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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.

SSME POWERHEAD COMPONENT ARRANGEMENT

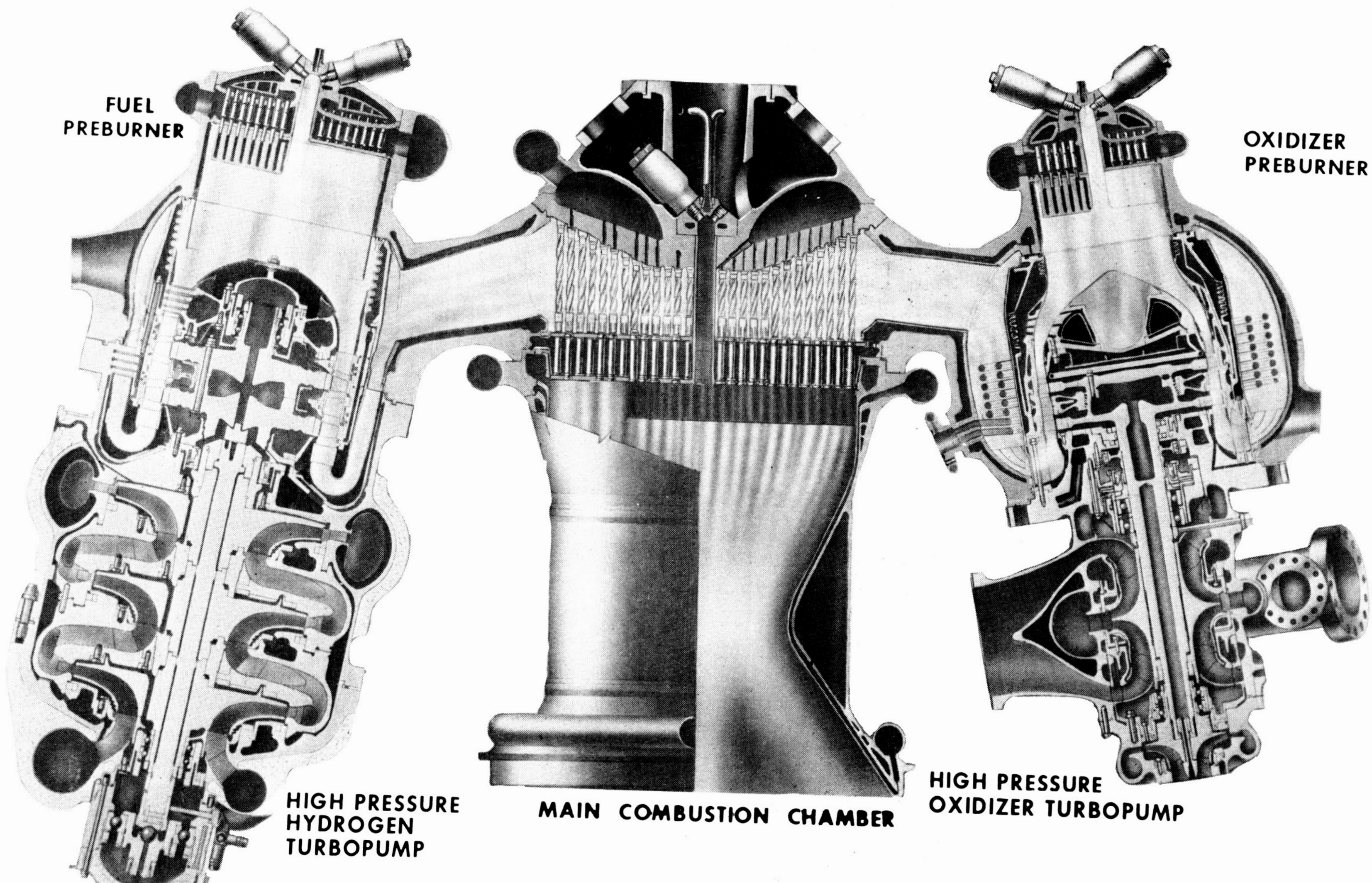


Figure 1.

PREMISE

- o 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
- o MODELS OF MULTI - STAGE FLOWS WHICH GIVE AN "AVERAGED" DESCRIPTION OF THE FLOW WITHIN TURBOMACHINERY PROVIDE USEFUL INFORMATION

Figure 2.

OBSERVATION

MOST MODELS CURRENTLY USED TO ANALYZE MULTI - STAGE FLOWS ARE BASED ON AN AXI-SYMMETRIC REPRESENTATION OF THE FLOW WITHIN THESE MACHINES

Figure 3.

QUESTION

GIVEN TODAY'S COMPUTER RESOURCES AND HIGH RESPONSE INSTRUMENTATION, IS IT TIME TO DEVELOPE MODELS WHICH PROVIDE A HIGHER DEGREE OF RESOLUTION OF MULTI - STAGE FLOWS THAN TODAY'S AXISYMMETRIC MODELS?

Figure 4.

CONSTRAINT

- o PROPOSED MODEL MUST BE COMPATIBLE WITH THE AVAILABLE COMPUTER RESOURCES AND INSTRUMENTATION LIMITS
- o PROPOSED MODEL MUST HAVE A RATIONAL BASIS

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

$$(d\lambda \underline{u}/dt) + L(\lambda \underline{u}) + \int \lambda \underline{S}\, dVol = \int \lambda \underline{K}\, dVol$$

$$\underline{u}^T = (\rho\, ,\, \rho v_r\, ,\, r\rho v_\theta\, ,\, \rho v_z\, ,\, \rho e_0\,)$$

$$L(\lambda \underline{u}) = \int_{dA} (\lambda \underline{F} \cdot d\underline{A}_r + \lambda \underline{G} \cdot d\underline{A}_\theta + \lambda \underline{H} \cdot d\underline{A}_z)$$

$\int \lambda \underline{S}\, dVol$ = *body forces, energy sources, momentum and energy temporal correlations associated with neighboring blade row (closure term)*

$\int \lambda \underline{K}\, dVol$ = *source term due to cylindrical coordinate system*

FOR ROTATING SYSTEMS

$$(d\lambda \underline{u}/dt)|abs = (d\lambda \underline{u}/dt)|rel - \Omega (d\lambda \underline{u}/d\theta)|rel$$

$$L(\lambda \underline{u}) = \int_{dA} (\lambda \underline{F} \cdot d\underline{A}_r + \lambda(\underline{G} - r\Omega \underline{u}) \cdot d\underline{A}_\theta + \lambda \underline{H} \cdot d\underline{A}_z)$$

Figure 7.

AVERAGE PASSAGE FLOW MODEL
AXIAL MOMENTUM EQN.

$$\frac{\partial}{\partial r}\lambda r\rho u v + \frac{\partial}{\partial \theta}\lambda\rho u w + \frac{\partial}{\partial z} r\lambda(\rho u^2 + P) = \text{Viscous Terms} + \text{Body Force} + \text{Correlations}$$

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 AVERGE" 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

$$(\partial u^{(1)} / \partial t)\, dV + \vec{L}(u^{(1)}) + \int S^{(1)} dV = 0$$

$$(\partial u^{(2)} / \partial t)\, dV + \vec{L}(u^{(2)}) + \underbrace{\int S^{(2)} dV}_{\text{Source Term}} = 0$$

Figure 9.

CLOSURE STRATEGY

BLADE ROW (1)

$$\vec{L}(u_n^{(1)}) + \int S^{(1)} dV = 0$$

BLADE ROW (2)

$$\vec{L}(u_n^{(2)}) + \int S^{(2)} dV = 0$$

WHERE

$$S^{(1),(2)} = S^{(1),(2)}(\textit{Body Force, Energy Src, Velocity Cor., Energy Cor.})$$

Figure 10.

ASSUME

$$S^{(1)} = S^{(1)}(u_{n-1}^{(2)})$$

$$S^{(2)} = S^{(2)}(u_{n-1}^{(1)})$$

LET A ----> AXISYMMETRIC AVERAGING OPERATOR

THEN

$$A\,L(u_n^{(1)}) + \int S^{(1)}(u_{n-1}^{(2)})\,A\,dV = 0$$

$$A\,L(u_n^{(2)}) + \int S^{(2)}(u_{n-1}^{(1)})\,A\,dV = 0$$

Figure 11.

BUT

$$A\,L(u_n^{(1)}) = L^{(nx)}(A\,u_n^{(1)}) + \int S^{(2)}(u_n^{(1)})\,A\,dV$$

$$A\,L(u_n^{(2)}) = L^{(nx)}(A\,u_n^{(2)}) + \int S^{(1)}(u_n^{(2)})\,A\,dV$$

FINAL RESULT

$$L^{(nx)}(A\,u_n^{(1)}) + \int S^{(2)}(u_n^{(1)})\,A\,dV + \int S^{(1)}(u_{n-1}^{(2)})\,A\,dV = 0$$

$$L^{(nx)}(A\,u_n^{(2)}) + \int S^{(2)}(u_{n-1}^{(1)})\,A\,dV + \int S^{(1)}(u_n^{(2)})\,A\,dV = 0$$

UPON CONVERGENCE

$$A\,u_n^{(1)} = A\,u_n^{(2)}$$

Figure 12.

MODULAR CODE CONSTRUCTION

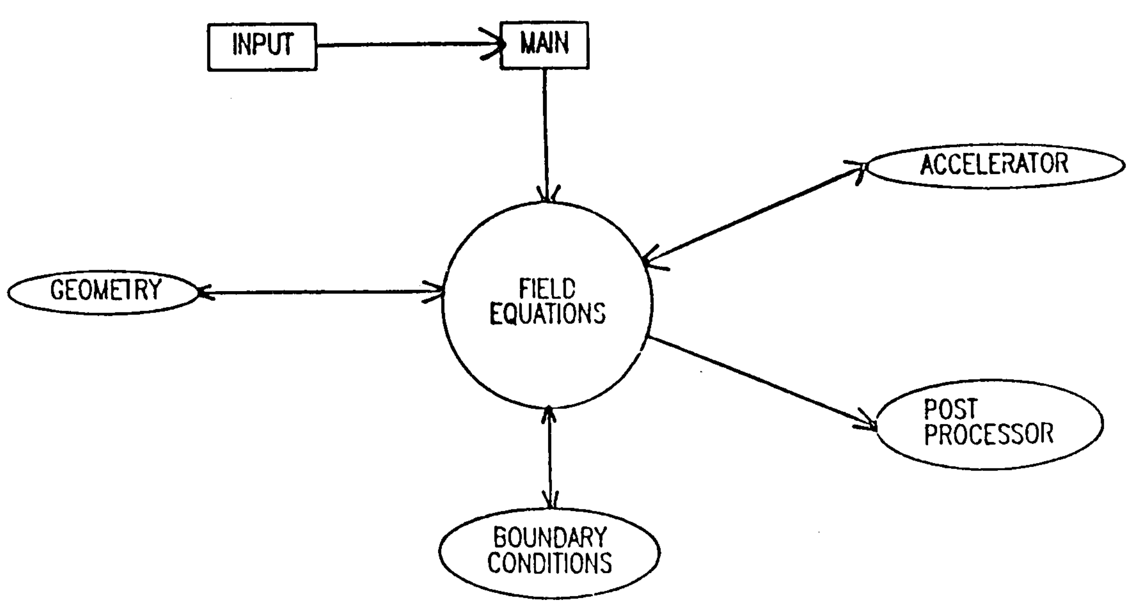


Figure 13.

AVERAGE-PASSAGE EQUATION SYSTEM

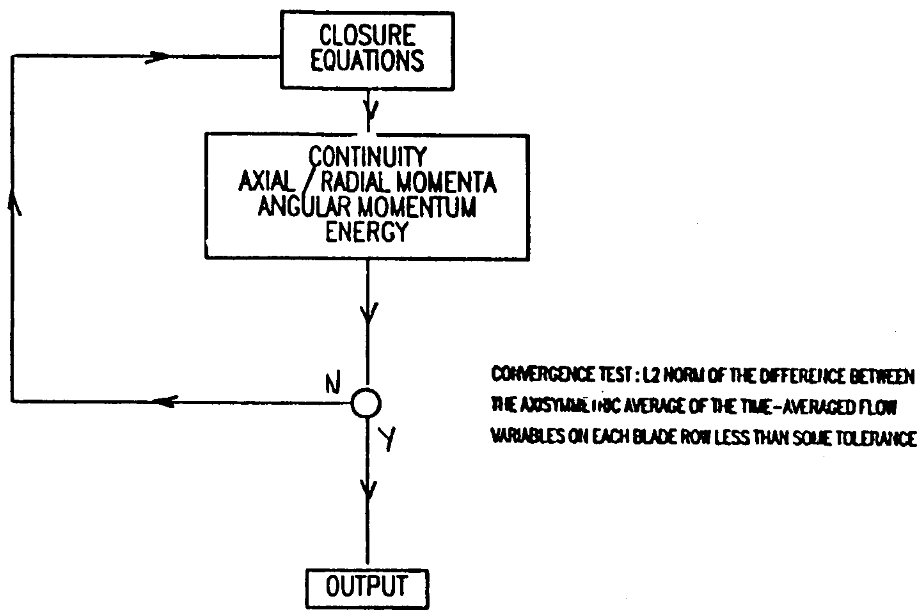


Figure 14.

MULTITASKING OF MULTISTAGE
3-D FLOW FIELD CALCULATION

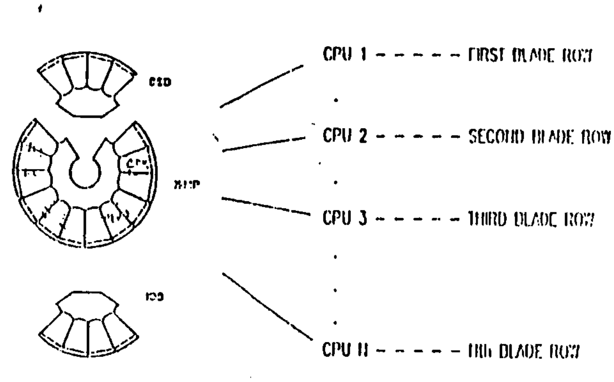
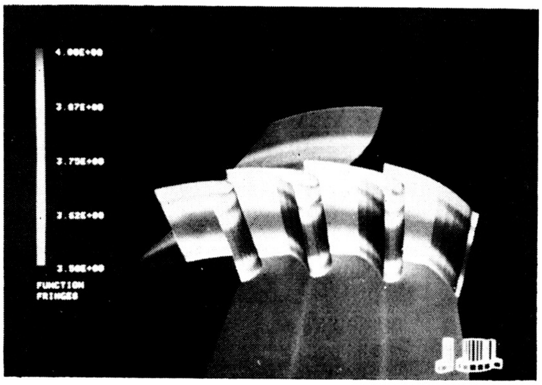
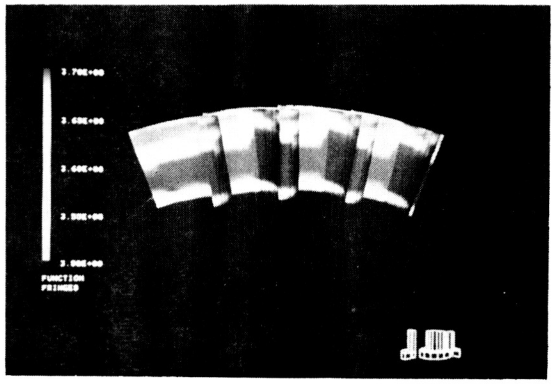


Figure 15.

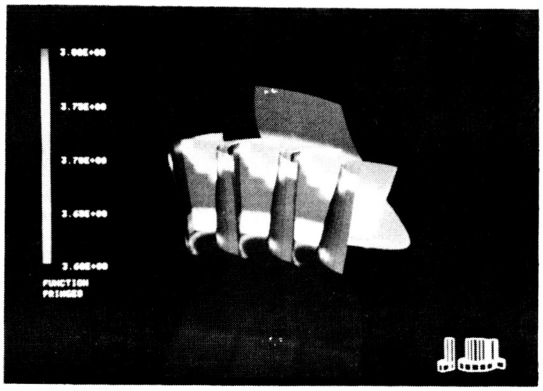
EVOLUTION OF THE TOTAL TEMPERATURE FIELD WITHIN THE S.S.M.E. FUEL TURBINE



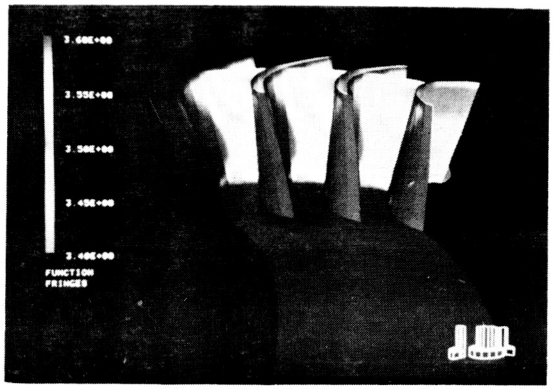
**1st VANE
MID PASSAGE**



**2nd VANE
MID PASSAGE**



**1st ROTOR
MID PASSAGE**



**2nd ROTOR
MID PASSAGE**

SIMULATION PERFORMED ON LEWIS CRAY XMP 24

Figure 16.