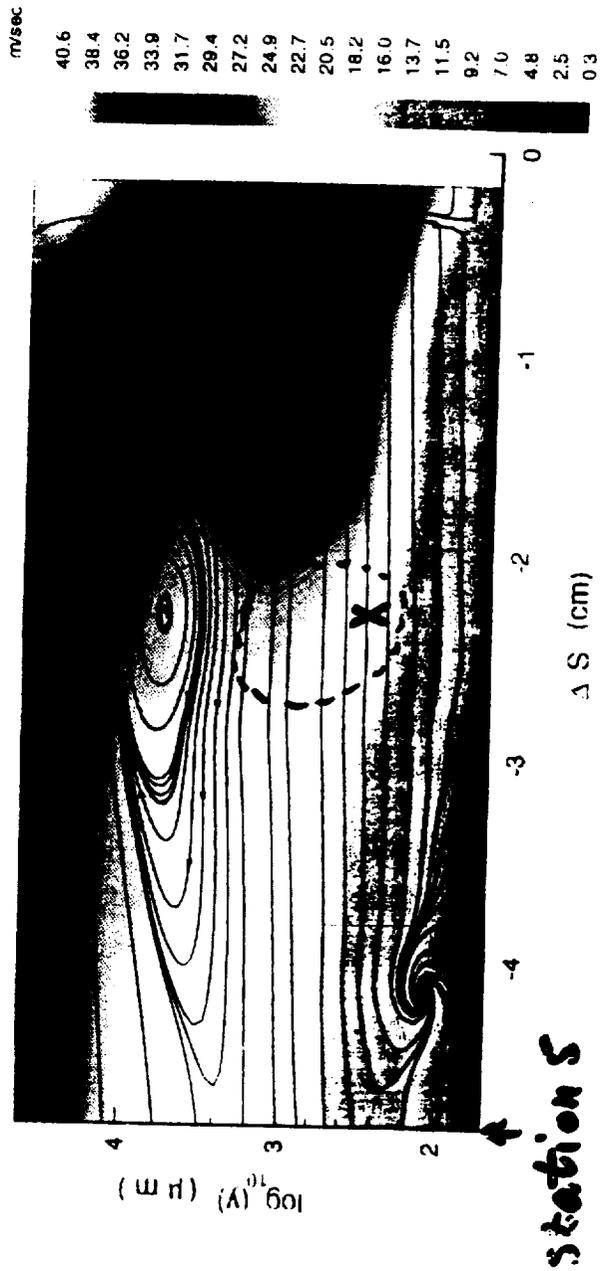
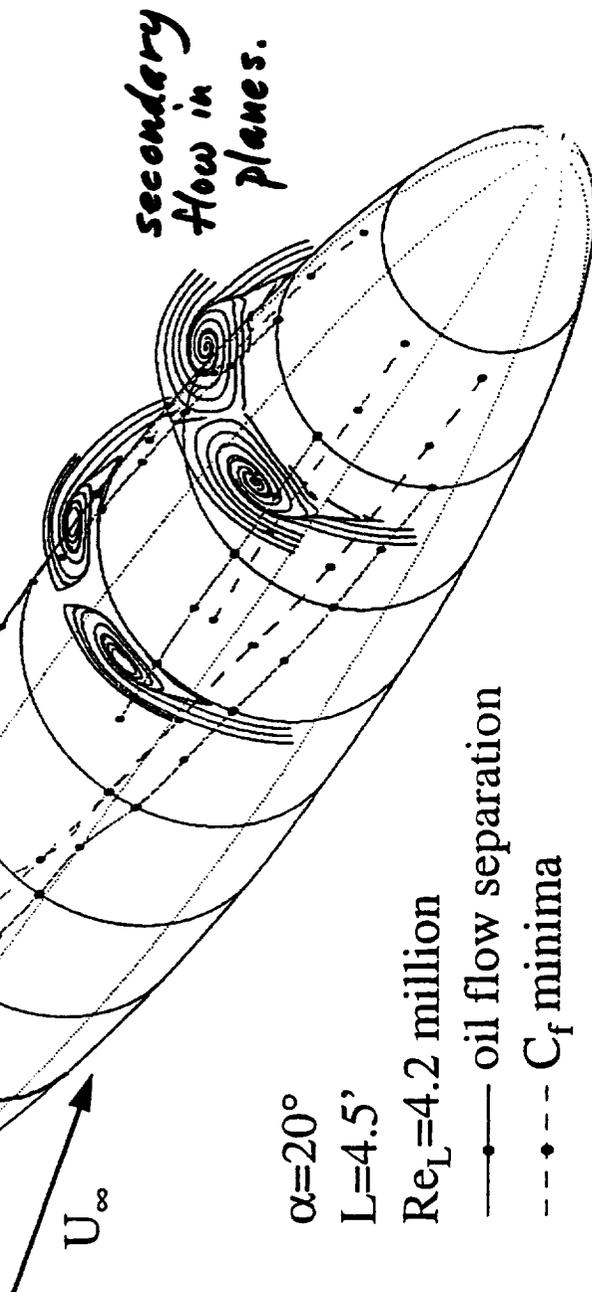


Figure 42. Mean secondary flow (V, W) streamlines from detailed 3-velocity-component laser-Doppler velocimeter measurements that show the horseshoe vortex in the measurement plane perpendicular to the wing of Figure 21(a), including station 5 of Ölçmen and Simpson⁽¹²⁶⁾. Total mean velocity magnitudes are shown as color contours. Note the logarithmic scale for y distance from the wall. Wing surface located at $\Delta S = 0$; separation and vortex near $\Delta S = -4$; corner vortex shown within $\Delta S = -0.4$ and wing; no separation shown at line of low shear. Approach velocity $U_a = 27.5$ m/s; $\delta_{0.995} = 39.6$ mm at station 5 on left edge of plot. From Ölçmen and Simpson⁽¹²⁶⁾.

Prog. Aerospace Sci. 1996.

Secondary Flow

Trip posts at $x/L=0.2$



$\alpha=20^\circ$

$L=4.5'$

$Re_L=4.2$ million

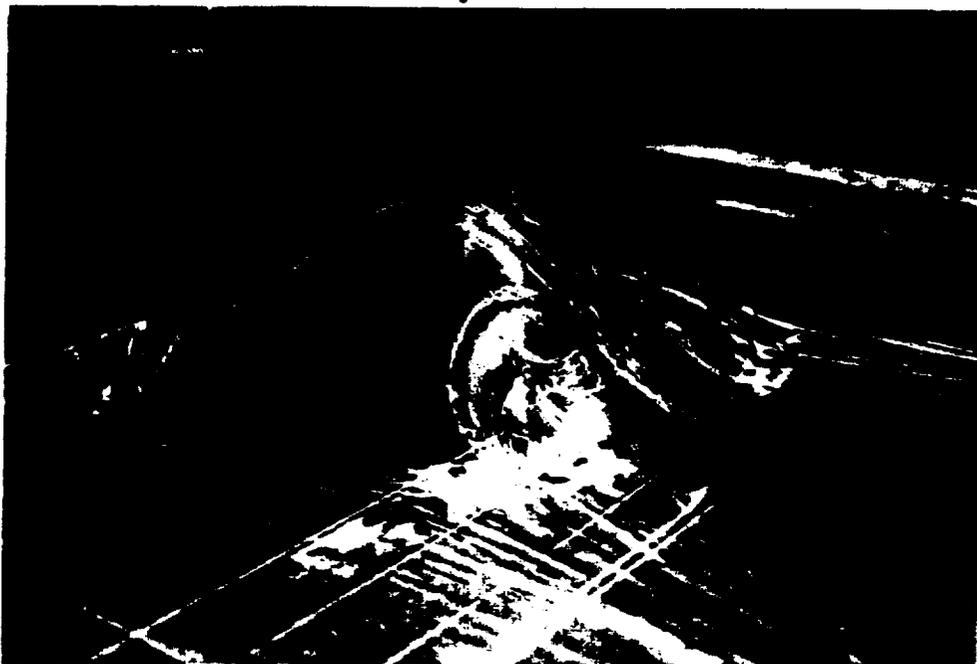
—•— oil flow separation

- - -• - - - C_f minima

secondary flow in planes.

U_∞

vortical separation on Bump



Perspective view of leeside (above)

Surface Oilflow over Large Bump #3

$U = 90.2\text{fps}$ (27.5mps), $Re_b = 6000$, $H/\delta = 2$, $\delta = 1.54\text{ in.} = 39\text{mm}$

Top view (below)



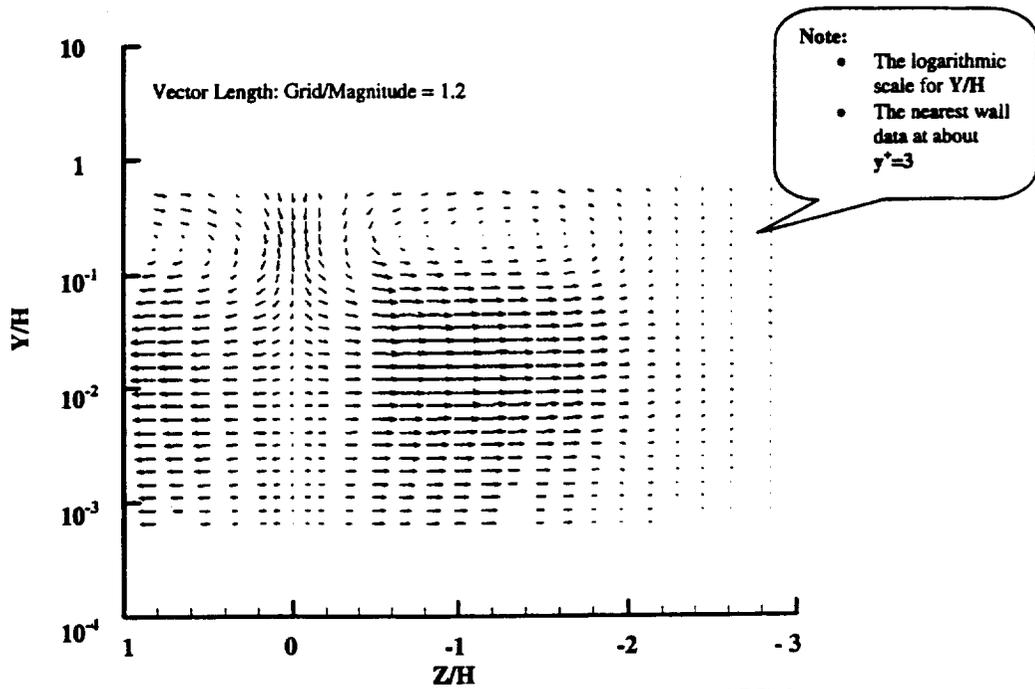
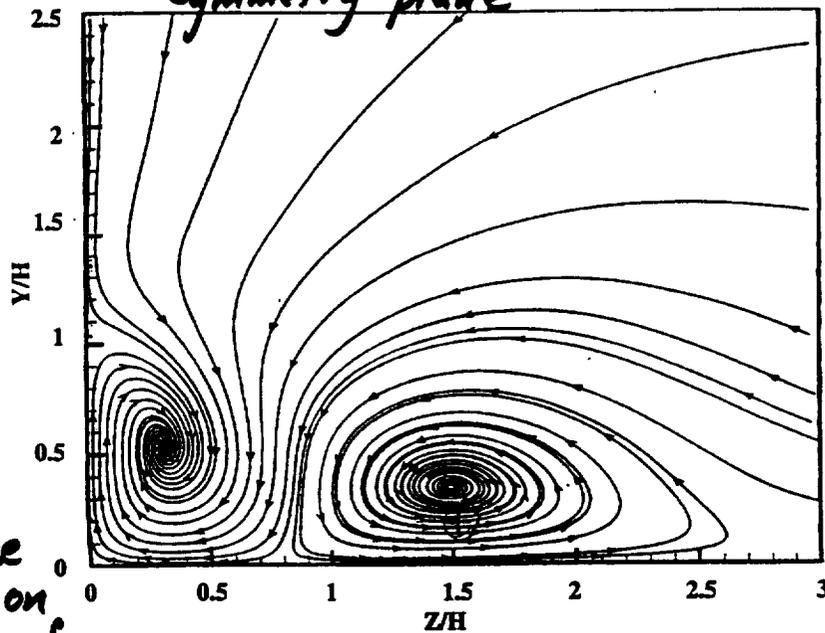


Figure 3: VW mean secondary flow vectors for 650 individual LDV data points at 11.14" downstream of the center of Bump#3 with $\delta/H=1/2$ ($X/H=3.63$).

One streamwise vortex on each side of symmetry plane

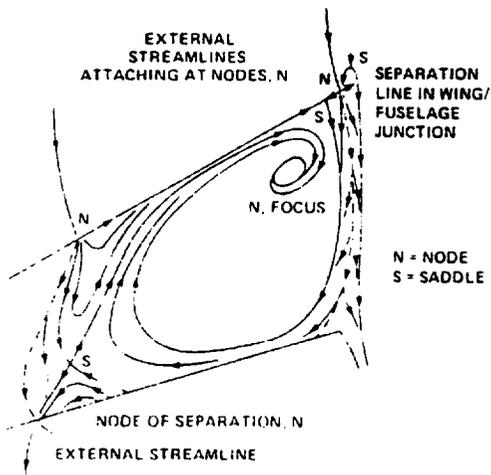


2 streamwise vortices on each side of symmetry plane.

Figure 4: Typical $k-\omega$ model computational solution for Bump#3 with $\delta/H=1/2$ at $X/H=6.5$.



OIL FLOW PATTERN (COURTESY OF ARA, BEDFORD)



INTERPRETATION OF SKIN-FRICTION LINES ON TOP SURFACE OF PORT WING

(c) TURBULENT FLOW ON SWEEP WING OF FIGHTER AT HIGH LIFT



(d) TURBULENT FLOW ON INBOARD TRAILING-EDGE REGION OF LIFTING HIGH ASPECT RATIO SWEEP WING OF TRANSPORT AIRCRAFT AT HIGH SUBSONIC SPEED (COURTESY OF B. ELSENAAR, NLR)

Fig. 14 Continued.

*from Peake and Jobak
AGARDograph*

SOME DIFFICULTIES OF TURBULENCE MODELING FOR THREE-DIMENSIONAL FLOWS

- Algebraic and second-order closure models are not robust in adverse pressure gradients and separated flows, e.g., leaside of vehicles. (Simpson, 1996)
- Reynolds-averaged Navier-Stokes (RANS) calculations fail to capture chaotic (Markovian) large-scale separation vortices that are responsible for large pressure fluctuations, e.g., horseshoe vortices around appendages. (Simpson, 1996; Rizzi and Vos, 1998)
- Some models for terms in RANS codes are not supported by experimental data, e.g., turbulence diffusion (Ölçmen and Simpson, 1997).
- Effects of surface roughness are not well described; scales produced by the roughness govern the near-wall behavior and are larger than the Kolmogorov scales.

SOME CONTINUING NEEDED EXPERIMENTAL INFORMATION

- Forced basic experiments can lead to improvements in turbulence modeling for 3-D flows, e.g., measurements of quantities in second-order closures useful; anisotropic coherent structural features are essential. (Simpson and Ölçmen, 1998)
- Well-posed and documented practical application experiments that capture all relevant flow physics, e.g., high Reynolds numbers and chaotic vortical structures.
- Unsteady maneuvers that capture unsteady flow effects on separations, e.g., submarines (Wetzel and Simpson, 1998) and aircraft carriers.

Equations for Modeling

x- direction momentum equation:

$$\frac{DU}{Dt} \equiv U \frac{\partial U}{\partial x} + V \frac{\partial U}{\partial y} + W \frac{\partial U}{\partial z} = \frac{-1}{\rho} \frac{\partial P}{\partial x} + \nu \frac{\partial^2 U}{\partial y^2} - \frac{\partial \overline{uv}}{\partial y}$$

z- direction momentum equation:

$$\frac{DW}{Dt} \equiv U \frac{\partial W}{\partial x} + V \frac{\partial W}{\partial y} + W \frac{\partial W}{\partial z} = \frac{-1}{\rho} \frac{\partial P}{\partial z} + \nu \frac{\partial^2 W}{\partial y^2} - \frac{\partial \overline{vw}}{\partial y}$$

Continuity Eq.;

$$\frac{\partial U}{\partial x} + \frac{\partial V}{\partial y} + \frac{\partial W}{\partial z} = 0$$

Transport of $\overline{-uv}$ Stress:

$$\frac{D(\overline{-uv})}{Dt} = \overline{v} \frac{\partial U}{\partial y} - \frac{\overline{p'}}{\rho} \left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x} \right) + \frac{\partial}{\partial y} \left(\frac{\overline{p' u}}{\rho} + \overline{uv^2} \right) - \nu (\overline{v \nabla^2 u} + \overline{u \nabla^2 v})$$

Transport of $\overline{-vw}$ Stress

$$\frac{D(\overline{-vw})}{Dt} = \overline{v} \frac{\partial W}{\partial y} - \frac{\overline{p'}}{\rho} \left(\frac{\partial w}{\partial y} + \frac{\partial v}{\partial z} \right) + \frac{\partial}{\partial y} \left(\frac{\overline{p' w}}{\rho} + \overline{v^2 w} \right) - \nu (\overline{w \nabla^2 v} + \overline{v \nabla^2 w})$$

Transport of $\overline{v^2}$ stress

$$\frac{1}{2} \frac{D(\overline{v^2})}{Dt} = -\overline{v^2} \frac{\partial V}{\partial y} - \frac{\partial}{\partial y} \left(\frac{\overline{v^3}}{2} \right) - \frac{\overline{v}}{\rho} \frac{\partial p}{\partial y} + \nu (\overline{v \nabla^2 v})$$

Turbulent Transport Rate Budgets from Data
AGREEMENT OF TRENDS
 (Isotropic dissipation, near wall correction of LRR) *Olsman & Simpson, 1997*

	2D station	Station 5	Separation station	Vortex station
$\overline{u^2}$	OP, LRR	None	None	OP, FLT1, FLT2, $y^+ < 15$, None above
$\overline{v^2}$	LRR $y^+ > 30$	None	None	None
$\overline{w^2}$	GL, LRR	LRR, $y^+ > 30$	None,	None
\overline{uv}	SSG, LRR, FLT1 $y^+ > 20$	LRR, GL, FLT1, $y^+ > 15$	GL, LRR, $y^+ > 15$	GL, $y^+ > 50$
\overline{uw}	-	All models except FLTs $y^+ > 30$	All models except FLTs, $y^+ > 20$	None
\overline{vw}	-	GL, LRR, FLT1, $y^+ > 15$	SSG, GL, LRR, $y^+ > 15$	None

CONCLUSIONS

- 1) Low uncertainty data set above $y^+=3$ at 30 stations are used to obtain the transport rate budgets at 4 stations.
- 2) The pressure-diffusion term largely affects the transport rate budget of the $\overline{v^2}$, \overline{uv} and \overline{vw} stresses at all stations near wall.
- 3) At Station 5, Separation and Vortex-core stations the distributions of the transport budget terms decrease progressively more steeply to approximately zero values than the 2-D flow station at lower y^+ locations.
- 4) Anisotropic dissipation rate model of Hallback et. al. shows that the dissipation rate is increasingly anisotropic with increased three-dimensionality.
For 3-D flow stations dissipation rate distributions are approximately isotropic above $y^+ 100$. However for 2 -D flow it becomes isotropic above $y^+ 350$.
- 5) Comparison of the present data to the DNS results show that the present data are in better agreement with the DNS solutions using the anisotropic dissipation rate approximation.

Effect of Re_θ on 2-D & 3-D Structure

Ölçmen, Simpson, George, Review 1998

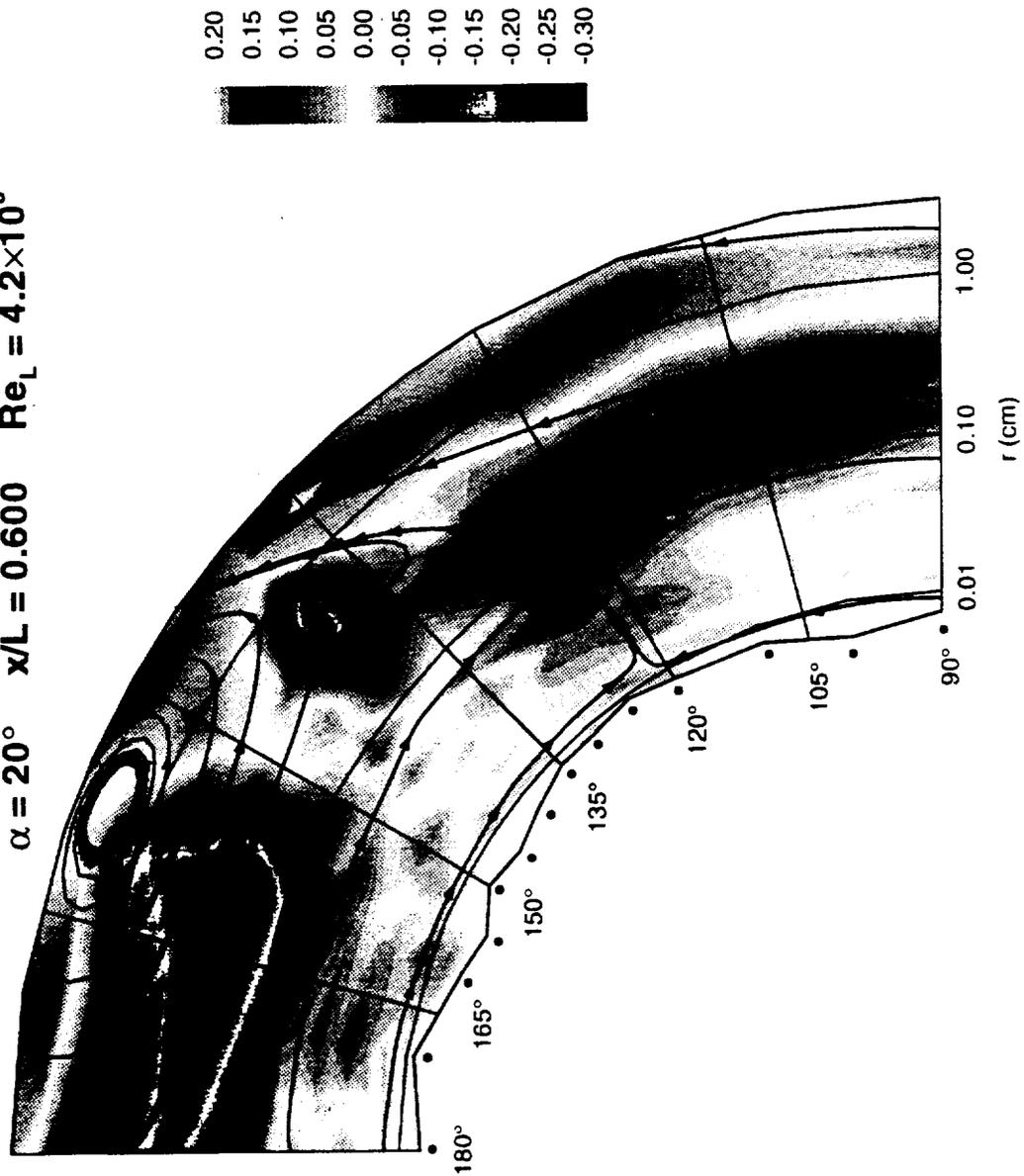
CONCLUSIONS

- Inner layer structure scaled on wall variables seems weakly Reynolds number dependent, except for u related terms such as u^2 , which are more strongly Reynolds number dependent.
- Outer layer structure has a significant Reynolds number dependence.
emerging semi-log overlap region for some triple products at high Re_θ .
- Active motions for shear stresses and turbulence diffusion are closely related to v' over various experiments and available Reynolds numbers.
- Transport equations which can mimic the lags between the mean flow and shearing stress structure must be used for non-equilibrium 3-D turbulent boundary layers.
- Better models for turbulent diffusion and pressure-velocity fluctuation relationships are needed, especially near the wall. Data are needed for these models.

6:1 PROLATE SPHEROID

Secondary Streamlines with Contours of p_w/v Correlation Coefficient

$\alpha = 20^\circ$ $x/L = 0.600$ $Re_L = 4.2 \times 10^6$



cannot measure p' within flow; can get $\overline{p_w v}$ correlations

CONSTANT TEMPERATURE HOT-WIRE ANEMOMETRY FOR 3-D FLOWS

Advantages:

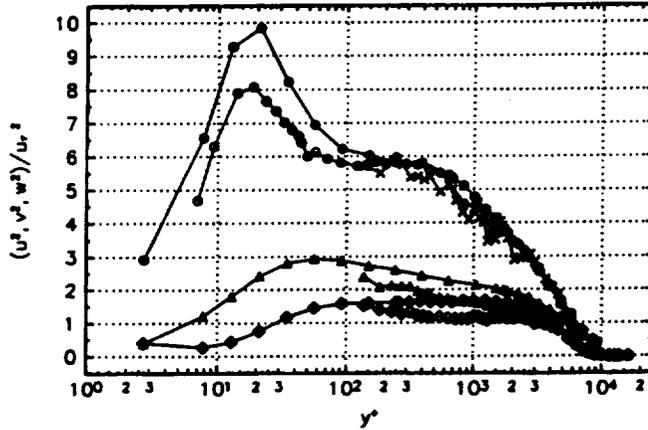
- Continuous time series data from multiple sensors
 - Frequency response: 30KHz flat response; carefully matched phasing flat up to 50KHz; calibrated matched phasing up to 150KHz.

Disadvantages:

- +/- 40 degrees total included angle for 4 sensor probe for mean velocities
 - +/- 20 degrees for turbulence for triple products
 - 0.5mm^3 smallest measurement volume
 - 1mm closest near-wall measurement
- Near-wall flow interference, even with single wires

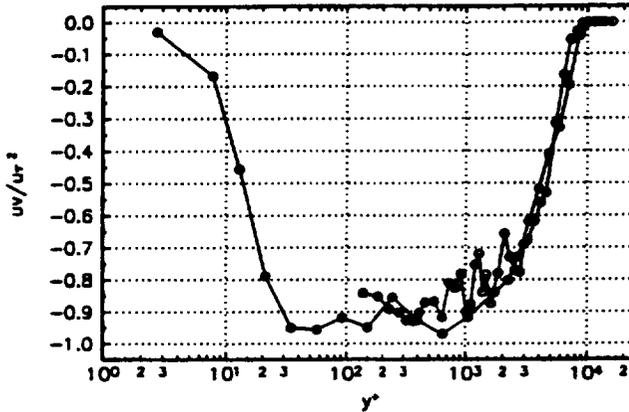
DNW: $\overline{L^+} = 22.5 = 2^4$

Present LDV: $L^+ = 1.85$ near wall;



$L^+ = 5.43$
away from
wall.
Ligani &
Bradshaw
(1987)
suggest
 $L^+ < 20$ for
no wire length
effects.

Figure 4. 2-D flow normal stress data comparison: $\circ, \overline{u^2}$; $\diamond, \overline{v^2}$; $\triangle, \overline{w^2}$, $Re_0=22140$; $\times, \overline{u^2}$, $Re_0=20920$ (Nockemann et al, 1994). Solid symbols present $Re_0=23200$ data.



DNW: wire
sensing length
appears too
long; $\overline{v^2}, \overline{w^2},$
 $-\overline{uv}$ too low?

Figure 5. DNW (\circ , $Re_0=22140$) data and present 2D (\bullet , $Re_0=23200$) data shear stress comparison.

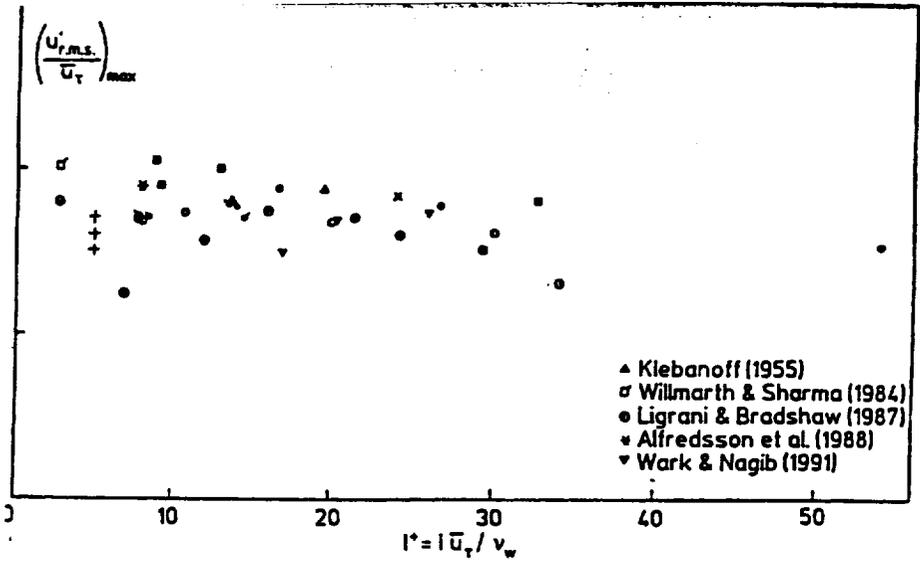


Figure 19: The influence of the characteristic dimensionless hot-wire length scale l^+ on the maximum value of $\sqrt{u'^2}/u_\tau$ in subsonic boundary layers. $Re_\delta > 700$ and $l/\delta > 180$. For additional symbols see Table 1. Figure from Fernholz & Finley (1995).

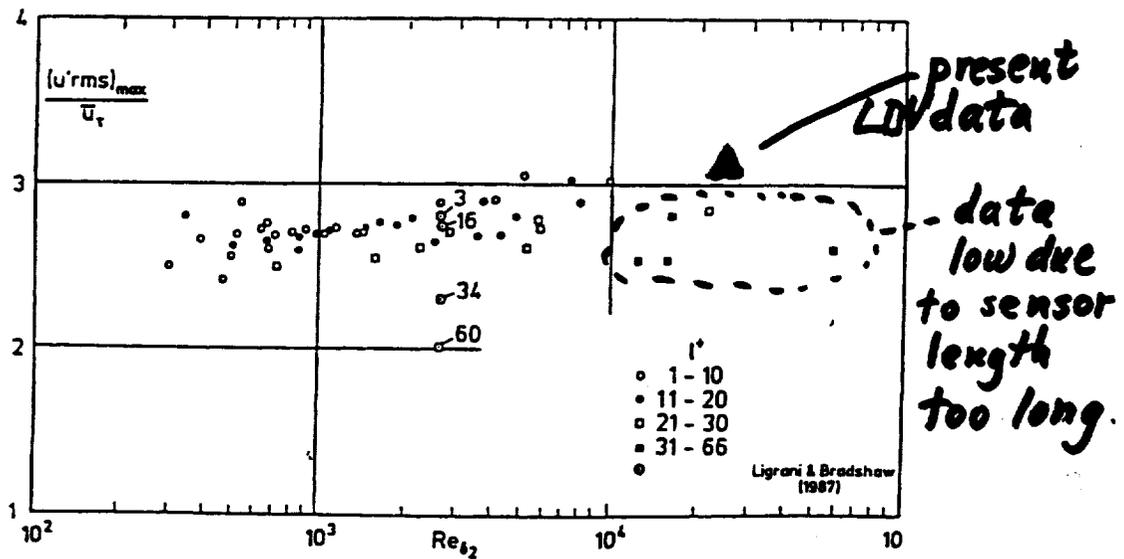


Figure 20: The influence of l^+ and Reynolds number on the maximum value of $\sqrt{u'^2}/u_\tau$. Data from 13 experiments. Figure from Fernholz & Finley (1995).

From AGARDograph 335, 1996.

LASER DOPPLER VELOCIMETRY

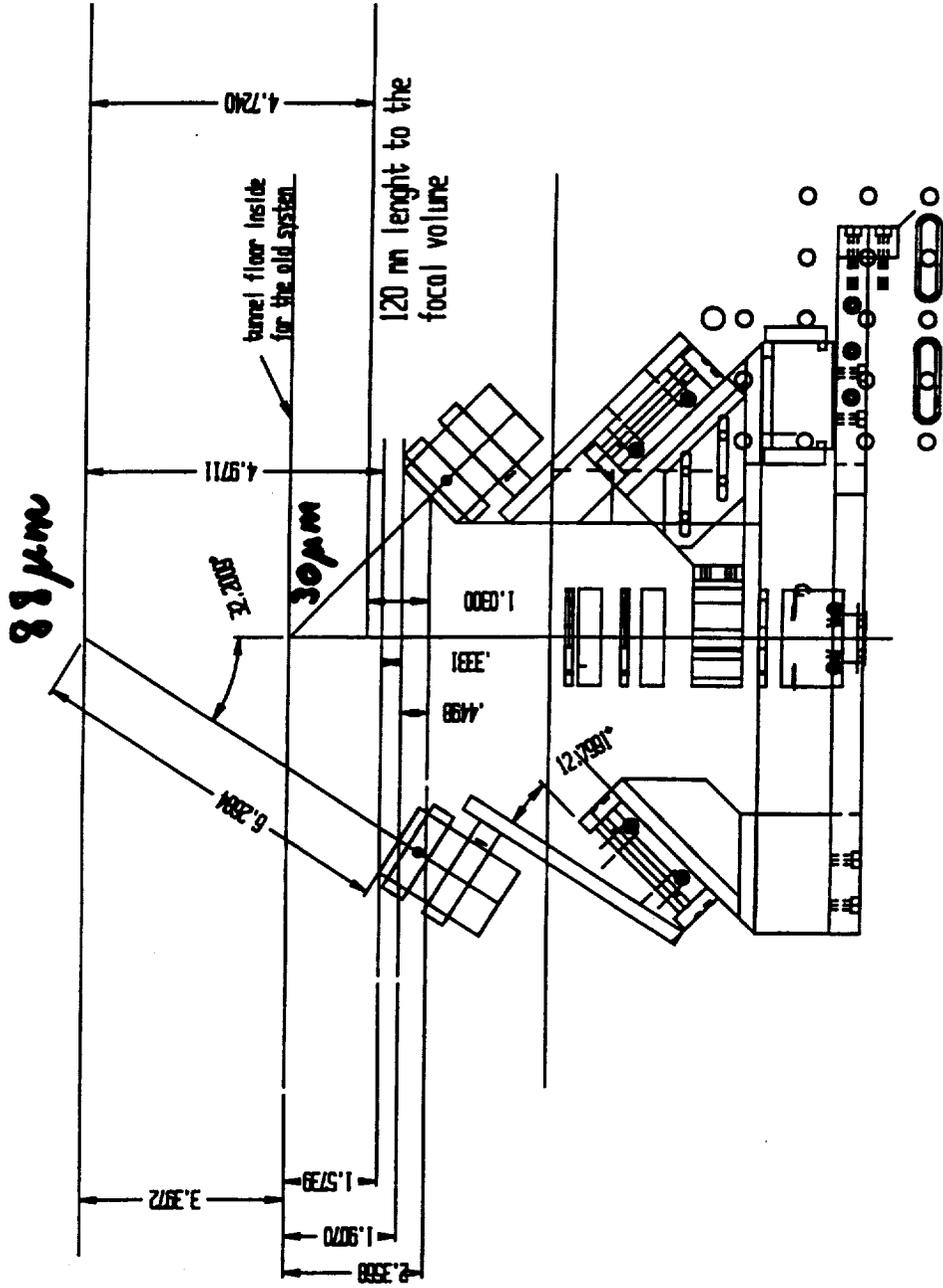
Advantages:

- Linear Doppler frequency – velocity relationship
- Miniature 3-velocity-component probes with low uncertainties of each velocity component
 - Fine spatial resolution measurements – 30µm spherical measurement volume within 30µm of wall
- Rate of strain, vorticity, dissipation measurements possible

Disadvantages:

- Flow seeding required
- Low data rate – 10^3 to 10^4 coincident signals per sec.
 - Single point data
 - Setup and data acquisition time
- Probe hardware restricted to model interior

6



Ölçme ve Simpson (1995), (1998)

LDV Set-up

- 3 orthogonal velocity component
- 3 green (514.5 nm), 2 blue (488 nm)
- Fringe spacing around 5 μm
- Spherical 50 μm diameter control volume
- 3 Macrodyne model FDP3100 Processors
- Dostek DAQ board
- Seeded with dioctal phthylate



Virginia Polytechnic
Institute and State
University

Lisbon, Portugal
July 12, 2000

Department of
Aerospace and Ocean
Engineering

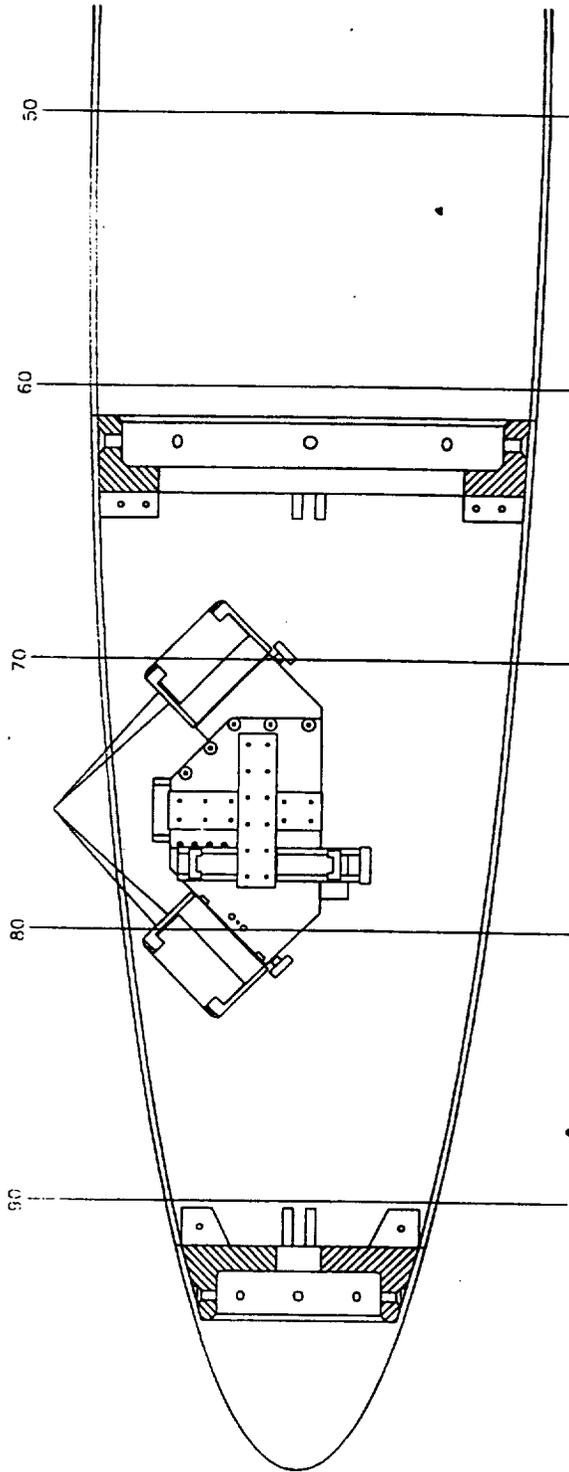
Kubal & Simpson

Corrections and Biases

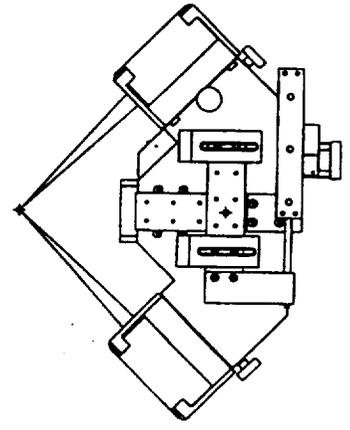
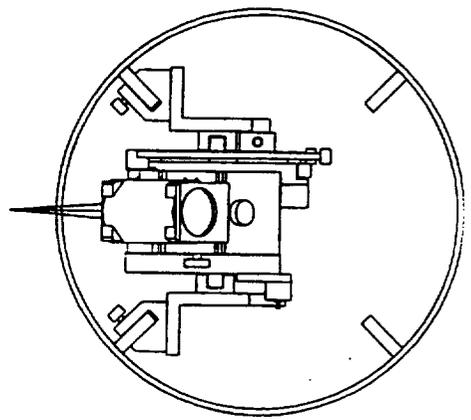
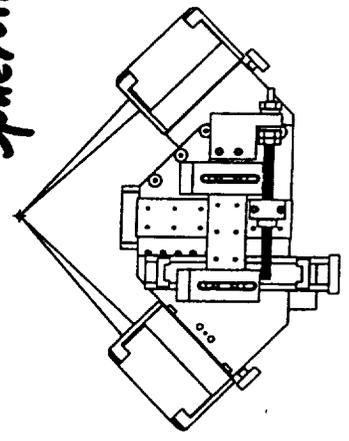
- Noise removal
- Wall location correction
- Coordinate transformation correction
- Negligible Broadening:
 - Velocity gradient broadening
 - Finite transient time broadening
 - Instrument broadening
- No Biases Present:
 - Angular bias
 - Fringe bias
 - Geometric bias
 - Velocity Bias

TABLE 3. 20:1 odds +2 σ uncertainties of means velocities, Reynolds' stresses and triple products.

Term	Uncertainty	Term	Uncertainty
U/u_τ	0.148	$\overline{U^2 V}/u_\tau^3$	0.082
V/u_τ	0.033	$\overline{U^2 W}/u_\tau^3$	0.144
W/u_τ	0.097	$\overline{V^2 W}/u_\tau^3$	0.051
$\overline{U^2}/u_\tau^2$	0.062	$\overline{UV^2}/u_\tau^3$	0.055
$\overline{V^2}/u_\tau^2$	0.04	$\overline{UW^2}/u_\tau^3$	0.165
$\overline{W^2}/u_\tau^2$	0.07	$\overline{VW^2}/u_\tau^3$	0.053
\overline{UV}/u_τ^2	0.025	\overline{UVW}/u_τ^3	0.05
\overline{UW}/u_τ^2	0.037	$\overline{U^3}/u_\tau^3$	0.254
\overline{VW}/u_τ^2	0.019	$\overline{V^3}/u_\tau^3$	0.043
		$\overline{W^3}/u_\tau^3$	0.424



Chesnabas & Simpson (LDV inside prolate spheroid)



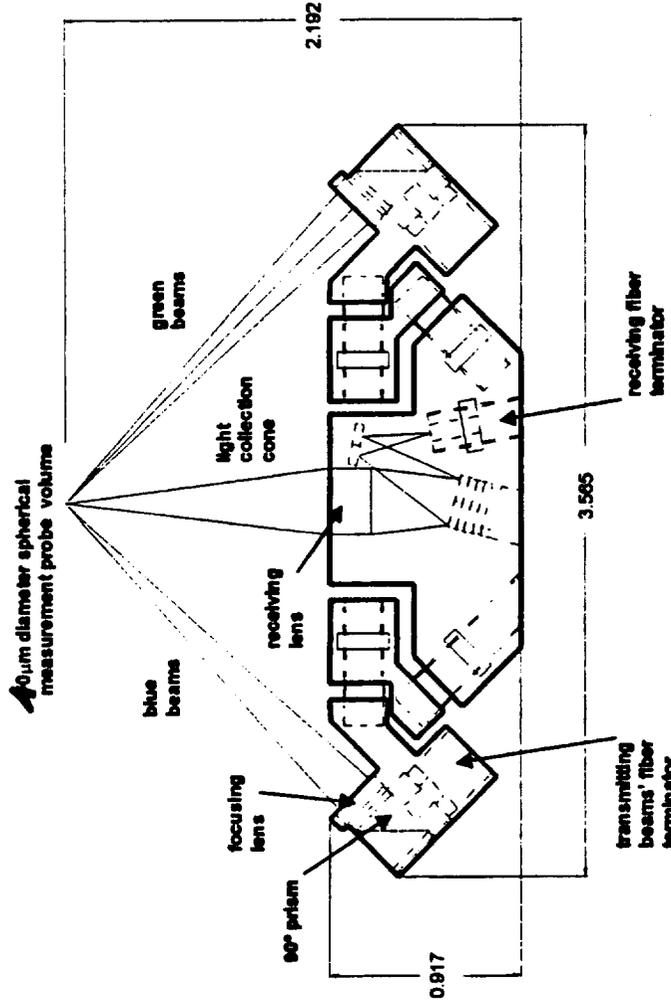


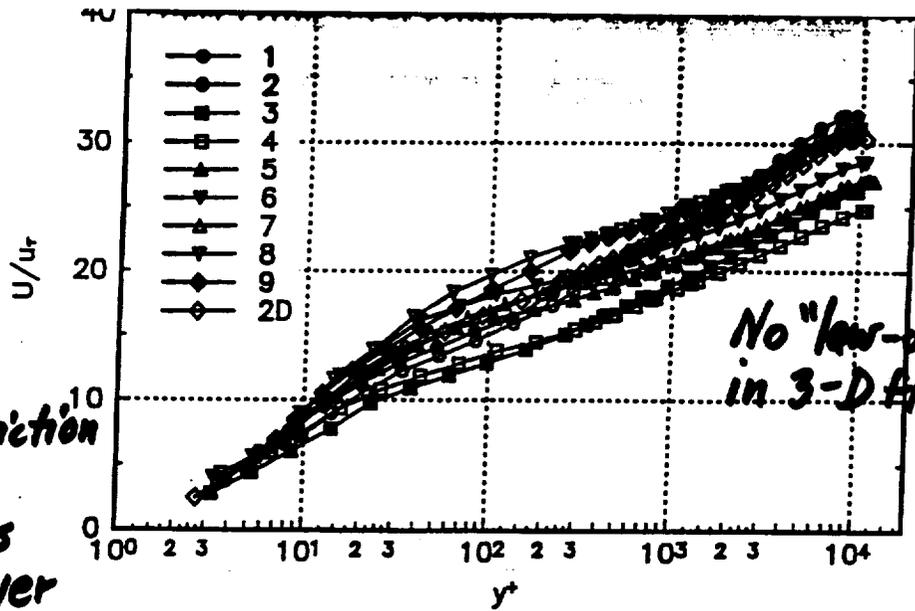
Figure 2. Sub-miniature, 3-simultaneous velocity component LDV probe head. Dimensions are in inches. The probe thickness is 0.344 inches.

NEXT GENERATION LDV PROBE

- Miniature in size (3.6" x 1" x 0.35")
- Flow submergible with negligible disturbance
- Can be inserted into models
- Can be used in highly vibrational environments
- Can be modified in size easily for different applications

- Three simultaneous velocity components with 40 microns resolution

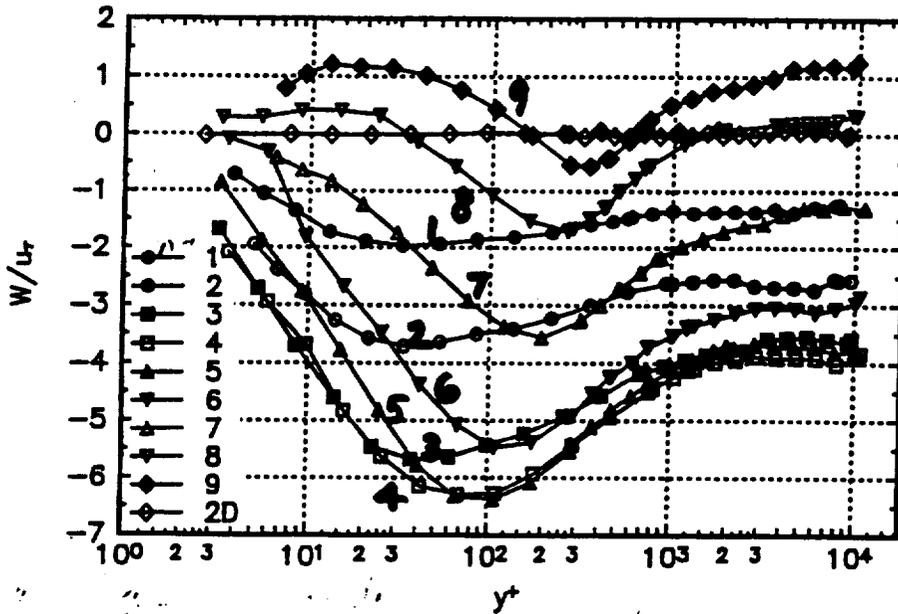
skin friction
from
viscous
sublayer



No "law-of-wall"
in 3-D flows.

$Re_x = 23,000.$

U/u_t mean velocity profiles in tunnel coordinates.

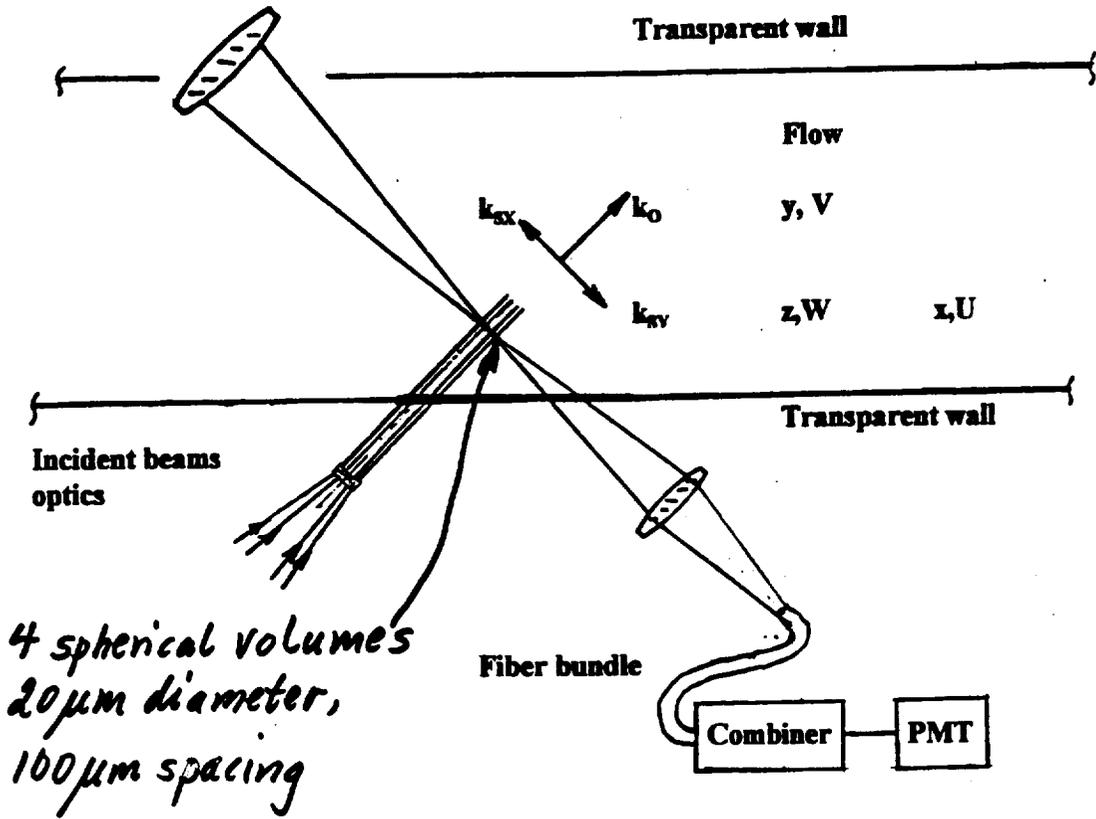


W/u_t mean velocity profiles in tunnel coordinates.

stations 1-4 $\partial P/\partial z > 0$

stations 5-9 $\partial P/\partial z < 0$

Receiving optics for $\Delta U/\Delta x$, $\Delta U/\Delta y$, $\Delta U/\Delta z$



Receiving optics for $\Delta V/\Delta x$, $\Delta V/\Delta y$, $\Delta V/\Delta z$

Figure 1. Schematic of ΔU and ΔV incident and receiving optics for ROSVOR LDV. ΔW incident and receiving optics same as arrangement for ΔU , but lying in the YZ plane.

ROSVOR - Rate of Strain/Vorticity

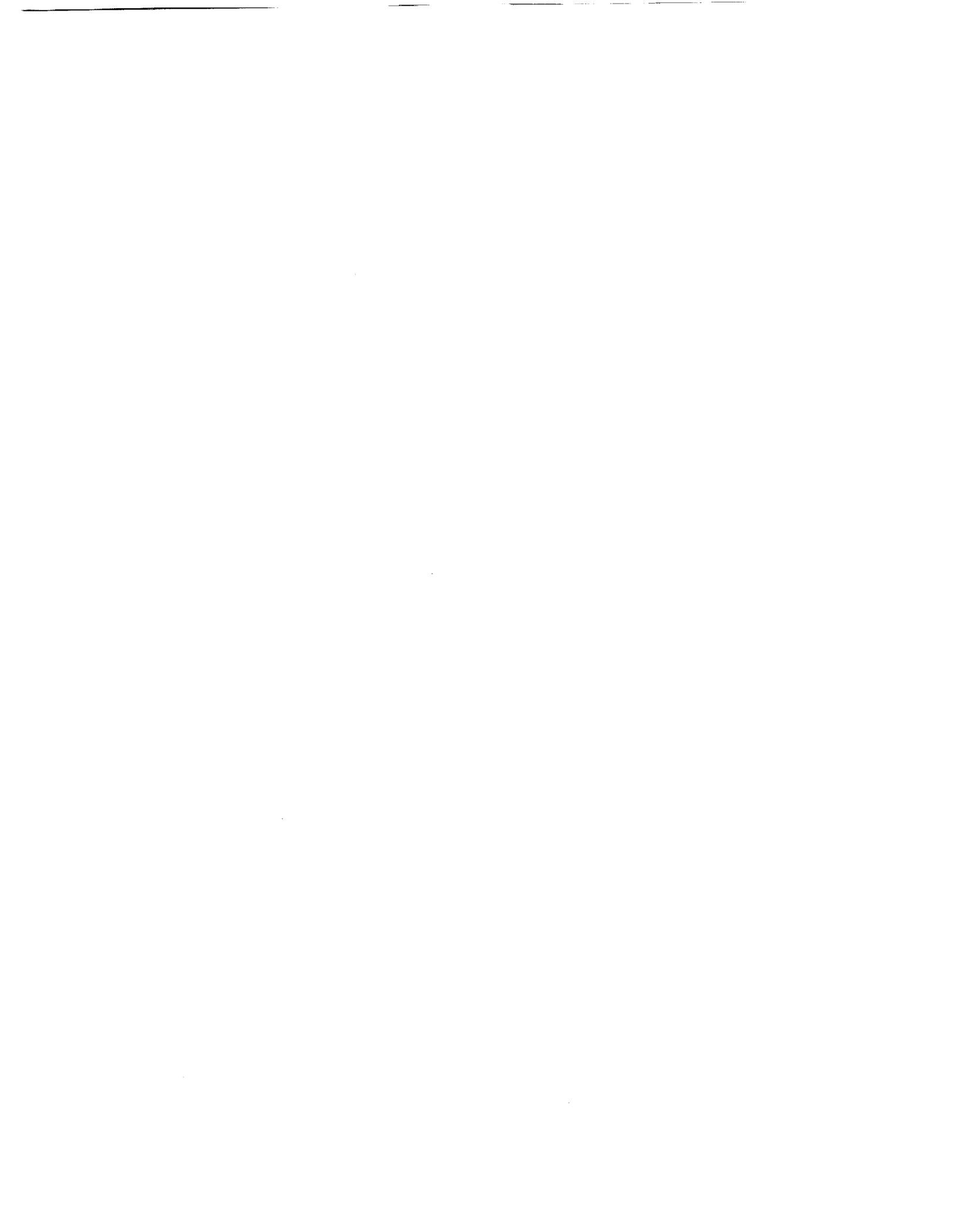
PARTICLE IMAGE VELOCIMETRY

Advantages:

- Global measurements
- Faster data acquisition time for one plane

Disadvantages:

- Flow seeding required
- Setup and data processing time
- Only planar data with lower uncertainties
(out of plane data with much higher uncertainties)
- Higher uncertainties for u' , v' than hot-wire and LDV;
much higher triple product uncertainties
- Multiple fields of view required to resolve various scales



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13. ABSTRACT (Maximum 200 words) Advances in turbulence modeling are needed in order to calculate high Reynolds number flows near the onset of separation and beyond. To this end, the participants in this workshop made the following recommendations. (1) A national/international database and standards for turbulence modeling assessment should be established. Existing experimental data sets should be reviewed and categorized. Advantage should be taken of other efforts already underway, such as that of the European Research Community on Flow, Turbulence, and Combustion (ERCOTAC) consortium. Carefully selected "unit" experiments will be needed, as well as advances in instrumentation, to fill the gaps in existing datasets. A high priority should be given to document existing turbulence model capabilities in a standard form, including numerical implementation issues such as grid quality and resolution. (2) NASA should support long-term research on Algebraic Stress Models and Reynolds Stress Models. The emphasis should be placed on improving the length-scale equation, since it is the least understood and is a key component of two-equation and higher models. Second priority should be given to the development of improved near-wall models. Direct Numerical Simulations (DNS) and Large Eddy Simulations (LES) would provide valuable guidance in developing and validating new Reynolds-averaged Navier-Stokes (RANS) models. Although not the focus of this workshop, DNS, LES, and hybrid methods currently represent viable approaches for analysis on a limited basis. Therefore, although computer limitations require the use of RANS methods for realistic configurations at high Reynolds number in the foreseeable future, a balanced effort in turbulence modeling development, validation, and implementation should include these approaches as well.				
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