SIMULATION OF MULTISTAGE TURBINE FLOWS

John J. Adamczyk
NASA Lewis Research Center
Cleveland, Ohio

and

Richard A. Mulac
Sverdrup Technology, Inc.
Middleburg Heights, Ohio

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**

0. 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.

0. Models of multi-stage flows which give an "averaged" description of the flow within turbomachinery provide useful information.

**Observation**

- 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?

**Constraint**

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

- Proposed model must have a rational basis.
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)
  • TIME AVERAGED 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

\[
\begin{align*}
\frac{d\lambda u}{dt} + L(\lambda u) + \int \lambda S dV = \int \lambda K dV \\
\lambda u^T = (\rho, \rho u, \rho v, \rho w, \rho e) \\
L(\lambda u) = \int_{\Delta R} (\lambda F dA_r + \lambda G dA_\phi + \lambda H dA_z) \\
\int \lambda S dV = \text{body forces, energy sources, momentum and energy} \\
\text{temporal correlations associated with neighboring} \\
\text{blade row (closure term)} \\
\int \lambda K dV = \text{source term due to cylindrical coordinate system}
\end{align*}
\]

FOR ROTATING SYSTEMS

\[
\begin{align*}
\frac{d\lambda u}{dt}\abs = \frac{d\lambda u}{dt}\rel - \Omega\frac{d\lambda u}{d\theta}\rel \\
L(\lambda u) = \int_{\Delta R} (\lambda F dA_r + \lambda (G - \tau \Omega u) dA_\phi + \lambda H dA_z)
\end{align*}
\]

Figure 7.

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Average Passage Flow Model

Axial Momentum Eqn.

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

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)

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

\[ \frac{\partial u^{(1)}}{\partial t} dV + \overline{L}(u^{(1)}) + \int S^{(1)} dV = 0 \]

\[ \frac{\partial u^{(2)}}{\partial t} dV + \overline{L}(u^{(2)}) + \int S^{(2)} dV = 0 \]

Source Term

Figure 9.

BLADE ROW (1)

\[ \overline{L}(u_n^{(1)}) + \int S^{(1)} dV = 0 \]

BLADE ROW (2)

\[ \overline{L}(u_n^{(2)}) + \int S^{(2)} dV = 0 \]

WHERE

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

Figure 10.
Assume

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

Let \( A \rightarrow \) axisymmetric averaging operator.

Then

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

Figure 11.

\[
\begin{align*}
AL(u^{(1)}_{n}) - L^{(1)}(A u^{(1)}_{n}) + \int S^{(1)}(u^{(1)}_{n}) A \, dV &= 0 \\
AL(u^{(2)}_{n}) - L^{(2)}(A u^{(1)}_{n}) + \int S^{(2)}(u^{(1)}_{n}) A \, dV &= 0
\end{align*}
\]

Final result

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

Upon convergence

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

Figure 12.

**MODULAR CODE CONSTRUCTION**

**INPUT**  

**MAIN**  

**ACCELERATOR**

**GEOMETRY**  

**FIELD EQUATIONS**

**POST PROCESSOR**  

**BOUNDARY CONDITIONS**

Figure 13.
AVERAGE-PASSAGE EQUATION SYSTEM

- CLOSURE EQUATIONS
- CONTINUITY
- AXIAL / RADIAL MOMENTA
- ANGULAR MOMENTUM
- ENERGY

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

OUTPUT

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.