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Simulations of Boundary-Layer Transition

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For incompressible benchmark flows, we have demonstrated the capability of the parabolized stability equations (PSE) to simulate the transition process in excellent agreement with microscopic experiments and direct Navier-Stokes simulations at modest computational cost. Encouraged by these results, we have developed the PSE methodology[1] for three-dimensional boundary-layers in general curvilinear coordinates for the range from low to hypersonic speeds, and for both linear and nonlinear problems. For given initial and boundary conditions, the approach permits simulations from receptivity through linear and secondary instabilities into the late stages of transition where significant changes in skin friction and heat transfer coefficients occur.

We have performed transition simulations for a variety of two- and three-dimensional similarity solutions and for realistic flows over swept wings at subsonic and supersonic speeds, the pressure and suction side of turbine blades at low and medium turbulence levels, and over a blunt cone at Mach number $Ma = 8$. We present selected results for different transition mechanisms with emphasis on the late stage of transition and the evolution of wall-shear stress and heat transfer.

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Outline

Parabolized Stability Equations

- → PSE Development
- Stability Studies
- ? → Receptivity, Forced Problems
- Transition Mechanisms
- → Engineering Applications
  - Swept Wings
  - →Gas Turbine Blades
  - High-Speed Flows
- Conclusions, Open Issues

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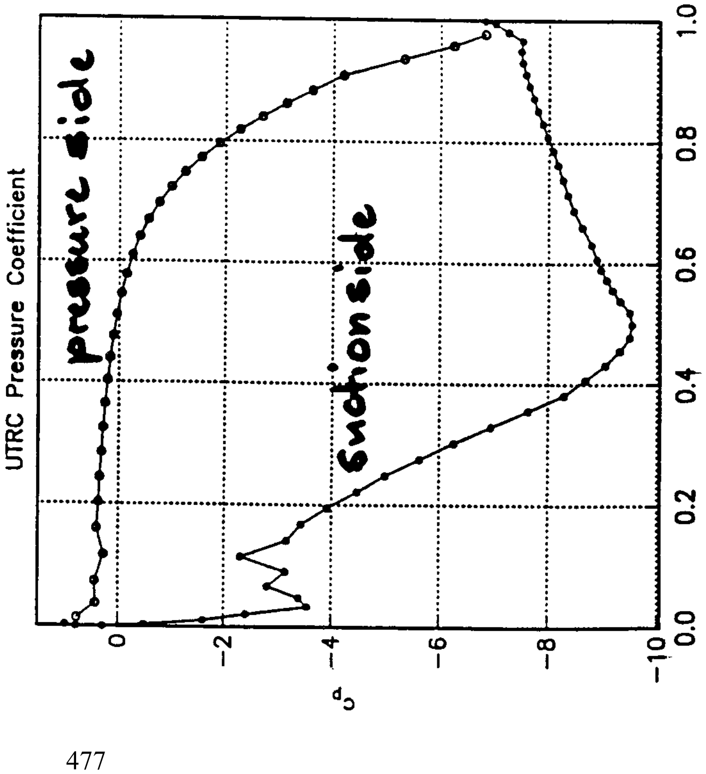
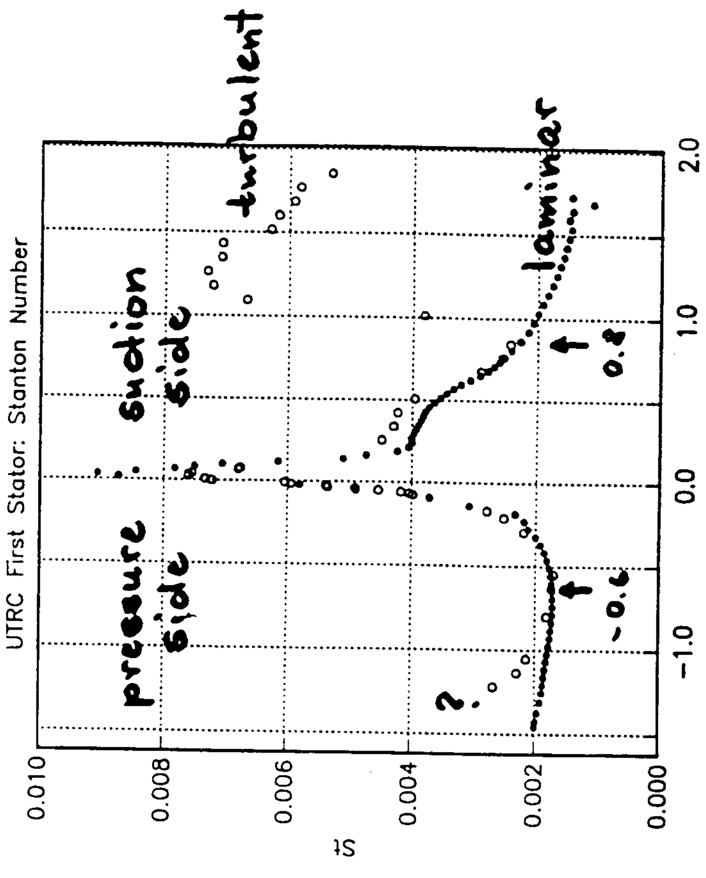
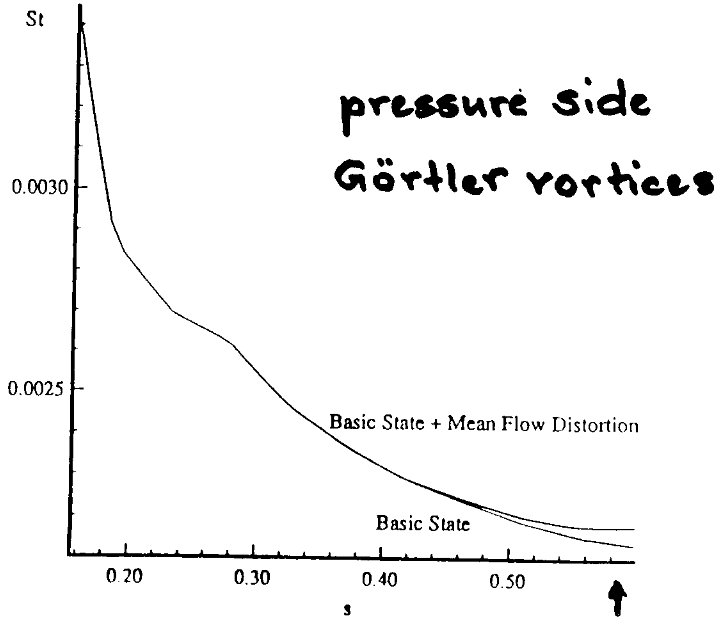
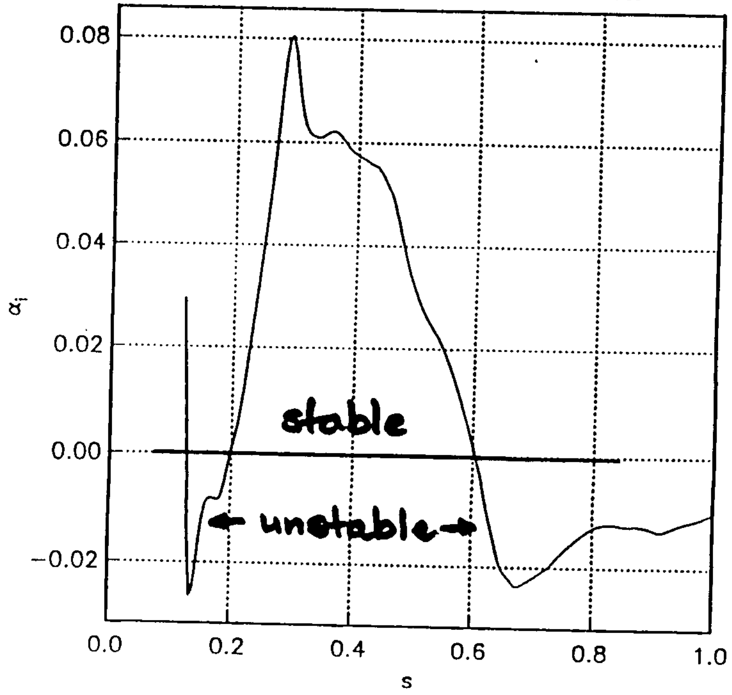

UTRC Pressure Coefficient
c_p
0
-2
-4
-6
-8
-10
0.0
0.2
0.4
0.6
0.8
1.0
x
pressure side
suction side


UTRC First Stator: Stanton Number
St
0.010
0.008
0.006
0.004
0.002
0.000
-1.0
0.0
1.0
2.0
s
pressure side
suction side
turbulent
laminar
?
-0.6
0.8

Stanton Number as a Function of Position
UTRC First Stator, Lower Surface; $Re_{\delta^*} = 413.7436$, $\beta = 1.0$



UTRC Upper Surface: TS Growth Rate

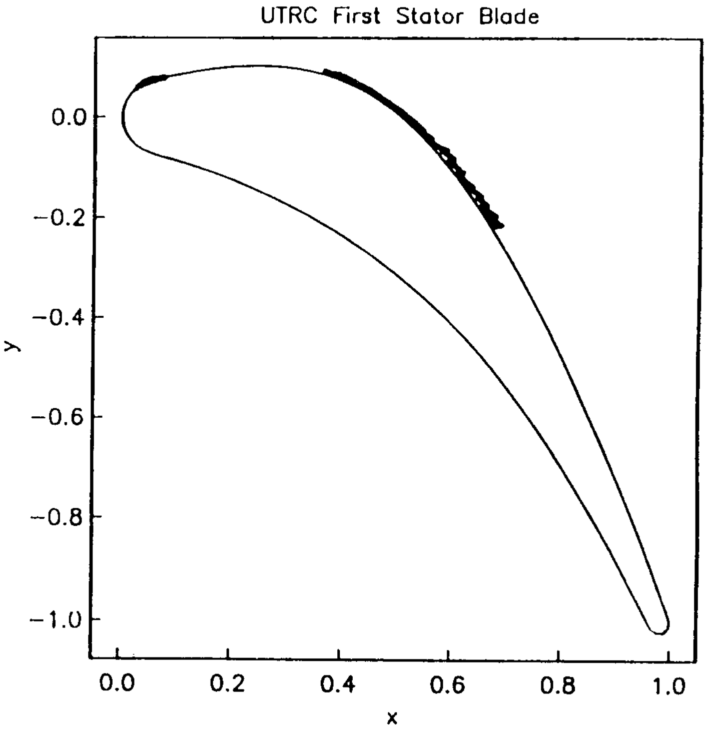


UTRC Turbine Experiments
First Stator Blade

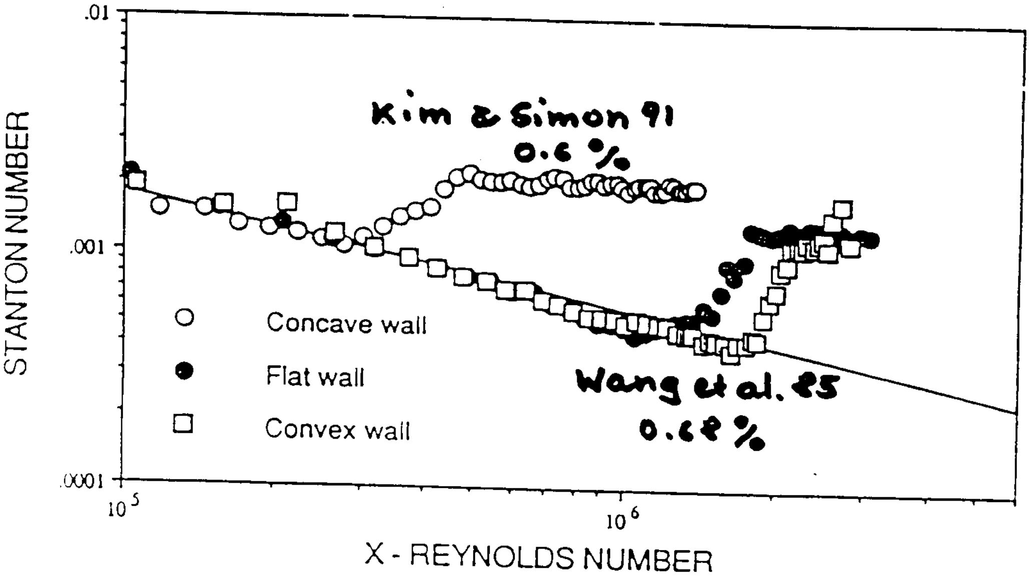
Dring, et al, 1986, 1987

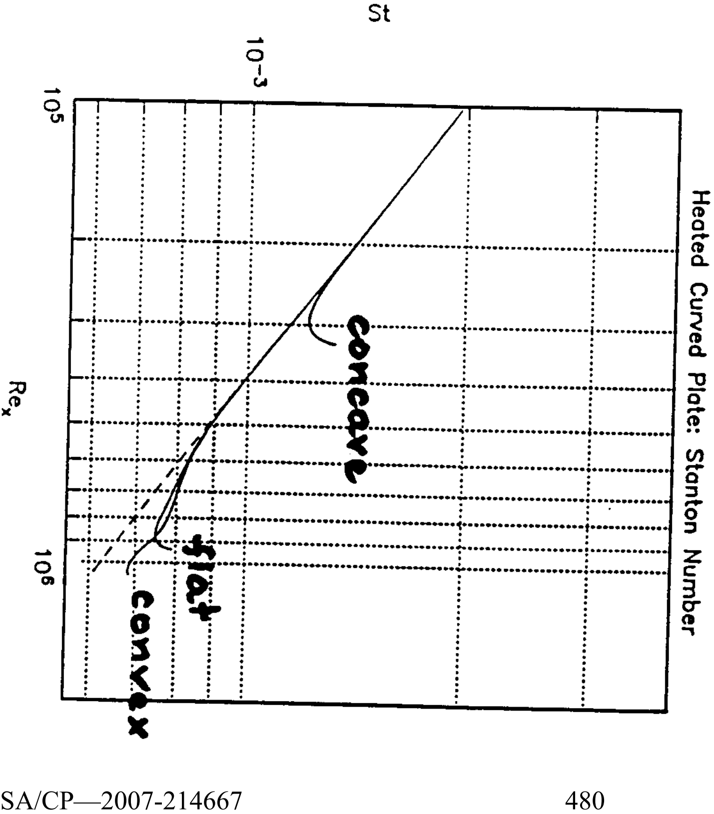
- Test run R53PD1 inlet conditions
  - 22.8 m/s
  - 15° C
  - 1 atm
- Uniform heat flux: 1.5775 kW/m^3
- Turbulence levels at inlet to first stator
  - 0.5% (grid out)
  - 9.8% (grid in)

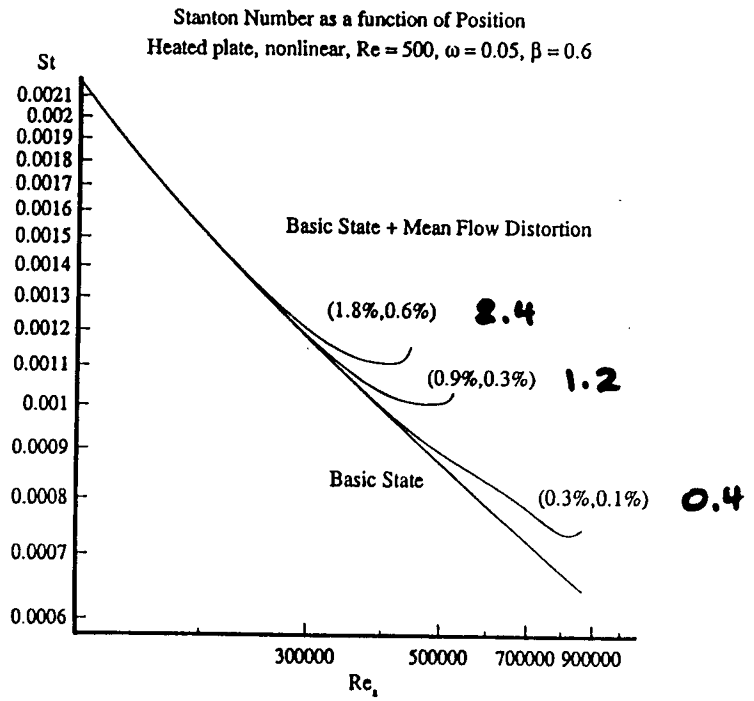
HEAT TRANSFER
ON GAS TURBINE BLADES
Dring et al. 1986



EFFECT OF STREAMWISE CURVATURE ON BYPASS TRANSITION







Experiments on Heated Curved Plates

Wang, Simon & Buddhavarapu 1985

- → flat plate, $R=\infty$, $U_\infty=35\,m/s$, $Tu=0.68\%$
- flat plate, $R=\infty$, $U_\infty=15\,m/s$, $Tu=2\%$
- → convex plate, $R=1.8\,m$, $\underline{0.9\,m}$, $U_\infty=34\,m/s$, $Tu=0.68\%$
- convex plate, $R=1.8\,m$, $0.9\,m$, $U_\infty=15\,m/s$, $Tu=2\%$

Kim & Simon 1991

- flat plate, $R=\infty$, $U_\infty=28\,m/s$, $Tu=0.32\%$, (no heat)
- flat plate, $R=\infty$, $U_\infty=17\,m/s$, $Tu=1.5\%$
- → concave plate, $R=0.97\,m$, $U_\infty=17\,m/s$, $Tu=0.6\%$

Experiments on Heated Flat Plates

Sohn & Reshotko 1991

- $U_\infty = 30.48\, m/s$
- Unheated starting length 35 *mm*
- Constant heat flux 0.42 KW/m^2
- Turbulence levels

  0.4% grid 0
  0.8% grid 0.5
  1.1% grid 1
  2.4% grid 2
  5.0% grid 3 (no transition point)
  6.0% grid 4 (no transition point)

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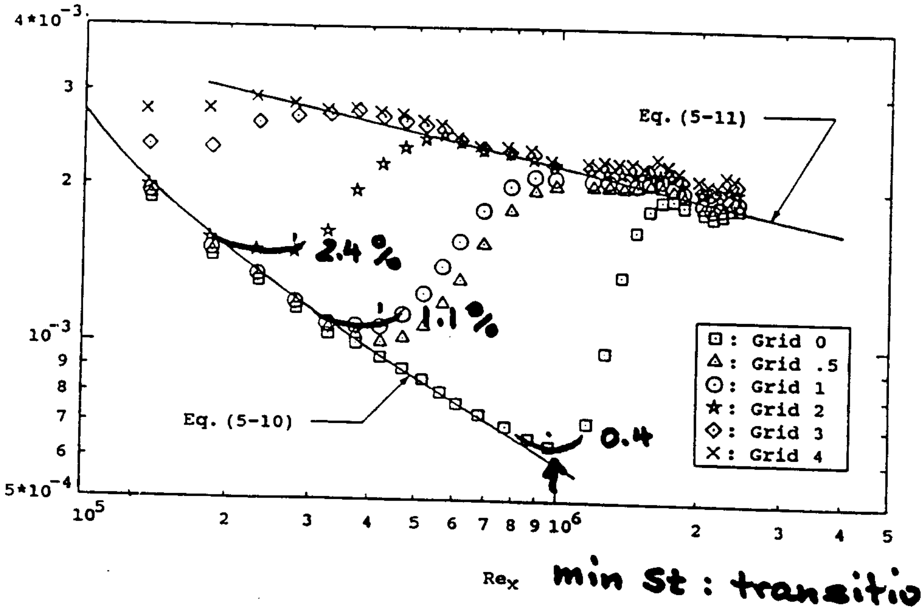
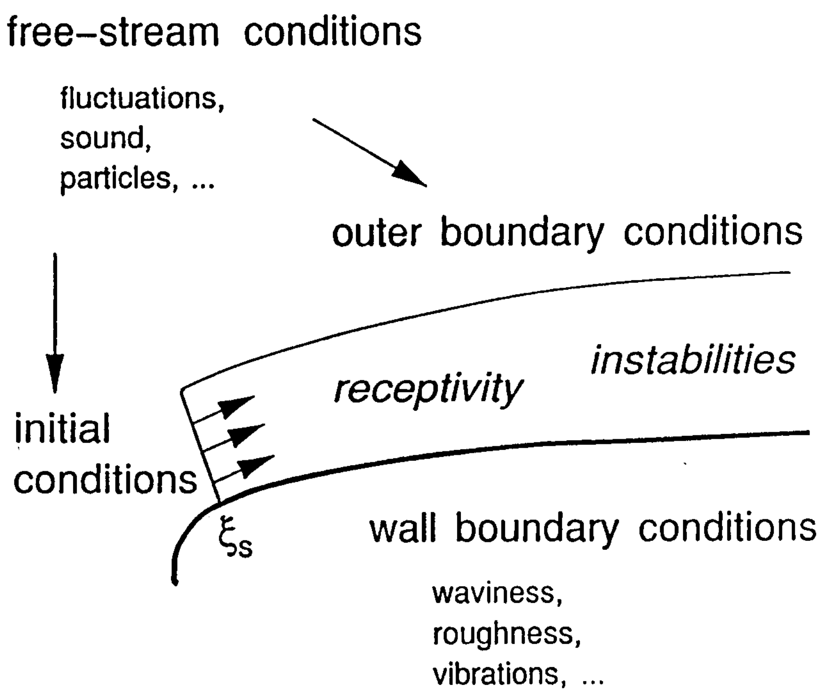
Heated Flat Plate
Sohn & Reshotko 91



min St : transition location nonlinear!

Input Model



free–stream conditions

fluctuations,
sound,
particles, ...

outer boundary conditions

receptivity

instabilities

initial
conditions

ξ_s

wall boundary conditions

waviness,
roughness,
vibrations, ...

Need:
time scale, spanwise length scale,
amplitudes

Model Environment

2D flow, wind tunnel, $Tu \geq 0.4\%$

- Initial conditions:
  receptivity
- Boundary conditions:
  area-distributed receptivity
- Spanwise scale:
  longitudinal vortex
  $\lambda_z \approx 2\delta$ (Kendall)
- Time scale:
  single frequency TS wave
  linear stability analysis
- Amplitudes:
  one "intelligent" guess
  linear receptivity

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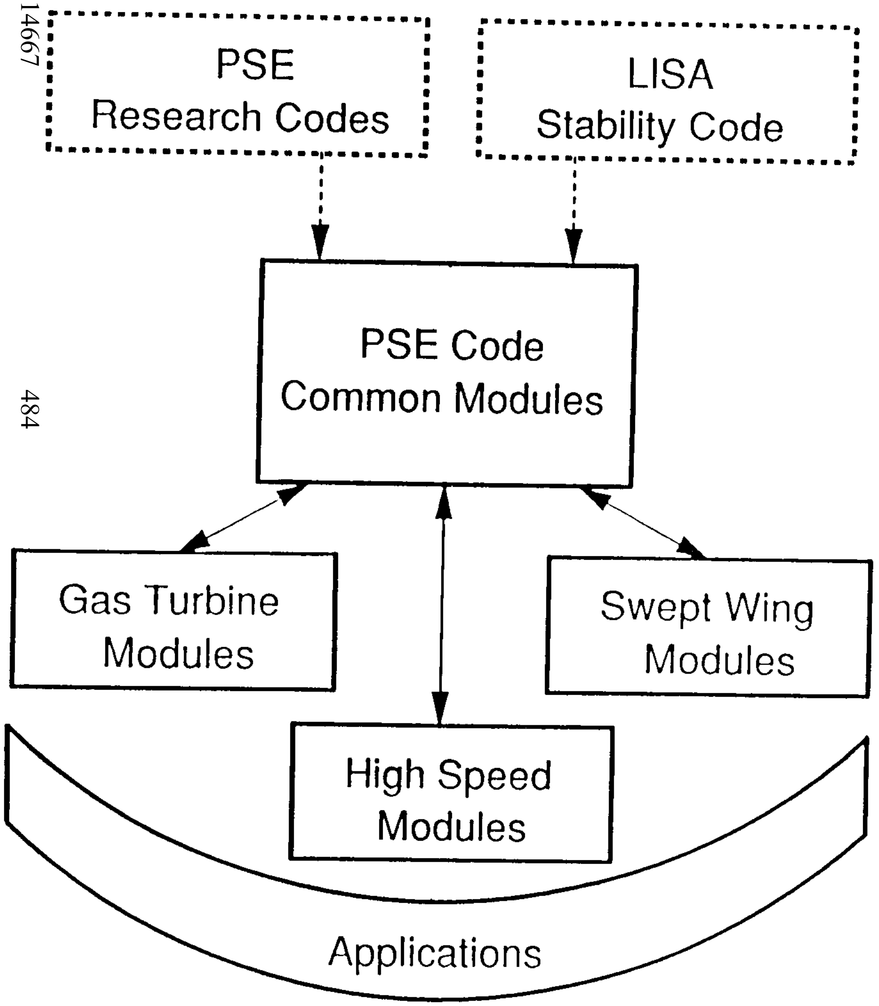
Code Development



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Support Codes

- Inviscid compressible flow in cascades:
  PCPANEL by E.R. McFarland (NASA Lewis)
  -- ported to Unix workstations
- Boundary-layer calculations:
  WING by Kaups & Cebeci,
  (undocumented version from NASA Langley)
  -- improvements/extensions implemented
- Local stability analysis:
  LISA by Th. Herbert,
  -- integrated with PSE code
- Codes for similarity solutions etc.

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Engineering Method

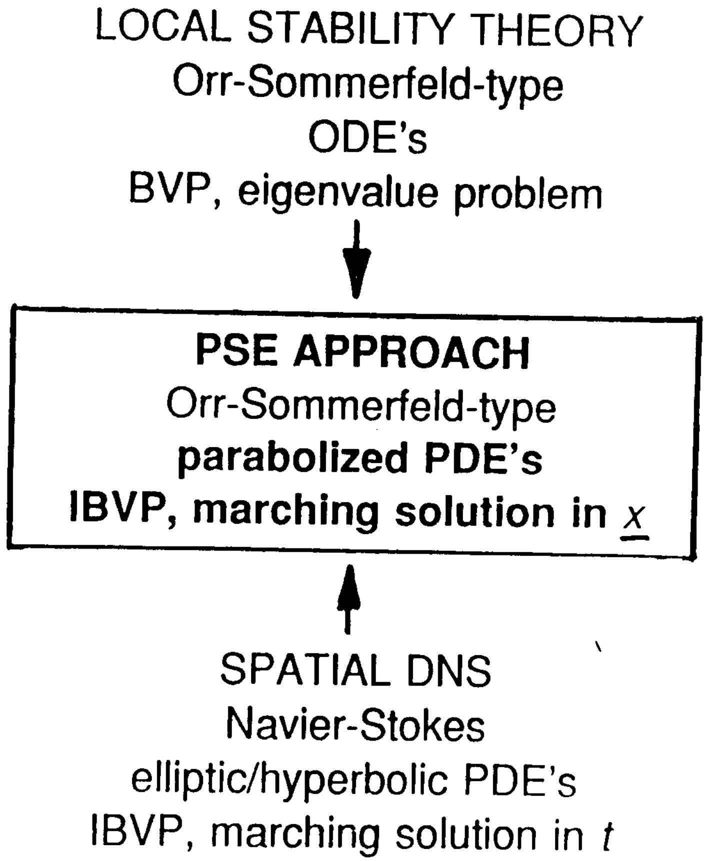
- PSE Extension to
  compressible, hypersonic,
  3D boundary layers in
  general curvilinear coordinates

+ Modular Code Design
+ Numerical Methods
+ Basic Flow Interfaces, Interpolation
+ Support Codes
+ Real-Life Data, Smoothing
+ Efficiency, Robustness
+ Ease of Use

Major Problems

- Compressible Nonlinear Terms
- Numerical Integration
- ◉ Basic Flow Accuracy
- Basic Flow Interpolation
- ◉ Absence of Test Data
- ◉ Lack of Physical Understanding

Parabolized Stability Equations (PSE)



LOCAL STABILITY THEORY
Orr-Sommerfeld-type
ODE's
BVP, eigenvalue problem

PSE APPROACH
Orr-Sommerfeld-type
parabolized PDE's
IBVP, marching solution in $\underline{x}$

SPATIAL DNS
Navier-Stokes
elliptic/hyperbolic PDE's
IBVP, marching solution in t

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Validation of Concepts

(Blasius flow, Falkner-Skan flow)

Single Modes
- nonparallel linear stability
- direct calculation of N factors
- nonlinear evolution

Multiple Modes
- linear secondary instability
- mode interactions
- transition simulations
- studies at low frequencies

Conclusion: PSE
- are accurate and efficient, <30 min ~~Cray~~
- should replace existing e^N codes

◉ provide the potential for "transition prediction" in engineering practice

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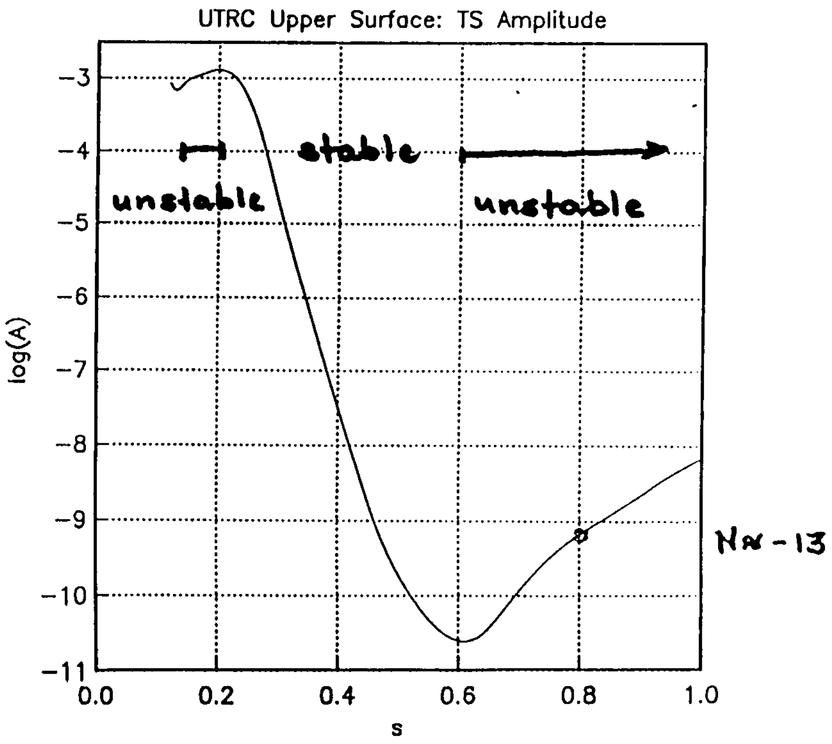

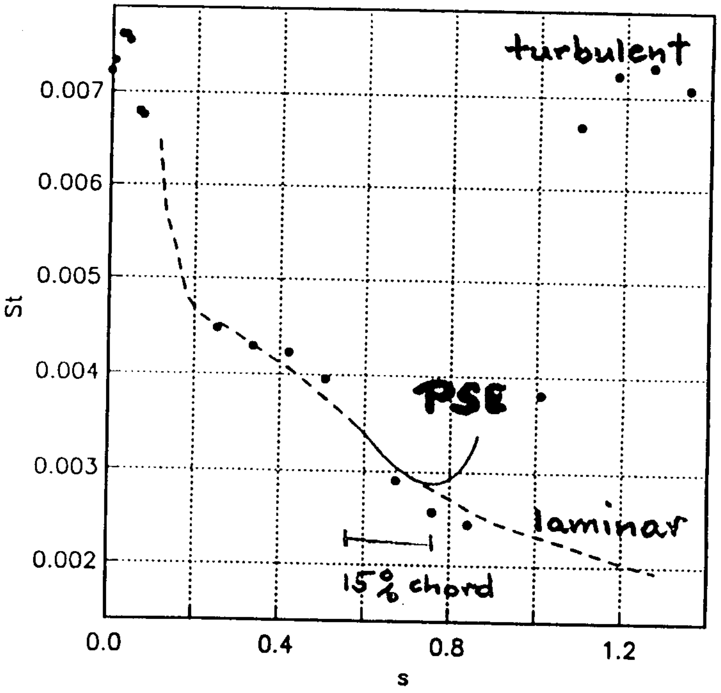

: also Rai & Moin AIAA 91-1607

Random noise 7.6% upstream →