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SECOND-ORDER CLOSURES FOR COMPRESSIBLE TURBULENCE

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OUTLINE

- I. Project Description
- II. Turbulence Modeling
- III. Computational Engine / Results

FUTURE WORK

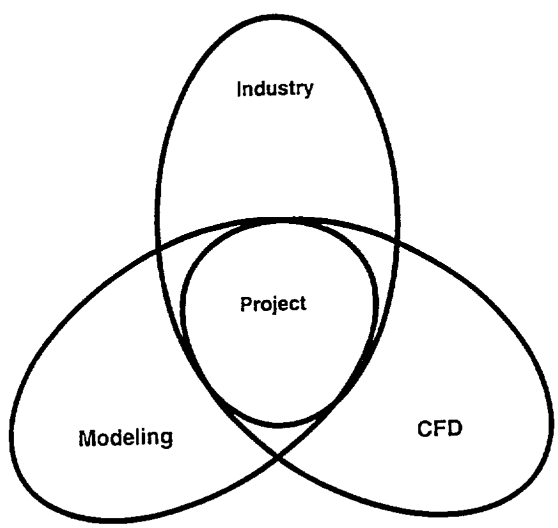
I. PROJECT DESCRIPTION

1. Flows of Interest
2. Motivation
3. Method

Schlieren photograph of a shock-wave turbulent boundary-layer interaction

M=0.90 Re=1,750,000 [Liepmann]

I.2.MOTIVATION



- Physics
  - Boundary Layer Separation & Wall Heat Transfer
  - Spreading rate

- Modeling
  Account for Compressibility Effects
  on Turbulence

- Numerics
  Compare 1-point Closures on Identical Solver

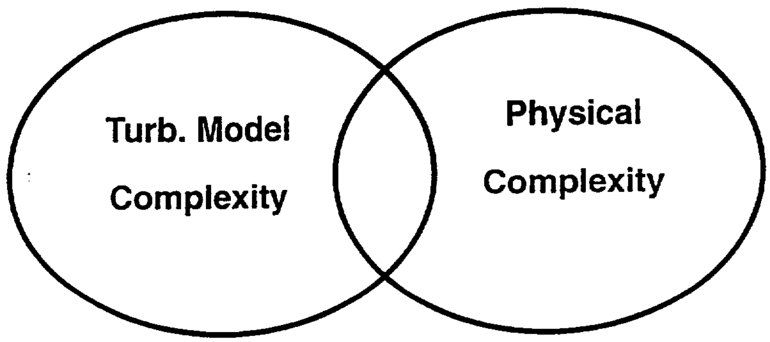
I.3. METHOD

- 1-Point Closures: from EVM to Second-Order Closures

- Dynamical Compressibility Effects

- 3D / Finite Volume Approach

II. TURBULENCE MODELING



1. <u>Closure Levels</u>

2. <u>Compressibility Effects</u>

3. <u>Shock Wave Interactions</u>

II.1. Closure Levels

1. EVM Mixing-Length
   (Baldwin-Lomax)

2. EVM Multi-Equation
   (k-ε-S)

3. Second-Order Closure
   (Shih and Lumley)

II.2. Compressibility Effects

1. New Physics & Averaging

2. Models

II.2.1. New Physics
(Turbulent Kinetic Energy Sink)

$$- < \tau_{ij} u_{i,j} > = \Pi_d - \varepsilon_d - \varepsilon_s$$

- $\varepsilon_d = (\mu_B + \frac{4}{3}\mu) < d^2 >$

- $\Pi d = < pd >$

II.2.3. Turbulence Modeling
(Zeman, Sarkar et al., Yoshizawa)

- <u>dilatation dissipation:</u>

$$\varepsilon_d = (\mu_B + \frac{4}{3}\mu) < d^2 >$$

  - Sarkar et al. (asymptotic analysis)

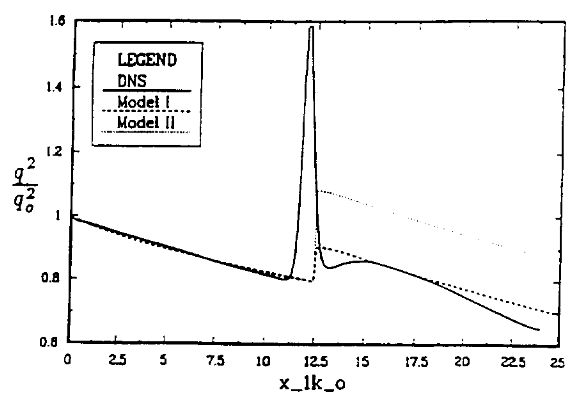
  - Zeman
    (Shocklet model)

- pressure-dilatation correlation:

$$\Pi_d = \langle pd \rangle$$

  – Zeman (acoustic model):

  – Sarkar et al.
    (DNS & asymptotic analysis)



Response of turbulence kinetic energy to the passage through shock

II.3. Shock Wave Interactions

1. Experimental Observations

2. Physics

3. Modeling

II.3.1. Experimental Results

- Oscillation increases with Shock Strength (Dolling)

- Oscillation increases with Separation Region

- Normal Stresses Preferentially Amplified (Délery et al.)

II.3.2. Physics

Oscillation Caused by (?):

- "Breathing" of Separation Region

- Vortex Bursting
  in Incoming Boundary Layer
  (Dolling)

II.3.3. Shock Oscillation Modeling

- Parametrized Source Terms
  in Normal RS Evolution Equation
  (gradient activated)

- Separation region Extend

III. COMPUTATIONAL ENGINE

1. Numerical Method

2. Turbulence Models

3. Validation Procedure / Results

III.1. Numerical Method

Initial Code: flo103 (A.Jameson L.Martinelli, Princeton)

1. **Geometry**
   C-mesh
   2D
2. **PDE Solver**
   spatial discretization: FV
   time integration: RK
3. **Convergence Acceleration:**
   variable time step
   residual smoothing
   artificial dissipation
   multigrid preconditioning
4. **I/O**
   PLOT3D format
5. **Turbulence Models**
   Baldwin-Lomax

Current Code: cyste (D.Caughey)

1. **Geometry**
   O- R-meshes
   (EAGLEView MSU)
2. **PDE Solver**
   variable number of PDE's
   consistent gradient comp.
3. **Convergence Acceleration**
   Enhanced multigrid sequencing
4. **I/O**
   Restart option
   Post-processing (DX,Tecplot,...)
   convergence histories
5. **Turbulence Models**
   k-epsilon (-S)
6. **Software Engineering**
   Dynamical mem. allocation (C)
   Vectorized data structure
   Unix Integration

Future

1. **Geometry**
   3D
2. **Turbulence Models**
   SOC

III.2. Turbulence Models:

Incompressible / Compressible: an additive approach

- Baldwin-Lomax

- k-Epsilon / k-Epsilon-S: B.C's

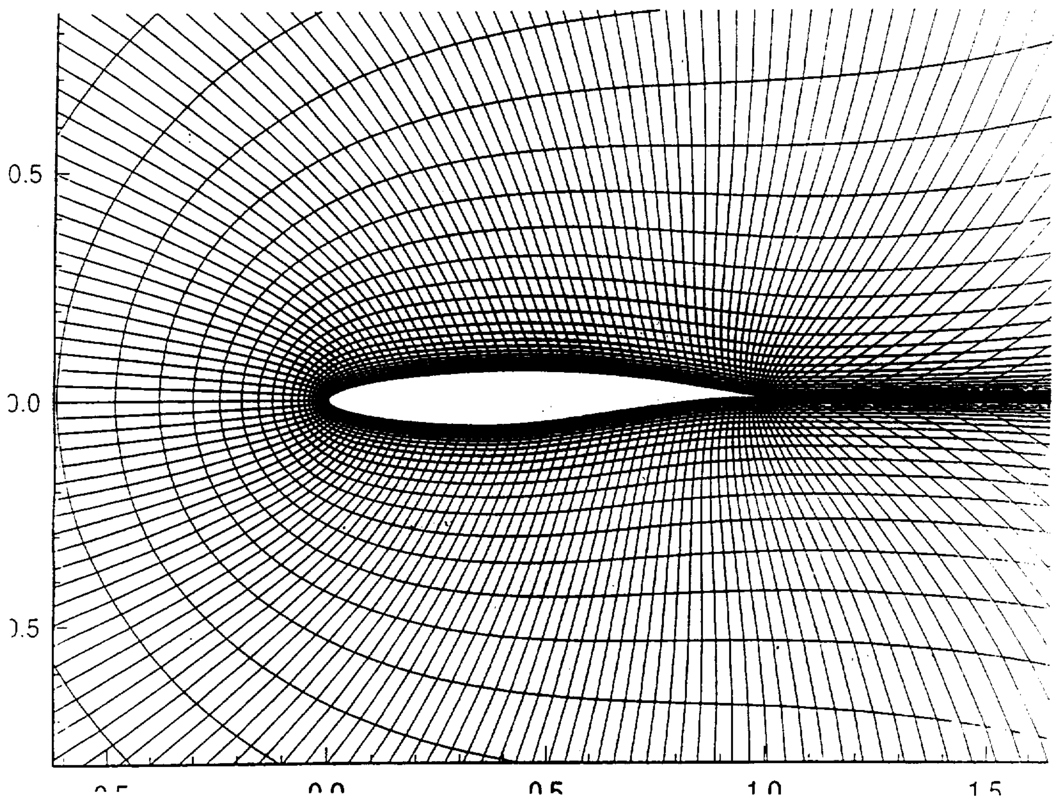
- Second-Order Closures

Boundary Conditions: Wall-Functions

III.3. Validation Procedure / Results

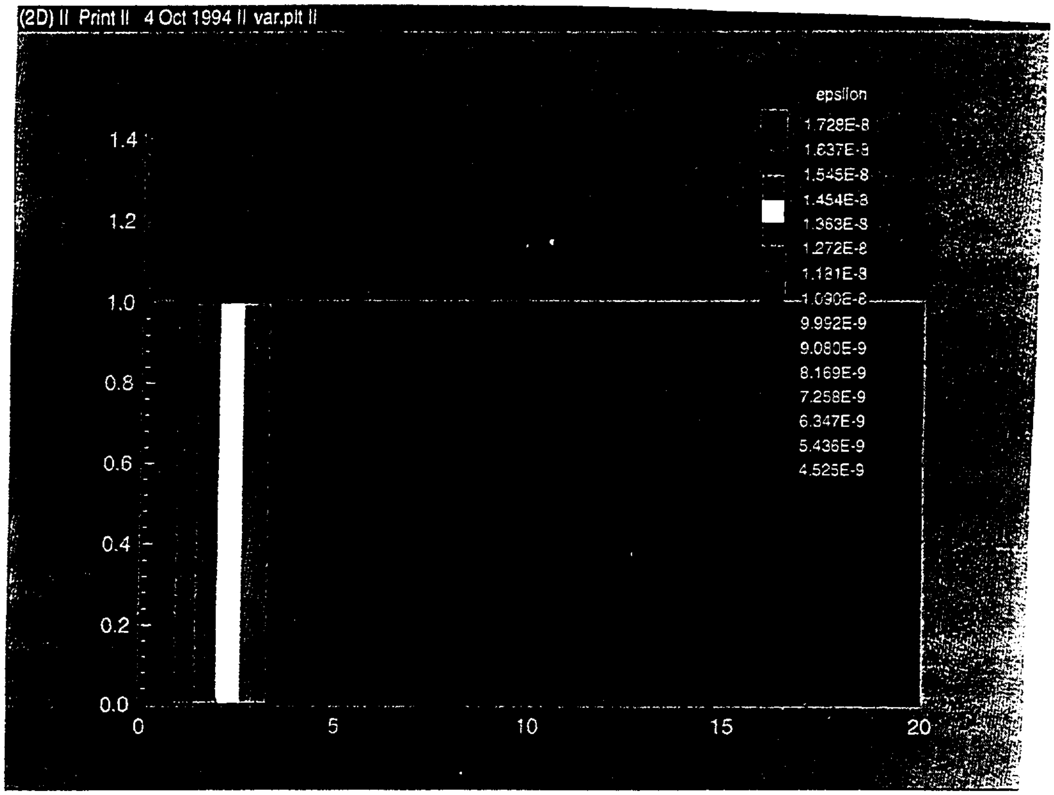
- Calibration against simple well-documented flows (flat plate, jet)

- Results and Comparison of models

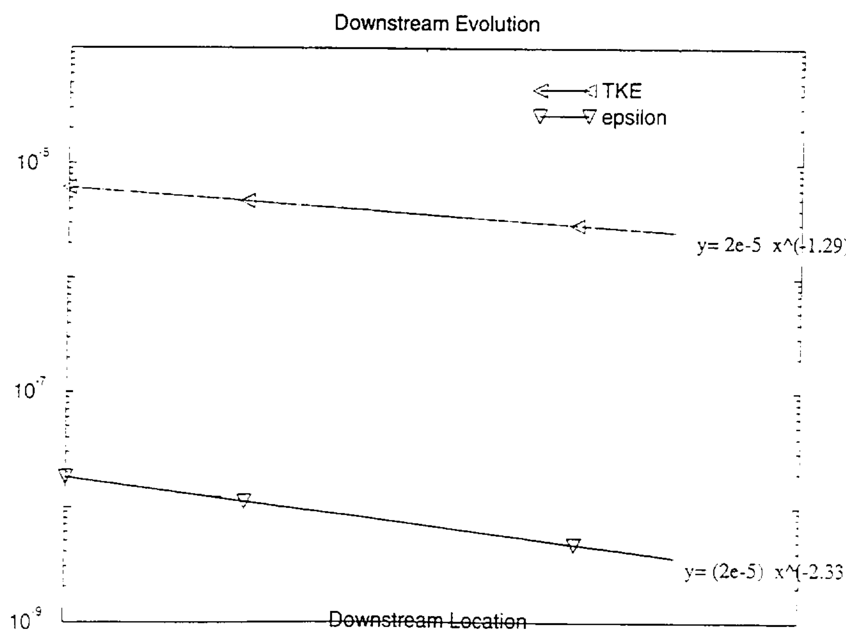


FUTURE WORK

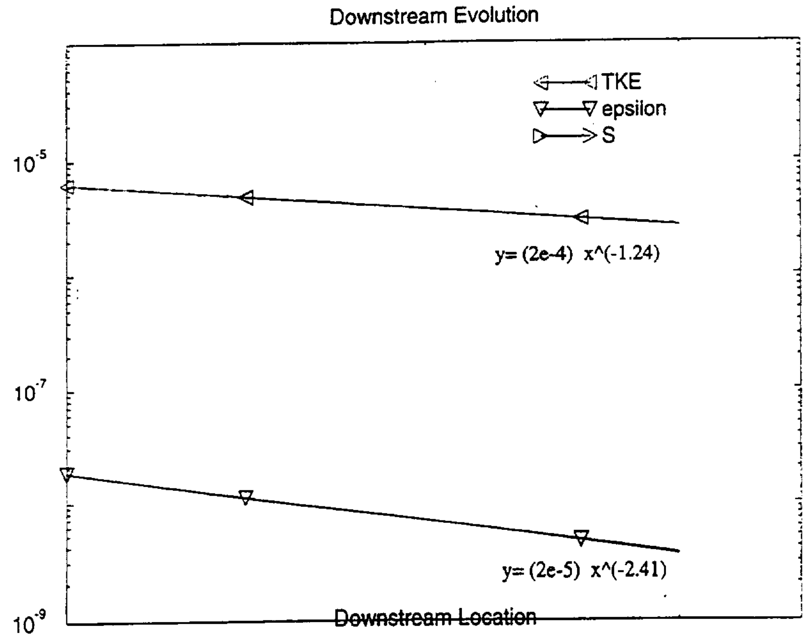
- Numerics
  - 2D ⇒ 3D
  - More Complex Wall Functions
  - Realizability Conditions (SOC)
- Modeling
  - Refinement of Existing Models (ε_d , $< pd >$)
  - Shock Oscillation Model



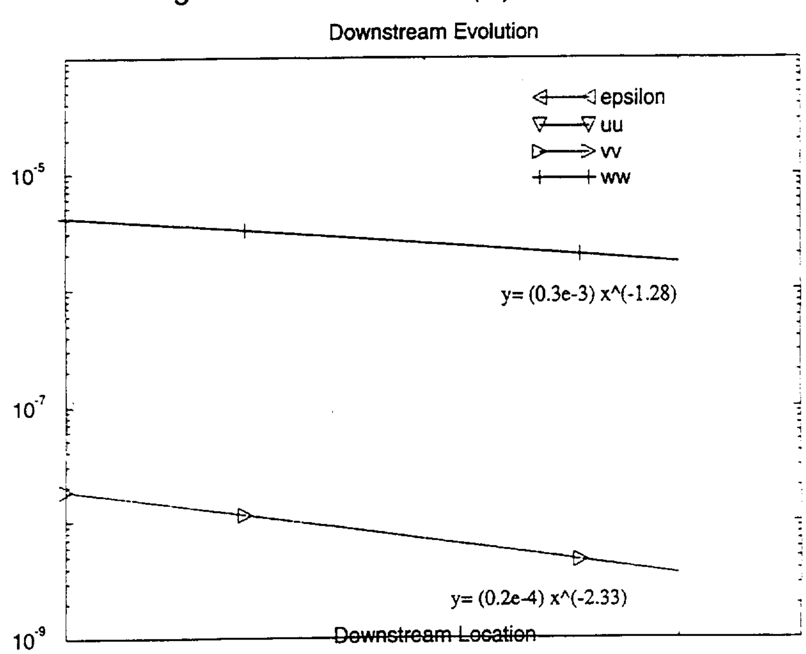
Homogeneous Turbulence (R) / k-eps / Mach=0.045 Re=24357



Homogeneous Turbulence (R) / k-eps-S / Mach=0.045 Re=24357



Homogeneous Turbulence (R) / RSC / Mach=0.5



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