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Numerical Wind Tunnel Project and Computational Fluid Dynamics at National Aerospace Laboratory, Japan

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ABSTRACT

The National Aerospace Laboratory (NAL) is the only research organization under the Science and Technology Agency which performs aerospace research in Japan, with NAL being actively involved in conducting computational fluid dynamic (CFD) and supercomputer research and development. This paper summarizes the Numerical Wind Tunnel Project and associated CFD work carried out by NAL.

Keywords: CFD, Supercomputer, Aerodynamics

概　要

NLR（オランダ国立航空宇宙技術研究所）主催第3回ISNaS（Information System for flow simulation based on the Navier−Stokes equations）シンポジウムが1991年9月19日から20日にオランダのノールドーストポルダーのNLRにおいて開催された。本報告はNLRの要請に基づき同シンポジウムにおいて「航空宇宙技術研究所（日本）における数値風洞計画と計算空気力学」として発表するために，数値シミュレーション技術等検討委員会のワーキンググループである「先進的研究課題ワーキンググループ」が取り纏めた数値風洞に対するユーザー検討と計算空気力学の現状についての報告の概要(NAL SP−13，日本航空宇宙学会誌1990年10月号にて発表済）をもとに英文でまとめたものである。

1. NUMERICAL SIMULATOR

1.1 History of NAL Computer System

NAL was established in 1955 to promote aeronautical engineering technology and belongs to Science and Technology Agency. Computer was brought into as a part of data processing machine for 2m x 2m Transonic Wind Tunnel. When machine time was available, it served as the calculator for theoretical fluid dynamics which includes transonic flow problem.

Since then the role of computer at NAL has been changed significantly just like sister organizations in other countries. Table 1. shows the time chart of NAL computer system and its major applications. The epoch making decision was made in 1974 when NAL and Fujitsu Co. started joint development of the first Japanese super-computer FACOM 230-75-AP (Array Processor). NAL was the only one institute who correctly evaluated the significance of numerical simulation such as CFD and the needs of supercomputer. The experience of using 75-AP resulted in the start of Numerical Simulator Project in 1979.

* Received 7, October 1991
*1 Aircraft Aerodynamics Division

Table 1. History of NAL Computer System

year	machine	major applications
1960 - '66	Burroughs DATATRON 205	TWT data processing theoretical fluid dynamics
1967 - '74	Hitachi HITAC 5020 (32kw)	TWT data processing fundamental CFD researches
1968 - '74	HITAC 5020F (65kw)	FEM for structure mechanics
1974	Joint Development of first Japanese Supercomputer 75AP	
1975 - '81	Fujitsu FACOM 230-75 2CPU (640kw, 3.5MIPSx2)	2D-Euler and 3D potential CFD 2D-NS solver development
1977 - '81	FACOM 230-75-CPU+APU (1000kw, 22MFLOPS)	FEM for structure mechanics TWT data processing
1979	Start of Numerical Simulator Project	
1982 - '86	FACOM M380+M180IIADx2 (44MB/HD9GB, 27MIPS)	2D-NS code for YXX design 3D-NS solver development
1985 Oct.	Exp. STOL "ASKA" maiden flight	
1987 - '90	Numerical Simulator Facility (24hr Operation)	
	FACOM VP-400 (1GB, 1.14GFLOPS) FACOM VP-200 (128MB, 0.57GFLOPS) FACOM M-780 (128MB, 45MIPS / SSD 32MB / HD 90GB / OptD 180GB)	3D-NS code (wing, wing-body) for YXX, HOPE, SP etc. 3D-NS code development for complicated geometry reactive flow code
1989 June	Numerical Wind Tunnel Feasibility Study Started	
1991 -	VP-2600 replaced with VP-200, reinforced HD (512MB, 5GFLOPS)	LAN (Ethernet)

Three major companies: Fujitsu, Hitachi and NEC began to sell commercial models of supercomputers in early '80's. Universities installed these models competitively. During the most part of '80's, budget for computer was tight at NAL because the entire Japan government budget environment itself was very severe and also NAL has been engaged in the experimental STOL plane 'ASKA' R&D program as well. From author's point of view, it might be very difficult for NAL to invest money to more than one project. After the major peak of ASKA was passed, Numerical Simulator Peoject was funded to realize in 1987.

1.2 Numerical Simulator – Present System

In 1987, Numerical Simulator (NS) facility began its operation. NS consists of Fujitsu VP-400, VP-200 and M-780. VP's are back-end vector processors for CFD and M-780 manages job scheduling and TSS as the Front-end processor. Since 1991, VP-2600 replaced VP-200 and hard disc capacity was increased. Major features of the present system are shown in Table 2. In 1989, Numerical Wind Tunnel (NWT) Feasibility Study was started to seek the next step.

Table 2. Numerical Simulator ... Present System

Processors			
	VP-2600	5 GFLOPS	512 MB
	VP-400	1.14 GFLOPS	1 GB
	M-780	45 MIPS	128 MB
External Storage			
	Solid State Disk		64 MB
	Magnetic Hard Disk		125 GB
	Magneto-Optical Disk		180 GB
High-Speed Network			
	Ethernet Type LAN		10 Mbit/s
	Channel Interface		3 MByte/s
	CCP Interface		64 Kbit/s
	NTT network links to Chofu Branch, Kakuda Branch, MHI, KHI, FHI and IHI		

1.3 Graphics Tool

Graphics hardwares are listed in Table 3. Most of these terminals are non-intelligent type and linked to FEP by channel to get high-speed data transfer. Total of 60 personal computer FMR-60HX and TSS/GD terminals are located at various buildings and linked with FEP using Ethernet type NAL-LAN. 2D color graphic monitoring can be made at these terminals as well as at 48 TSS/GD terminals.

Recently, work station type terminals are increasing its number. But major owners of WS are not CFD researchers yet. Some people are testing how to use WS in the present circumstances, especially for local handling of post-processing graphics. Titan 3000, 750, IRIS and SUN are used for this purpose. But most CFD users remain in the world of main frame. There may be several reasons for this.

As the unified graphic software which can be used regardless of hardware types, Graphic Control Package Library; GCP was developed at NAL. CFD user only need to call GCP subroutines in his FORTRAN program. By specifying library of Graphic Hardware at linkage, user can output graphic data from any device in batch or TSS jobs. For example, only TSS command:

>GLIB GRIP CR

is needed when TSS session on 3D-GD (COMTEC) is opened.

1.4 Job Classes

Since Numerical Simulator was introduced for large-scale CFD simulations, priority of large jobs are made. Present job classes are shown in Table 4. To process these large jobs, Numerical Simulator operates 24 hours everyday.

2. FUTURE DEVELOPMENT: NWT (Numerical Wind Tunnel)

2.1 Our Estimation of Requirements

As significance of CFD as a design tool of aerospace development became to be recognized, the needs of CFD research and computer demands both in NAL and other government agencies are increasing. Even before Numerical Simulator was installed, such needs were strong, the achievement of NS enhanced these request. We came to a conclusion that new computer with reasonable performance and cost should be introduced to replace the present system in a few years.

Opinions and needs were collected from CFD researchers and aerospace industries. The follow-

Table 3. Graphic Hardwares

NEXUS 6410 x 1 set 20" 3D-image display 512 x 480 resolution, 24 bit colors non-intelligent terminal with film recorder (35mm, Polaroid), VTR, optical disk, digitizer
FIVIS F6510 x 3 set 20" 3D-image display 1280 x 1024 resolution, 24 bit colors non-intelligent terminal with film recorder (35mm, Polaroid), hard copy, 16mm movie camera
COMTEC DS351B x 8 set 20" 3D-image display 1280 x 1024 resolution, 24 bit colors local-handling terminal with film recorder (35mm, Polaroid), hard copy,
TSS/GD F6683 x 48 set 14" 2D-display 960 x 672 resolution, 3 bit colors non-intelligent TSS terminal with graphics with hard copy,
TSS/PC FMR-60HX x 50+10 set 14" 2D-display 960 x 672 resolution, 3 bit colors non-intelligent terminal. FMR can monitor graphics using F6680 Emulator* * most popular NEC-PC9800 cannot handle graphics.
Work Stations ... Titan 3000, Titan 750, IRIS, SUN etc. are recently introduced.

Table 4. Job Classes of Present System

SHP2 (VP-2600)

Job Class	Memory Max Size	CPUT Max
SHRT	450 MB	5 min
MIDL	50 MB	30 min
LONG	450 MB	100 min
HJOB	450 MB	300 min

SHP1 (VP-400)

Job Class	Memory Max Size	CPUT Max
SMAL	50 MB	60 min
LARG (shrt)	968 MB	3 min
LARG (Long)	968 MB	100 min
HUGE	968 MB	300 min

ing is the result of requirement estimation.

1. Main Memory Size Estimation
   1. Grid points:
      1) for full configuration analysis with engine, flap, SRB, etc.
         $5 \sim 15 \times 10^6$ grid points
      2) for practical applications of LES
         150×10^6 grid points
   2. Data:
      conventional Time-Averaged Navier-Stokes (TANS) analysis
      (perfect gas, algebraic turbulence model, steady flow)
      $30 \sim 50$ data / grid point
      high level TANS analysis
      (real gas, refined turbulence model)
      twice as above
   3. Data accuracy:
      $4 \sim 8$ Byte
      (4 B for primitives, 8 B for works)

   Result:
   1) $15 \times 10^6 \times (200 \sim 400$ B) $\rightarrow 3 \sim 6$ GB
   2) $150 \times 10^6 \times (200 \sim 400$ B) $\rightarrow 30 \sim 60$ GB

   Total memory size of at least 30 GB is required.

2. Processing Speed Estimation
   1. Typical CPU time on VP-400
      TANS analysis with 10^6 points
      .... 10 hours
      Stiff problems such as real gas takes $2 \sim 3$ times longer.
      average/peak speed ratio in highly vectorized FORTRAN code is $0.5 \sim 0.3$
   2. Data Productivity Requirement
      at NASA, NAS is:
      practical application: 10 min/data point
      research computation: 1 hr/case
      at NAL, it will be:
      practical application: 1 hr/data point
      research computation: 10 hr/case

   Result:
   Effective speed should be:
   150 x VP-400 average speed.

2.2 Numerical Wind Tunnel (NWT)

To realize NWT with above requirement, RFP for Feasibility Study was released in 1989. RFP was opened to foreign computer makers as well as to Japanese makers. It was found that no commercially developed machine to fulfill our requirement is available to replace VP-400 within 2-3 years. Therefore if we do not develop by ourselves we will not be able to realize NWT. Study how to realize NWT is continued by research staff of Mathematical Sciences Division and CFD user scientist group.

3. CFD RESEARCHES

3.1 Common Fundamental Researches

It is difficult to separate fundamental CFD researches common to many disciplines and application oriented researches. Most of works are outcome of latter, although a few number of researchers are working on fundamental works.

Grid Generation Methods:

Various kind of methods has been developed such as elliptic equation method, hyperbolic equation method, algebraic construction, electro-potential line method, multi-block, chimera, unstructured grid similar to FEM grid and combination of structured and unstructured grids. There are pros and cons about the choice of methods. Each researcher choices his method as best one for his particular application.

Use of graphic tools and automatic definition of surfaces and 3D grid is important. A unified approach to this is not yet accomplished.

Schemes for Euler/N-S Equations:

Various kind of scheme has been tried and improvements are studied by researchers. IAF method developed by Beam-Warming-Steger was the first scheme used. Later many variants and improvements – exact formulation, diagonal approximation, LU-ADI, addition of TVD evaluation in RHS etc. were made by various researchers. Point implicit scheme is used in reactive flow analysis. TVD approach is often used for better resolution of shock waves. Explicit and implicit TVD evaluations such as Roe's approximate Riemann solver, Yee-Harten's scheme, Chakravarthy method are utilized. Gaussian elimination method is also tried. Higher order time-accurate scheme for unsteady flow problems are studied. Mathematical analysis of finite difference scheme is also made.

Choice of scheme is made by each researchers and no unified approach is made. We think such unification should not be taken at research institude.

Turbulence model:

Well-known Baldwin-Lomax model is mostly used in many applications. The agreement with wind tunnel experiment is not necessarily excellent when B-L model is used. Higher-order turbulence models such as Johnson-King model, k-ϵ model and Coakley's q-ω model are compared in cascade flow problem. k-ϵ model is also used in SST and ASKA analyses.

There are too many items which lead to disagreement besides selection of model. In 3-D analysis, model evaluation at confluent corner flow holds ambiguity and computation is not fine and exact enough to conclude the validity of turbulence model's accuracy. As computer speed is not enough to run many parametric studies to evaluate model's accuracy, such research must be done on NWT.

3.2 Applications to National Aerospace Developments

3.2.1 Aircraft Aerodynamics Simulations

Navier-Stokes code development for 2-D transonic airfoil analysis began before 1980 and it was applied to transonic airfoil design and analysis by NAL scientists and by JADC (Japan Aircraft Development Center) for YXX. This code uses IAF scheme.

Next, 3-D N-S code using LU-AID scheme with B-L model for thin-layer N-S equations was developed. 3-D wing and transport-type wing-fuselage configuration were computed. Grid generation method to cover such geometry was also developed. Practical application includes analysis of Boeing-747, YXX (B-7J7) and MHI-MU-300. The code has been improved from time to time by addition of TVD terms in RHS etc. A typical computation uses 730,000 grid points in one side of symmetric plane and CPUTime is 3-10 hours on VP-400. Parametric computations of alpha-sweep and Mach number-sweep at transonic speed were made and the result was compared with 2m x 2m Transonic Wind Tunnel test. This is a joint work with JADC and MHI.

Same code was applied to a 3-D flow simulation of 2-D airfoil model in 2-D High Reynolds number Transonic Wind Tunnel to evaluate the side wall effect on two-dimensionality of testing.

Another N-S code using implicit TVD finite volume scheme was developed and applied to YXX (Boeing-7J7) analysis. O-mesh generator based on electro-potential line method was used to cover main wind, fuselage, horizontal and vertical tail wings. Only 250,000 grid points was required to cover the entire geometry because of efficiency of O-O-O topology. Pressure comparison with experiment at $M_\infty=0.9$, $\alpha=2^\circ$ and $Re=1.2\times10^6$ is shown in Figure 1. Notice pressure distribution along fuselage agree.

Euler and N-S analysis of USB-STOL "ASKA" full-configuration using multi-block mesh of 510,000 to 1,270,000 grid points is another demonstration of large scale computation (Figure 2). 2-step Runge-Kutta FVM was used in Euler code and implicit plane Gauss-Seidel relaxation was used in N-S code. Roe's approximate Riemann solver is used for flux evaluation. 4-7 hours are required on VP-400.

Supersonic flow analysis for SST (Super Sonic Transport) configuration was also made using the same N-S code with 2-equation turbulence model.

In unsteady aerodynamics analysis, Euler analysis of aeroelastic characteristics of YXX main wing, N-S analysis of transonic swept wing in pitching motion and N-S analysis of dynamic stall and pitching airfoil are made.

The followings are the findings: overall aerodynamic characteristics obtained for clean

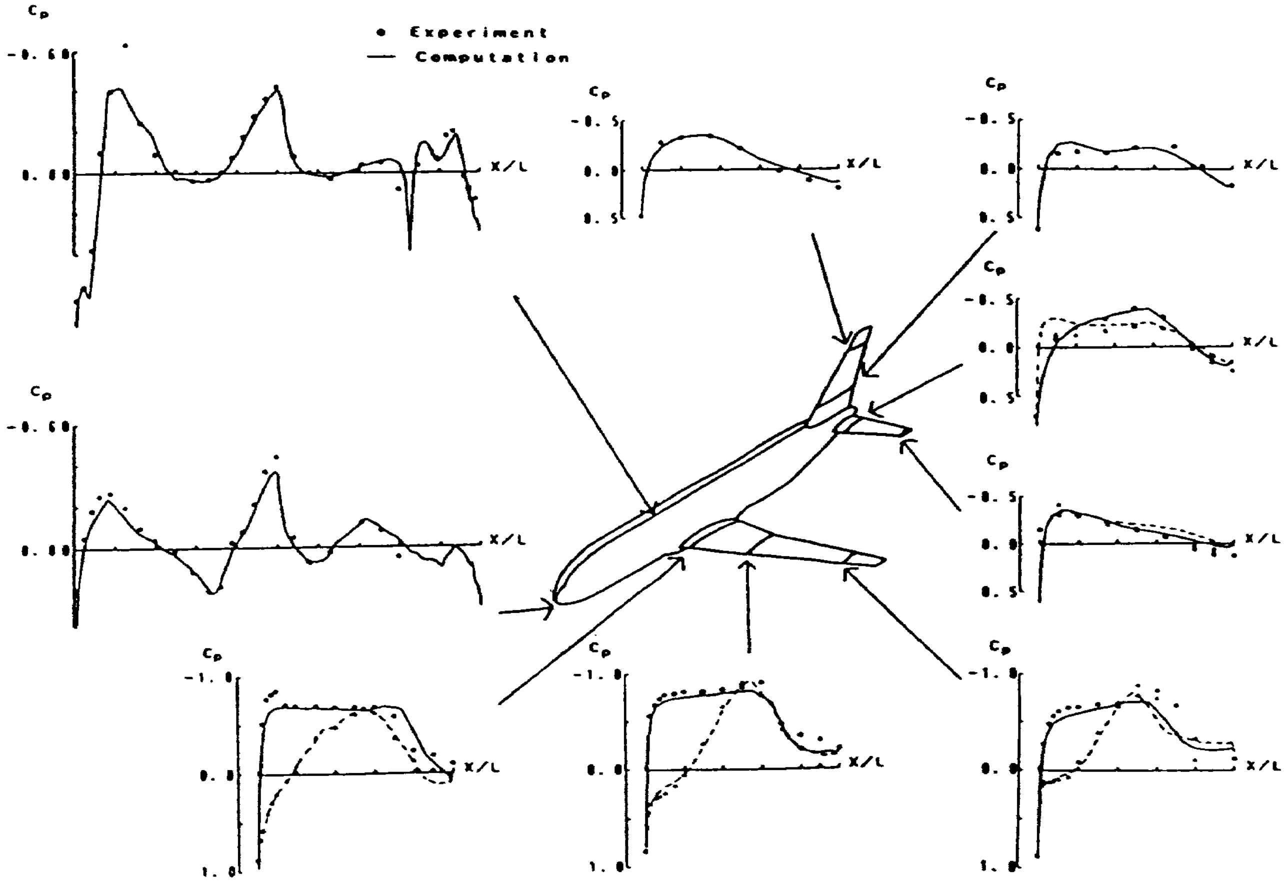

Figure 1. Pressure comparison with experiment of N-S analysis of YXX.

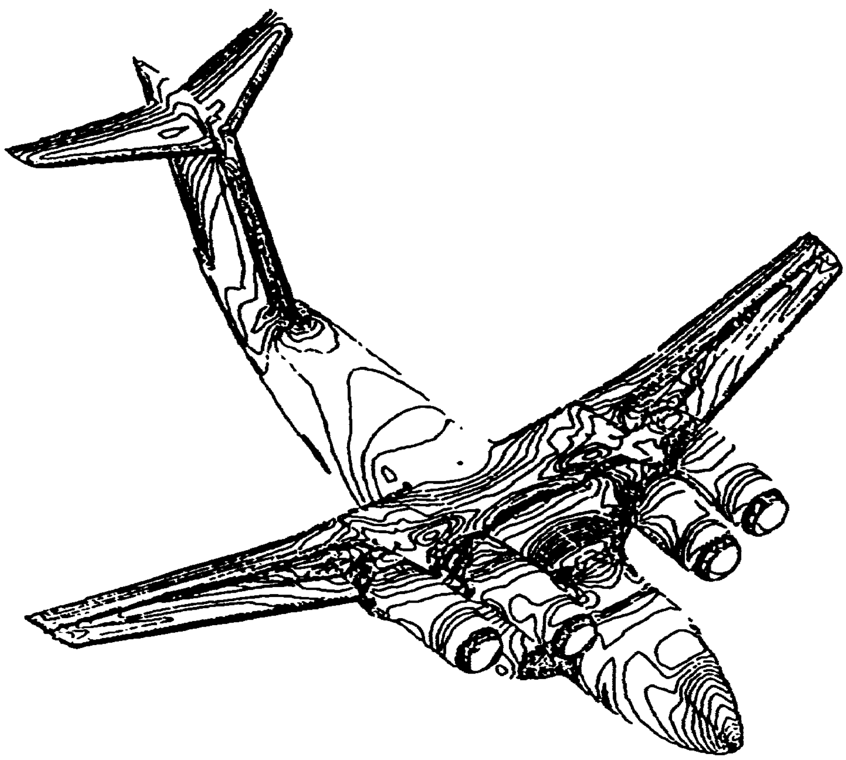

Figure 2. Euler analysis of STOL "ASKA"

body at design condition compares excellently with wind tunnel data. However, in the case of flow with strong shock wave and separation, the comparison is not good. Wind tunnel wall interference correction is not included in the computation and it must be taken into account when comparison is made. Absolute value of C_{d0} is difficult to agree and α_0 correction is needed. High angle of attack flow problem is different from these experiences. Obtaining good agreement is difficult. VP-400 is too slow for parametric study.

3.2.2 Space Vehicle Aerodynamics Simulations

Recently demands of CFD for space vehicle aerodynamics are increasing. NAL is proposing Space Plane (SP) research and NAL-NASDA is jointly working on HOPE development. Euler and N-S codes were developed by various scientists. Analyses were made in low speed, transonic, supersonic, hypersonic and reactive flow regimes.

An example of complex geometry analysis using Euler code is the analysis of space launcher H2 with HOPE and 2 SRB's. Chimera type multiblock mesh of 0.29 million points was used. Scheme is ADI scheme with Yee-Harten TVD evaluation. It took 3–4 hours on VP-400. Figure 3 shows surface pressure distribution at $M_\infty = 1.8$, $\alpha = 3°$.

Recently this analysis was extended to N-S equations. Chakravarthy's implicit TVD scheme is applied. 1 million grid points were used for six SRB configuration. CPU time was 3 hours on VP-2600 for a case of $M_\infty = 3.0, \alpha = 0°$.

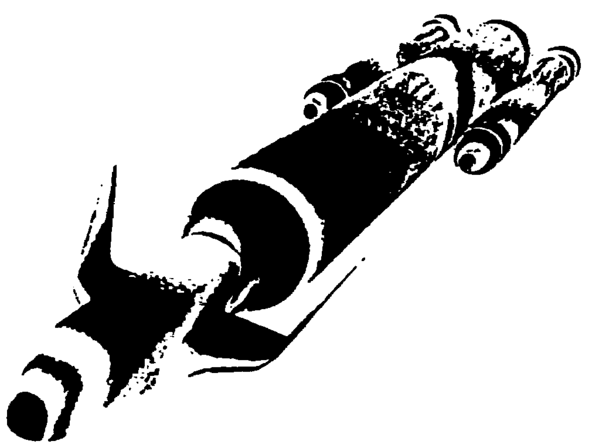

Figure 3. Computation of HOPE-H2-SRB geometry.

An analysis of Space-Shuttle Orbiter using diagonalized IAF and explicit viscous terms with Harten-Yee type TVD flux was made. 180,000 grid points were generated by hyperbolic equation generator. Computation was made from Mach number 0.1 to 4.0, $\alpha = 0°$ to $30°$ and $Re = 1 \times 10^7$. It takes 2 hours/case on VP-400.

Hypersonic flow analysis for Space Plane and HOPE was made using non-diagonalized IAF scheme with flux-splitting 2nd order upwind TVD flux term. 330,000 to 900,000 grid points were generated by hyperbolic equation method. Using full geometry, sideslip characteristics and aileron effect were computed at $M = 7, \alpha = 0°$ to $20°$, $\beta = 0°$ to $5°$ and $Re = 4.4 \times 10^6$. The pressure and heat transfer distributions were compared with experimental data obtained at NAL Hypersonic Wind Tunnel (Figure 4). It takes 15 hours on VP-400.

Transonic flow analysis of Space Plane and HOPE was made by another group using LU-ADI and B-L model. Shock-boundary layer interaction between fuselage and wing tip tail is very complicated. The detail of the flow field differs from experiment although C_l, C_d – α agrees well.

Hypersonic real gas analysis of Space Plane and HOPE was made with 7 species chemical reaction model. Non-MUSCL TVD scheme with Roe's Riemann solver was applied. Implicit point relaxation is used for reaction terms. Computation for 180,000 grid points at $M = 15$ and altitude 35km took 15 hrs on VP-400.

These analyses show that aerodynamic and heat-transfer characteristics qualitatively agree with experiment. It can be pointed out that the order of C_l or C_d values is different from values for aircraft in general. Yet present CFD analysis gives informative result for designing space vehicles. In transonic flow, disagreement is clear in oil flow pattern although detailed comparison is difficult due to experimental technique.

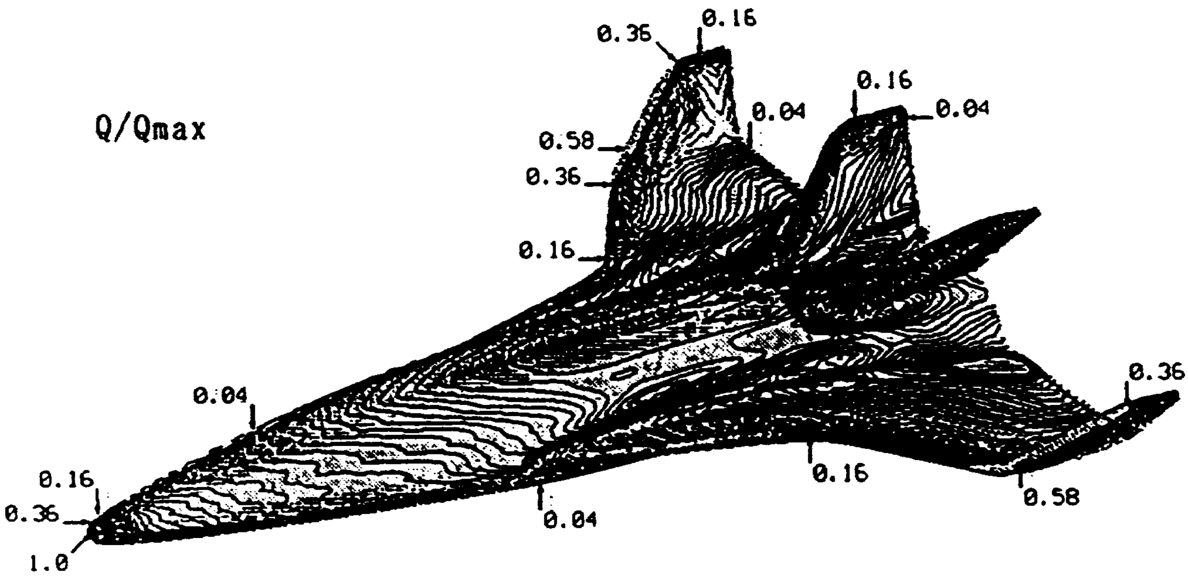

Figure 4. Heat transfer distribution on Space Plane

3.2.3 Propulsion Aerodynamics Simulations

Euler and N-S analyses were made for various flow regimes such as:

Euler/NS analysis and design of 2-D blade using zonal approach with IAF-FDM and Euler-FEM

NS analysis and design of 3-D ultra-high-bypass fan blade (Figure 5)

NS analysis of 3-D cascade fan blade including tip clearance region

Euler analysis of 3-D fanjet engine and turbine powered simulator

Euler/NS analysis of counter rotating 3-D ATP blades with 2-equation model

NS analysis of supersonic air intake configuration for SST

NS analysis of 2-D/3-D SCRAMJET of Langley model.

The analysis of SCRAMJET (Supersonic Combustion Ramjet) uses 9-species, 24 reaction steps in hypersonic flow and B-L turbulence model. 437 x 185 grid points were used for 2-D analysis of hypersonic side jet in detail. 100 x 52 x 41 grid points was used for 3-D analysis. This size is maximum allowable memory size in present system.

Findings in propulsion aerodynamics simulation do not differ from the previous simulations. In compressor and turbine analyses, N-S code gives qualitatively good total pressure loss distribution, etc. But quantitatively, choice of turbulence model significantly affects the result due to low Reynolds number flow. Inflow and outflow conditions still require improvements to compare with experiment. 3-D unsteady flow analysis and steady flow analysis of blade columns needs NWT.

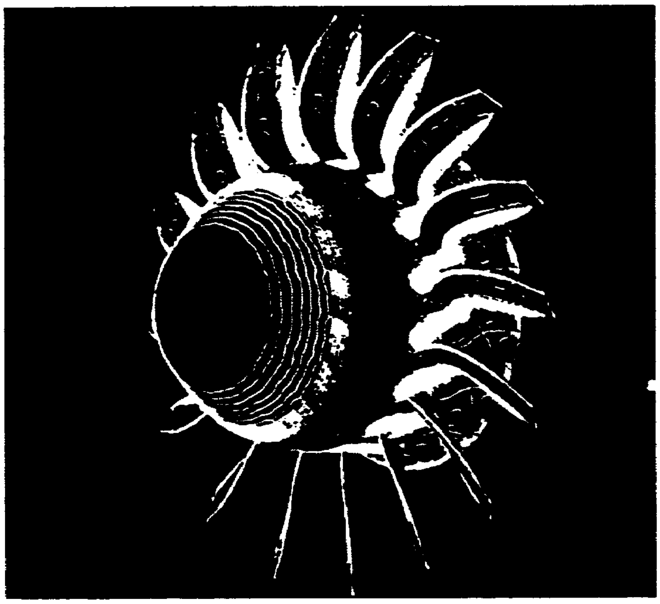

Figure 5. 3-D ultra-high-bypass fan blade analysis

3.2.4 Other CFD Researches

Numerical Simulator also provides CPU time for basic fluid dynamics research such as DNS (Direct Numerical Simulation). DNS is another field NAL has been engaged in. VP-400 enabled DNS with reasonable resolution. DNS for uniform homogeneous turbulence was computed using Runge-Kutta-Gill method in time advance and Fourier Spectral method in space. An analysis of 128^3 cube at $Re = 500$ took 12 hours. Reynolds number based on Taylor's micro scale, Re_λ is $O(10^2)$. The result shows that Kolmogoroff's spectrum $k^{-5/3}$ is obtained.

DNS for turbulence transition in channel flow was also made at $Re = 5 \times 10^3$ and 1×10^4 using $21 \times 21 \times 85$ and $85 \times 85 \times 341$ cube. The result shows that a finite amplitude T-S wave grows to turbulence at $Re = 10^4$ while it does not lead to turbulence at 5×10^3.

Large Eddy Simulation research is not pursued yet at NAL presently.

Another NS user is Monte Carlo Simulation of rarefied gas dynamics. DSMC (Direct Simulation Monte Carlo) method was developed and applied to 3D gas flows including practical application of flow past Space-Shuttle Orbiter.

3.2.5 SACAD Symposium

SACAD (Symposium on Aircraft Computational Aerodynamics) is the annual symposia hosted by NAL since 1983. The presentation is opened to universities and industries as well as to researchers at NAL. The sessions cover not only CFD but also supercomputer-related topics such as architecture, parallel processing and software. Through these symposia and joint researches with industries and universities, NAL promotes CFD researches.

4. PROSPECTS OF COMPUTER AND CFD

As shown in the previous section, present system is not sufficient for aerospace CFD researches. NWT is prerequisite for both CFD research and applications for national developments. NWT Project will be realized before mid '90's, possibly early in '93.

NAL has achieved 3-D N-S code development applicable to aerospace development and the obtained results are useful. However, the more CFD research is made, the more demands for high-quality analysis arise. As is well-known, shortage of computer power is not the only item left for the advancement of CFD.

Some of such items are:

1. Mathematics
   - flow model for separated flow
   - efficient scheme development
   - unsteady flow scheme
   - parallel processing algorithm
2. Grid generation technique
   - grid generation methods
   - complex geometry treatment
   - structured vs. unstructured grid
   - increase grid point numbers
   - easy to handle grid generator
3. Physical model
   - turbulence model for
     - 3-D boundary layer
     - adverse pressure gradient
     - shock-induced separation
     - large scale separation
     - hypersonic turbulent boundary layer
     - reactive flows
   - chemical reaction model for
     - combustion and real gas
   - nonequilibrium physics model
4. Experimental data for models and code validation.

NAL has been concentrated only in code development and computer power in the past. These has been and still are vital items in CFD research. But these items only are not enough to advance CFD in future. We need to give more efforts on these items listed above. Especially work on code validation using experimental data is not made much yet. In this aspect, European institutions' efforts should be respected.

5. CONCLUDING REMARKS

NAL's computer system: Numerical Simulator and NWT Project, CFD development and future efforts are presented. NAL's human resources are limited and it will be difficult to achieve CFD research advancement by NAL only. NAL is working on joint researches with other government agencies, industries and universities. International cooperation is important also for more advancement. In this regards, we already started preliminary cooperation in CFD with FFA. I hope this presentation to ISNaS Symposium will contribute the international cooperation between NAL and the Netherlands.

Acknowledgements

The present paper was presented to The Third Information System for flow simulation based on Navier-Stokes equations (ISNaS) Symposium hosted by National Aerospace Laboratory NLR, The Netherlands and held at Noordoostpolder on September 19–20, 1991. The presentation was made based on the request of NLR as a start of research cooperation on computer application technology and CFD between NAL and NLR.

The contents of the paper are based on works done at various divisions and only a summary is described herein. The more details should be found in NAL publication SP-13 and October 1990 issue of Japan Society of Aeronautical and Space Sciences Journal. All of those works are a part of activity of the Advanced Topics Working Group of Advisory Committee on Numerical Simulation Technologies, an internal committee at NAL although a single name of the author is represented. The author expresses his sincere gratitudes to the members of Advanced Topics Working Group whose contributions are very important. Special thanks go to the Group Leader Dr. Koji Isogai and Mr. Hajime Miyoshi, Head of Computational Sciences Division. Mr. Miyoshi read the manuscript and recommended a many valuable suggestions and modifications which are very important. He also provided a strong support to realize this presentation.

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