SIMULATION OF MULTISTAGE TURBINE FLOWS

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A flow model has been developed for analyzing multistage turbomachinery flows. This model, referred to as the "average passage" flow model, describes the time-averaged flow field with a typical passage of a blade row embedded within a multistage configuration. The presentation summarizing the work done to date, based on this flow model, will be in two parts. The first part of the talk will address formulation, computer resource requirement, and supporting empirical modeling, and the second part will address code development with an emphasis on multitasking and storage. The presentation will conclude with illustrations from simulations of the space shuttle main engine (SSME) fuel turbine performed to date.
**PREMISE**

- High speed multi-stage turbomachinery flows have too many length and time scales to be amenable to direct numerical simulation even on today's most advanced computers.

- Most models currently used to analyze multi-stage flows are based on an axisymmetric representation of the flow within these machines.

**QUESTION**

Given today's computer resources and high response instrumentation, is it time to develop models which provide a higher degree of resolution of multi-stage flows than today's axisymmetric models?

**OBSERVATION**

- Proposed model must be compatible with the available computer resources and instrumentation limits.

- Proposed model must have a rational basis.

**CONSTRANT**

*Figure 2.*

*Figure 3.*

*Figure 4.*

*Figure 5.*
TURBOMACHINERY MODELING EQUATIONS

- NAVIER STOKES (REYNOLDS AVERAGED EQNS.)
- ENSEMBLE AVERAGED EQNS.

- DETERMINISTIC FLOW FIELD
  - TIME AVERAGED EQNS.

- TIME AVERAGED FLOW FIELD
  - (TYPICAL BLADE PASSAGE FLOW FIELD)
  - AVERAGE-PASSAGE EQNS.

- BLADE-TO-BLADE PERIODIC FLOW FIELD
  - CIRCUMFERENTIAL AVERAGED EQNS.

- AXISYMMETRIC FLOW FIELD
  - QUASI 1-D EQNS.

Figure 6.

THREE-DIMENSIONAL CELL-CENTERED FINITE VOLUME FLOW SOLVER

ADAMCZYK'S AVERAGE-PASSAGE EQUATION SYSTEM

\[
\frac{d\lambda u}{dt} + L(\lambda u) + \int \lambda_S dVol = \int \lambda K dVol
\]

\[
\lambda_T = (\rho, \rho v_r, \tau_{v_r}, \rho v_\phi, \rho v_z, \rho_e)
\]

\[
L(\lambda u) = \int_{AR} (\lambda F dA_r + \lambda C dA_\phi + \lambda H dA_z)
\]

\[
\int \lambda_S dVol = \text{body forces, energy sources, momentum and energy}
\]

\[
\text{temporal correlations associated with neighboring}
\]

\[
\text{blade row (closure term)}
\]

\[
\int \lambda K dVol = \text{source term due to cylindrical coordinate system}
\]

FOR ROTATING SYSTEMS

\[
\left(\frac{d\lambda u}{dt}\right)_{abs} = \left(\frac{d\lambda u}{dt}\right)_{rel} - \Omega \left(\frac{d\lambda u}{d\theta}\right)_{rel}
\]

\[
L(\lambda u) = \int_{AR} (\lambda F dA_r + \lambda (C - \tau_{v_r}) dA_\phi + \lambda H dA_z)
\]

Figure 7.
AVERAGE PASSAGE FLOW MODEL

AXIAL MOMENTUM EQU.

\[ \frac{\partial}{\partial t} \rho \mathbf{u} \cdot \mathbf{v} + \frac{\partial}{\partial x} \rho \mathbf{u} \cdot \mathbf{v} + \frac{\partial}{\partial z} \rho \mathbf{u} \cdot \mathbf{v} = \text{Viscous Terms} + \text{Body Force} + \text{Correlations} \]

**Body Force** = \( F_1 \) (Non-Axisymmetric Component of the Neighboring Average Passage Flow's) + \( F_2 \) (Non-Axisymmetric Component of the "Unsteady Deterministic" Flow Field) + \( F_3 \) (Non-Axisymmetric Component of the "Time Average" Flow Field) + \( F_4 \) (Time Unresolved Flow)

**Correlations** = \( R_1 \) (Non-Axisymmetric Component of the Neighboring Average Passage Flow's) + \( R_2 \) (Non-Axisymmetric Component of the "Unsteady Deterministic" Flow Field) + \( R_3 \) (Non-Axisymmetric Component of the "Time Average" Flow Field) + \( R_4 \) (Time Unresolved Flow)

**Figure 8.**

**Closure Strategy**

**Field Equation**

\[
\begin{align*}
(\partial u^{(1)}/ \partial t) \, dV + \mathbf{L}(u^{(1)}) + \int S^{(1)} \, dV &= 0 \\
(\partial u^{(2)}/ \partial t) \, dV + \mathbf{L}(u^{(2)}) + \int S^{(2)} \, dV &= 0
\end{align*}
\]

\( \text{Source Term} \)

**Figure 9.**

**Blade Row (1)**

\[ \mathbf{L}(u^{(1)}) + \int S^{(1)} \, dV = 0 \]

**Blade Row (2)**

\[ \mathbf{L}(u^{(2)}) + \int S^{(2)} \, dV = 0 \]

**Where**

\( S^{(1)} - S^{(2)} \) (Body Force, Energy Source, Velocity Cor., Energy Cor.)

**Figure 10.**
ASSUME

\[ S^{(1)} = S^{(1)}(u^{(1)}_{n+1}) \]
\[ S^{(2)} = S^{(2)}(u^{(2)}_{n+1}) \]

LET \( A \to \) AXISYMMETRIC AVERAGING OPERATOR

THEN

\[ AL(u^{(1)}_{n}) + \int S^{(1)}(u^{(1)}_{n}) A \, dV = 0 \]
\[ AL(u^{(2)}_{n}) + \int S^{(2)}(u^{(2)}_{n}) A \, dV = 0 \]

**Figure 11.**

\[ A \cdot L^{(1)}(u^{(1)}_{n}) + L^{(2)}(A u^{(1)}_{n}) + \int S^{(1)}(u^{(1)}_{n}) A \, dV \]
\[ A \cdot L^{(2)}(u^{(2)}_{n}) + L^{(3)}(A u^{(2)}_{n}) + \int S^{(2)}(u^{(2)}_{n}) A \, dV \]

FINIAL RESULT

\[ L^{(1)}(A u^{(1)}_{n}) + \int S^{(1)}(u^{(1)}_{n}) A \, dV + \int S^{(1)}(u^{(1)}_{n}) A \, dV = 0 \]
\[ L^{(2)}(A u^{(2)}_{n}) + \int S^{(2)}(u^{(2)}_{n}) A \, dV + \int S^{(2)}(u^{(2)}_{n}) A \, dV = 0 \]

UPON CONVERGENCE

\[ A u^{(1)}_{n} = A u^{(1)}_{n+1} \]

**Figure 12.**

**MODULAR CODE CONSTRUCTION**

**Figure 13.**
AVERAGE-PASSAGE EQUATION SYSTEM

CONVERGENCE TEST: L2 NORM OF THE DIFFERENCE BETWEEN
THE AXIAL/RADIAL AVERAGE OF THE TIME-AVERAGED FLOW
VARIABLES ON EACH BLADE ROW LESS THAN SOME TOLERANCE

Figure 14.

MULTITASKING OF MULTISTAGE
3-D FLOW FIELD CALCULATION

Figure 15.
EVOLUTION OF THE TOTAL TEMPERATURE FIELD WITHIN THE S.S.M.E. FUEL TURBINE

1st VANE MID PASSAGE

2nd VANE MID PASSAGE

1st ROTOR MID PASSAGE

2nd ROTOR MID PASSAGE

SIMULATION PERFORMED ON LEWIS CRAY XMP 24

Figure 16.