TURBULENCE MODEL DEVELOPMENT AND APPLICATION AT LOCKHEED FORT WORTH COMPANY

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The CFD Environment at Lockheed Fort Worth Company

- Most codes developed or highly modified in house
- General grid generation and solvers for diverse applications
- Structured and unstructured solvers
- Computational efficiency important
  - Complex geometries, many gridpoints
  - Large arrays of flow conditions
Requirements for Turbulence Models

Turbulence Modeling Priorities for Industrial Application

- Validation
  - High accuracy for attached flows
  - Reasonable accuracy for all flows
  - High confidence level
- Computational efficiency
- Robust for complex geometries
- Transitional modeling capability

To obtain acceptable accuracy, propulsion flows demand more sophisticated turbulence models than do external aerodynamic flows.

The $k - kl$ and $k - l$ Two Equation Turbulence Models

Advantages of using $kl$ or $l$ instead of $\varepsilon$ or $\omega$

$k_l$ and $l$ equations are easier to resolve numerically than $\varepsilon$ equation

Dissipation Length Scale is an integral length scale

- Can derive equation for volume integral of two-point correlation function.
- Theoretical $\varepsilon$ equation is dominated by small scales

$k - kl$ and $k - l$ agree better with compressible boundary layer data than does $k - \varepsilon$

Disadvantage - current formulation requires calculation of distance to walls

$k - kl$ model
- Includes unique, consistent wall function
- Accurate for transonic flows

$k - l$ model
- Derived from $k - kl$ model - identical in high Re turbulence
- Near wall model simulates $k$ in viscous sublayer
The k – kl Model Wall Function

Wall layer model derived from and consistent with the k – kl model

- Assume convection in momentum, energy and turbulent kinetic energy equations to be negligible
- Boundary layer approximation

Match velocity, k and l at first grid point in Navier – Stokes solution

First grid point can be in viscous sublayer, buffer or logarithmic region

Boundary conditions on k and l simple for k – kl model

Advantages of wall functions

- Reduces number of necessary grid points
- Reduces number of iterations to converge steady state solution 60 – 90%

Wall Functions are Accurate for Separated Flow Applications

Axisymmetric Bump, Transonic Flow Experiment

Accurate predictions with and without wall functions

Experimental Data
- Fine Grid, \( y^+ = 1.5 \)
- Coarse Grid, \( y^+ = 40 \)

\( M = 0.925 \)

\( M = 0.875 \)

\( M = 0.80 \)

Velocity profiles with and without wall functions
The $k - I$ Model with Near Wall Model

$kI$ equation is transformed exactly to an $I$ equation

Advantages of $k - I$ formulation

- $I$ is linear near wall, $kI$ nonlinear and very small
- Near wall damping terms disappear
- Production term drops out with current choice of constants

$k - I$ model includes:

- Transitional flow modeling
- Compressibility corrections

Modeling of details of $k$ profile near wall important for hypersonic flows

- Magnitude of normal stress term comparable to static pressure
- Near wall density variations large

$I$ Equation Much Easier to Resolve than $\varepsilon$ Equation

$\varepsilon$ equation requires fine grid from wall to $y^+$ of 20 to resolve peak

- Exclusion of near wall viscous dissipation term aggravates problem
- Logarithmic region, $\varepsilon \propto 1/y$

$I$ equation is nearly linear near wall - much less sensitive to grid resolution
Resolution Study with $k-\varepsilon$ and $k-\omega$ Models

Sample Applications:

Mach 8 Shock Wave Turbulent Boundary Layer Interactions
F-16 Inlet Derivative, Isolated Duct Study
Multi-slot Ejector
F110 Nozzle Drag Reduction Study
k - I Model With Compressibility Correction gives Best Prediction
For Mach 8 Shock Boundary Layer Interaction

The k - I Model Predicts Turbulent Shock - Wave Boundary
Layer interaction Well
Mach 8, 10 Degree Wedge Generator
2D case, Separated Flow

Fine Grid Solution, 187x181
Coarse Grid, 97x111
Experimental Data
Afterbody/Nozzle Pressure Distributions Match Test Data

Mach 0.6

Upper Centerline

72 Degrees

Lower Centerline

Nozzle Surface Cp

At Near Leading Forward
Good Predictions of Multi-Slot Ejector Obtained with k-kl Model

NPR = 14

Mach Contours

k-kl Model Predicts Entrainment Effects Near Slots

Velocity vectors colored by Mach Number
Summary

Computationally efficient $k - 1$ and $k - kl$ models have been developed and implemented at Lockheed Fort Worth Company

Many years of experience applying two equation turbulence models to complex 3D flows for design and analysis