Program Overview and Intermediate Achievements of "Research and Development of Environmentally Compatible Propulsion System for Next-Generation Supersonic Transport (ESPR project)"

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Abstract

ESPR program was initiated in 1999 as the successor of HYPR program by NEDO under METI budget support in order to develop necessary technologies for the next-generation SST engine. In ESPR program, CO2 reduction technologies, NOx reduction technologies and noise reduction technologies are especially focused as environmentally compatible technologies, which are critical to realize next-generation SST. Targets of the above three subjects and validation methodologies are overviewed and some major topics of intermediate research results during initial three years of five years program are shown.

Abbreviation

AIST:	National Institute of Advanced Industrial Science and Technology
ESPR(project):	Research and Development of Environmentally Compatible Propulsion System for Next-generation Supersonic Transport
GE:	General Electric Company
HSRP:	High Speed Research Program
HYPR (project):	Engineering Research for Super /Hyper-sonic Transport Propulsion System
ICAO:	International Civil Aviation Organization
IHI:	Ishikawajima-Harima Heavy Industries Co. Ltd
KHI:	Kawasaki Heavy Industries, Ltd
METI:	Ministry of Economy, Trade and Industry
MHI:	Mitsubishi Heavy Industries, Ltd
NEDO:	New Energy and Industrial Technology Development Organization
NAL:	National Aerospace Laboratory
NASA:	National Aeronautics and Space Administration
RR:	Rolls-Royce plc.
UTC:	United Technologies Corporation
Snecma:	Societe Nationale d'Etude et de Construction de Moteurs d'Aviation
UEET:	Ultra Efficient Engine Technology

1.Introduction

HYPR program, 10 years program (1990-1999) supported by Japanese Government, was completed in March of 1999 with successful results. It showed the feasibility of Combined Cycle Engine (Turbofan and Ramjet Engine) concept for Hypersonic transport (HST ; Mach 0-5) and achieved TIT 1700 C realization in Turbofan. [1] (Von Karman Prize was given in 2000 by ICAS)

On the other hand, NASA had shown brilliant success in technology developments of next-generation HSCT in HSR Program up to the end of 1999. [2,3] NASA changed HSRP at the end of 1999 to UEET program [4] etc. which started to develop critical turbine engine technologies for both commercial/military and supersonic/subsonic applications

However, in 2001, Boeing announced to the world they would develop so-called "Sonic Cruiser". This may imply strong request upon high speed aircraft exists actually in the market, and high speed aircraft era might be initiated by "Sonic Cruiser". Furthermore, it is generally said the Concorde may retire around 2015 , it may become more realistic the successor of Concorde will be realized around 2015 to 2020. In addition, recently Supersonic Business Jet (SSBJ) is expected more realistically and practical studies are being carried out by aircraft companies.

ESPR started under the above-mentioned situation in the Autumn of 1999. Apart from HYPR, the target aircraft and engine was specified just to next-generation SST. In other words, the ramjet relevant technologies are excluded in the program, but instead of them, environmentally compatible technologies are focused because they are critical for next-generation SST. CO_2 reduction, NOx reduction and Noise reduction technologies will be developed with ambitious target values.[5]

2.Organization of the Project

Technology research and development in ESPR will be carried out, maintaining international collaboration formation established well in HYPR project. Three Japanese engine companies (IHI, KHI and MHI) and four foreign engine companies(UTC, GE, RR, Snecma) and ESPR Association share the research and Technology development activities under the contract with NEDO. In addition, two Japanese national laboratories, viz. NAL and AIST participate in this project. Fig.1 shows ESPR organization. All those members work together to achieve the goal of ESPR project.

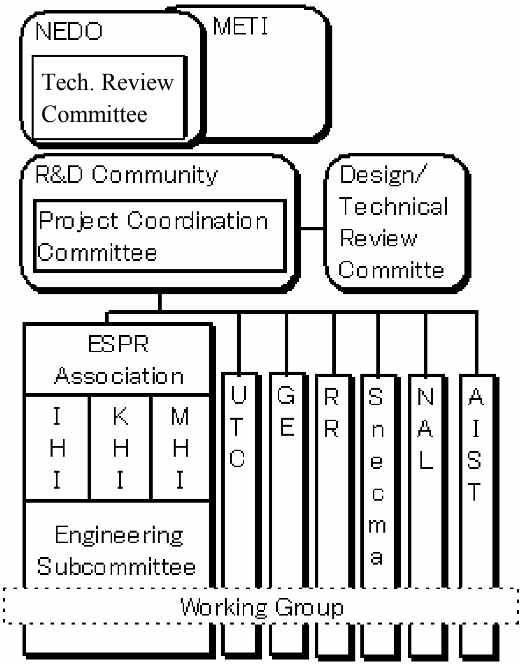


Fig.1 ESPR Organization

3.Environmentally Compatible Technologies

As is mentioned, environmentally compatible technologies are essentially important. 3 technological issues are described below.

3.1. CO2 Reduction

25% reduction has been chosen as engine CO_2 reduction target. In order to achieve it, reduction of engine weight and improvement of fuel consumption should be realized by developing such as advanced material application technology and advanced secondary air cooling technology.

3.2. NOx Reduction

As for the NOx emission, the depletion of ozone layer is particularly concerned at stratosphere where SST's fly. According to NASA studies, NOx reduction target should be **5 grams of NOx per kilogram of fuel (NOx E.I.=5)**.

This target corresponds to one seventh of current engine emission level.

3.3. Noise Reduction

Airport noise is one of biggest issues of SST operation. It was thought the noise regulations must become more stringent in future not only for subsonic transport but also for supersonic transport. This is the reason why the project target be set **minus 3dB below ICAO Chapter3** for fan noise at approach and jet noise at sideline, respectively. (As a result, it is equivalent with ICAO Chapter 4 which will be applied from 2006.)

3.4. ESPR Vision and Goal

As mentioned above, ESPR targets are as follows;

CO_2 Emission: 25% reduction
NOx Emission: 5gram/kg-fuel
Noise reduction :ICAO Chapter3-3dB.

4.Technology Concept Propulsion System

CO_2 reduction, NOx reduction and Noise reduction are opposite requirements each other from technological viewpoints. Therefore, trade-off and/or optimization among them must be needed on a technologically conceptual Propulsion System.

First of all, the specification of the target engine for SST is set up. Based on this target engine, the specification and target value of an individual research subjects are set up. After results are obtained, they should be fed back to the conceptual target engine and trade off among them also made.

Final evaluation for ESPR target achievement will be performed in this way (see fig.2).

4.1. Target Engine

First round Target engine was specified assuming following SST specification.

300 seats,
Cruising-speed Mach 2.2,
Cruising range of 10,200km.

About 13 for the whole cycle pressure ratio and 1923K (1650C) for turbine inlet temperature were assumed as a base engine cycle parameter.

Applications of the advanced heat resistance material and advanced air cooling technology are assumed to apply for target engine. So the amount of turbine cooling air for target engine was mostly reduced by half from a present technical level and weight was also reduced by 30% from current technology by application of advanced materials.

Figure 3 shows the target engine cross section. The feature of this target engine is that a bypass ratio is as high as 1.05.

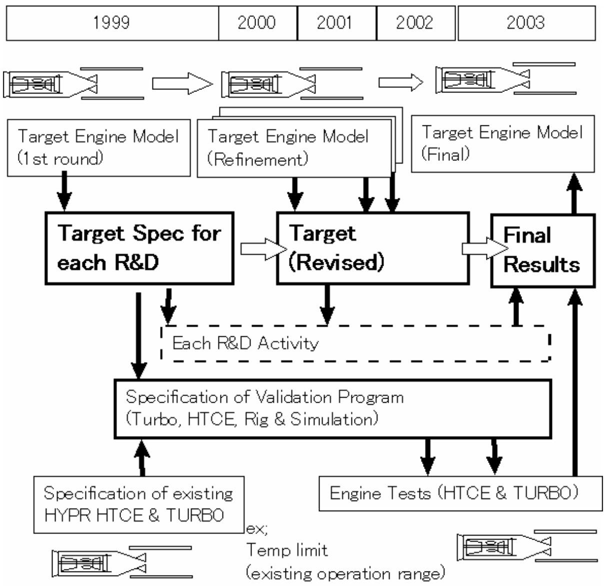


Fig. 2 Evaluation flow of ESPR target

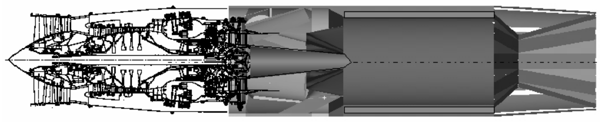


Fig.3 Cross section of target engine

5. Intermediate Achievements

5.1. CO_2 reduction

In order to achieve 25% CO_2 reduction, there are 4 aspects of challenges. First one is the light weight designs adopting the advanced materials, such as CMC (ceramic matrix composite) for turbine vane, shroud segment and combustor liners, MMC (metal matrix composite) for fan rotor and TiAl (titanium aluminide) for turbine parts etc. Second one is the high temperature resistant designs, such as advanced SC (Single Crystal) and TBC (thermal barrier coating) application on turbine parts. Third one is advanced blade cooling technology such as transpiration cooling. The above 3 aspects should result into 30% reduction in the engine weight and into 50% reduction in the secondary air. As fourth aspects, development of intelligent complex control technology will achieve 2.5% SFC improvement[6].

As intermediate results, CMC vane, TMC(Titanium Matrix Composite) fan rotor and transpiration cooling research are presented.

5.1.1. CMC Vane

In applying CMC material to turbine vane, main technical subjects are how the silicon carbide fiber is woven along with complicated form of vane shape and how the thermal stress of the joint parts due to differences of thermal expansion between CMC material and metal parts should be minimized.

Fig. 4A shows the perform appearance of trial product, adopting the cloth ply overlap structure at the aerofoil root(Fig. 4B) to enable to form a continuous shape between the braided aerofoil and the cloth ply platform. CMC Vanes will be ready to be applied in the engine demonstration in 2003.

Fig.4A CMC vane-preform appearance

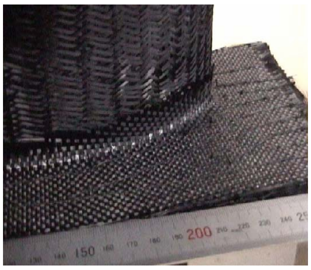


Fig. 4B CMC vane-cloth ply structure of aerofoil and platform Interface Portion

5.1.2. TMC Fan Rotor

Continuous fiber rein-forced TMCs are attractive as high potential materials to reduce the weight of fan rotor ring, shown in Fig. 5A. As a cost-effective process, monotape preform producing technique has been proposed and developed. Woven-fabric (continuous SiC fibers interwoven with Titanium ribbon) sandwiched by two matrix foils were moved into the hot press die in the vacuum chamber, then they were hot pressed until the opposite surface of matrix foils were diffusion-bonded. Repeating this route continuously, monotape preforms with 2-10 m in length were made. TMC ring specimens for burst spin test with a dimension of 130-114mm in diameter and 26mm in width MMC was manufactured, with the use of monotape perform as shown in Fig. 5B. The cost of TMC ring specimens could be reduced by 60%, compared with conventional methods. To evaluate the mechanical properties of TMC ring specimens, test equipment of burst spin test were developed. This equipment was designed to rupture the TMCs which has high rotation number in burst failure. Burst spin test is now ongoing .

Monotape producing unit of actual scale model were developed. This equipment was designed to manufacture the monotape preform with dimension of 160mm in width. Adjustment of the monotape producing unit and further development is now being conducted.

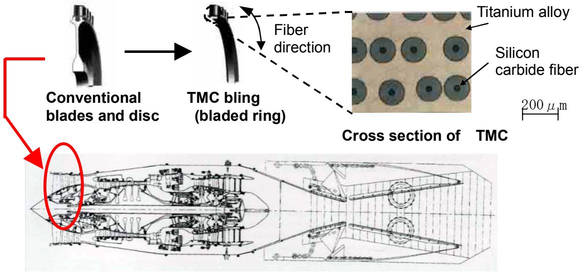


Fig. 5A TMC fan rotor application schematics

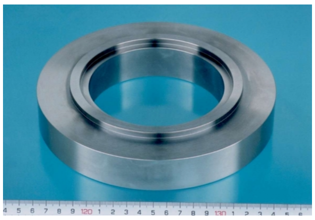


Fig. 5B TMC ring specimen for burst spin test

5.1.3. Transpiration Cooling

By applying the transpiration cooling structure (see fig. 6A) drastic improvement in a cooling performance is aimed at by multilayering the single crystal material which has enough strength and durability.

Several cooling configurations are being studied and cooling effectiveness of these configurations are evaluated by CFD. Sample of core structure for single crystal casting is shown in Fig. 6B.

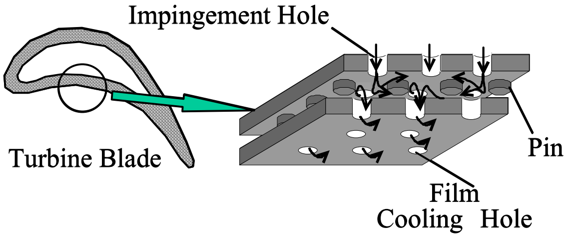


Fig.6A Structure of Transpiration Cooling

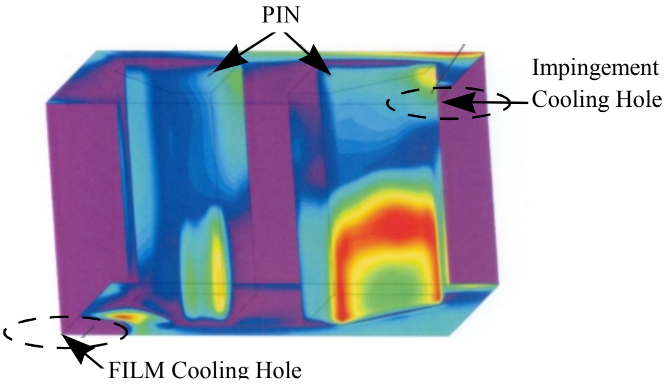


Fig. 6B Heat Transfer Analysis Result

Cooling performance was confirmed by the wind tunnel test, using test piece, and high cycle vibration test will be also carried out to acquire high cycle fatigue data.

5.2. NOx reduction

Ultra-low NOx lean premixed pre-vaporized (LPP) combustor technology is the major feature to achieve E.I.=5 g/kg-fuel at Mach 2.2 cruise. Mixing of fuel and air, prevention of flash back, auto-ignition and combustion oscillation are technical issues. Moreover, it is required for drastic reduction of air used for cooling of outer/inner combustion liners in order to realize lean fuel-air mixture.

5.2.1. LPP Combustor Research

In ESPR project, a combustor for the substantial NOx reduction is now being deceloped. An LPP burner are applied to an axially staged double-annular combustor [7] and CMC (Ceramics Matrix Composite) material, which has the advantage of heat durability over conventional metal, is used for the liner walls. (Fig.7A)

So far, series of combustion tests have been performed with the unit shown in Fig. 7B. The result shows that 10 E.I.NOx is currently promising (Fig.7C) and it corresponds to two-seventh of NOx emission level that a conventional combustion technology can achieve. Further modifications of the burners are planned to achieve the goal.

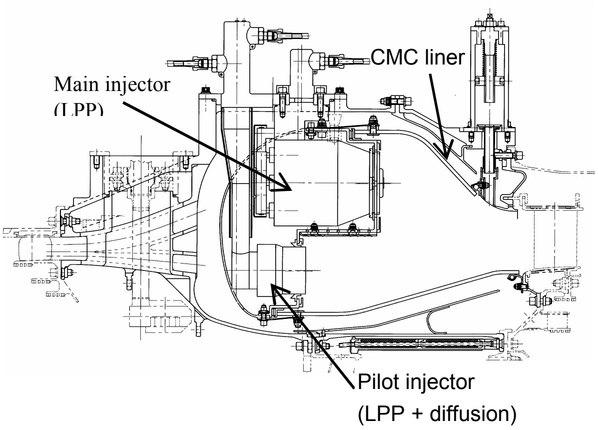


Fig. 7A Axially staged double annular combustor

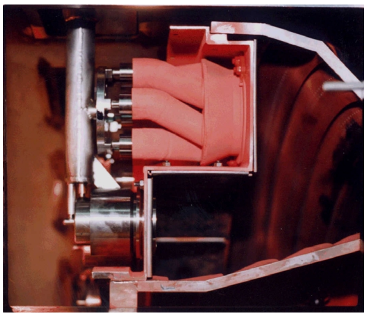


Fig.7B LPP combustor test unit

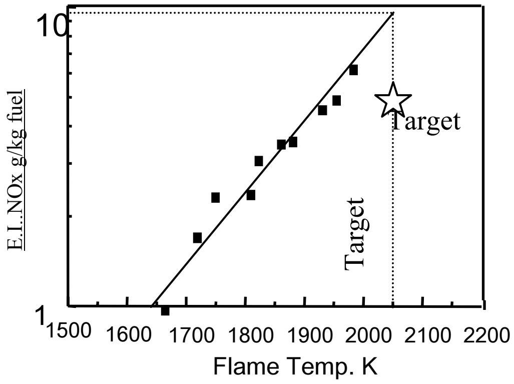


Fig. 7C NOx emission test results

5.2.2. CMC Liner

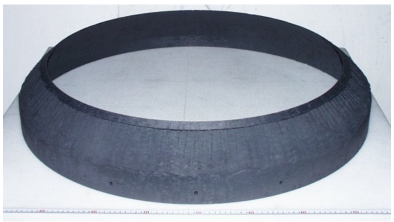
As a part of low NOx combustor research, in order to minimize liner cooling air, application of CMC to combustion liners is being investigated.

The followings are the major technical issues.

- Manufacturing technology for large size CMC parts.
- Mounting system for CMC liner

Through the trial fabrication, practical problems of shape accuracy, texture uniformity, and etc. have been improved. The first trial CMC liners in actual size are shown in the photos below.

Liner mounting systems have been designed and an applicable one was actually employed to fix the CMC liner to the combustion test rig. Combustion tests are scheduled to examine the mount system for its validity.



(a) Outer Liner

(b) Inner Liner

Fig. 8 CMC combustor liner

LPP combustor and CMC liner design will be demonstrated on the engine at the final part of the program to confirm design integrity.

5.2.3. NOx Feed-back AI Control System

NOx emission can be reduced more effectively even in aircraft engines in which the combustor works in very wide range condition if local equivalence ratio in the combustor can be controlled according to diagnoses of combustion condition (flame temperature, emission or pressure etc.). AI combustion control system has been developed, in which the air flow distribution in combustor is controlled according to measured NOx emission in order to achieve stable and low NOx combustion. Also, the device to control the air flow distribution in the high temperature condition such as in combustors is another technical topic, in order to apply this system to actual engines. Fluidic valves are appropriate rather than pure mechanical valve, in such conditions. The fluidic flow control is being studied by other party in this program.

The model combustor rig shown as in Fig.9 has been constructed. The test result shown as in Fig.9 successfully proves that NOx emission can be reduced by the control of equivalence ratio in primary combustion zone. Demonstration of feedback control by measured emissions is planned in future.

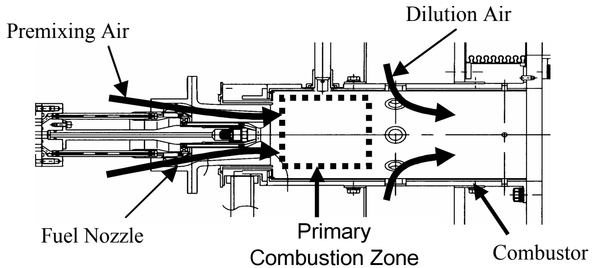
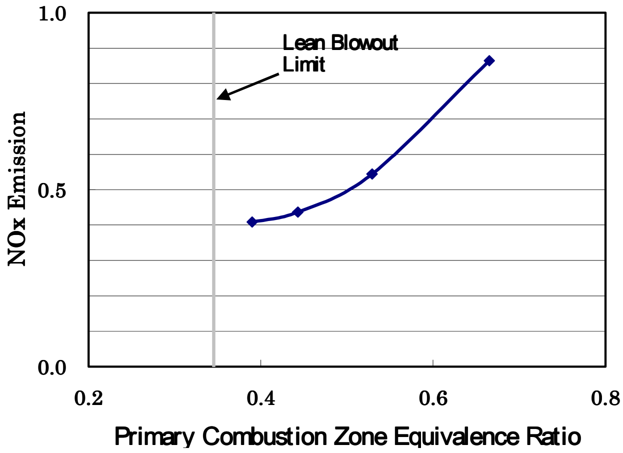


Fig. 9 AI control combustor rig and test results



5.3. Noise reduction

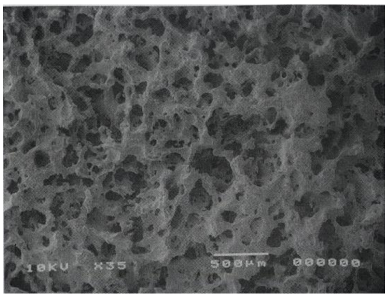
In order to achieve ESPR target, viz. ICAO Chapter 3-3dB, advanced porous material, Active noise control and advanced Low noise aerodynamics have been applied.

As for Jet Noise, supersonic transport aircraft requires high jet velocity to cruise at Mach 2.2, and this will result in high jet velocity also at take-off condition. It is as high as 900m/s for Concorde, and this will generate comparably large jet noise as fighter aircrafts. To reduce the noise around airports to that due to subsonic transport aircraft, researches on mixer-ejector and acoustic liner have been performed.

Understandings of correlation of a mixing flow with mixer and the noise characteristic and application and verification of CFD to the 3 dimensionally complicated flow are technical issues.

5.3.1. Porous Material Noise Absorber

As for Mixer-ejector, it will enable to reduce the jet velocity as low as 400m/s to achieve low enough noise level at minimum loss by introducing and mixing the ambient air into the jet flow, utilizing the effect of the stream-wise vortices. The extra noise generated by the mixing inside the mixer-ejector will then absorbed by acoustic liner placed on the inner wall of the ejector. The liner needs broad band-width of acoustic absorption frequency, and heat resisting property. The acoustic liner and its acoustic characteristics are shown in Fig. 10.



Porous Liner structure
(BMAS, Porosity 80%, ave.pore size 100 μ m)
BMAS : BaO-MgO-AL^{2}O^3-SiO^2

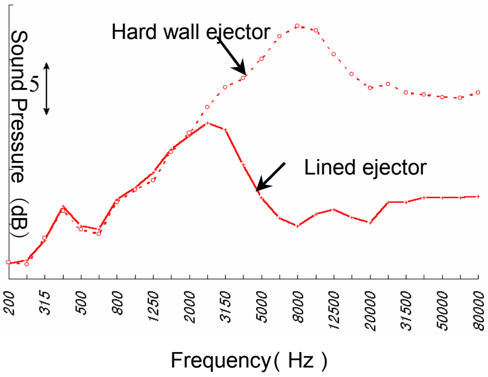
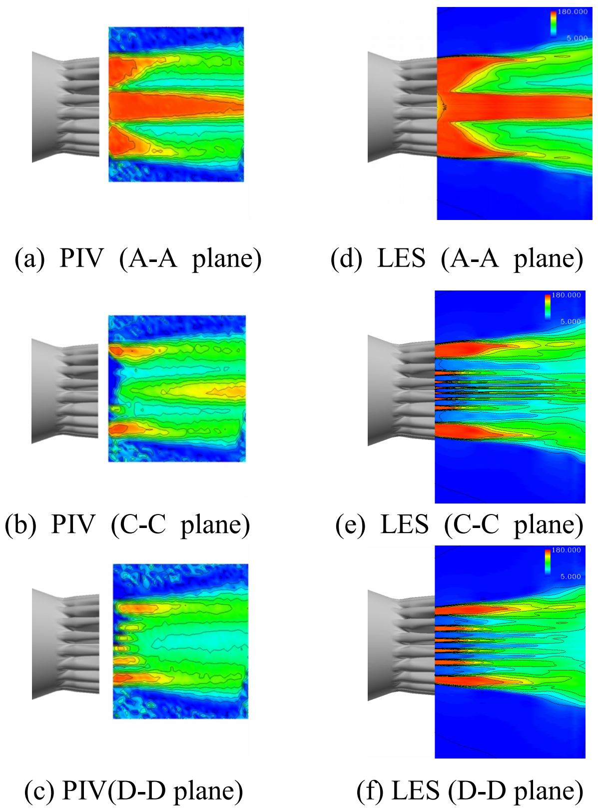


Fig. 10 Porous liner material and noise absorption effects

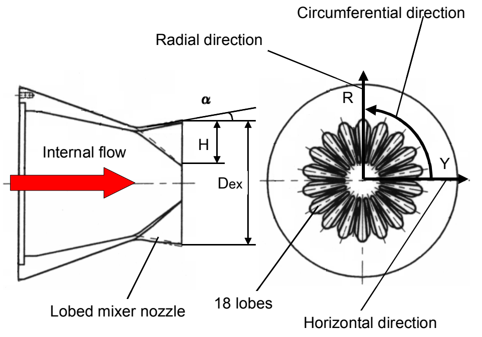
5.3.2. CFD Application to Jet Noise Reduction

As described above, larger reduction of the jet velocity tends to result in larger loss, and therefore the design optimization with the reasonable mixing loss is one of the important technologies for supersonic transport. The detailed mechanisms of mixing by stream-wise vortices and noise generation inside the mixer-ejector have been studied using a advanced CFD technology called LES (Large Eddy Simulation). The understanding of the complex flow field downstream the mixer nozzle will enable the design optimization of the low noise nozzle. The LES simulation results in Fig. 11 show reasonable match to the data measured by PIV (Particle Image Velocimetry) technique. The method to adapt the LES analysis to the nozzle design is going to be established.


(a) PIV (A-A plane) (d) LES (A-A plane)

(b) PIV (C-C plane) (e) LES (C-C plane)

(c) PIV(D-D plane) (f) LES (D-D plane)



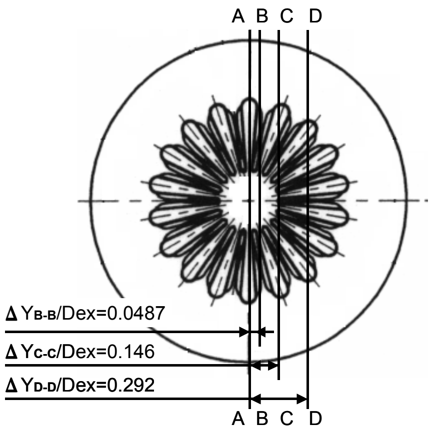


Fig. 11 CFD/LES vs PIV measurement results

So far, the prospect of achievement of Chap. 3-1.5dB has been obtained by the model test incorporating mixer ejector and the sound absorption liner. The modification will be continued to achieve further noise reduction.

The mixer-ejector type exhaust nozzle including acoustic ceramic liner features will be tested at outdoor stand of UTC to assess the overall performance of jet noise suppression system.

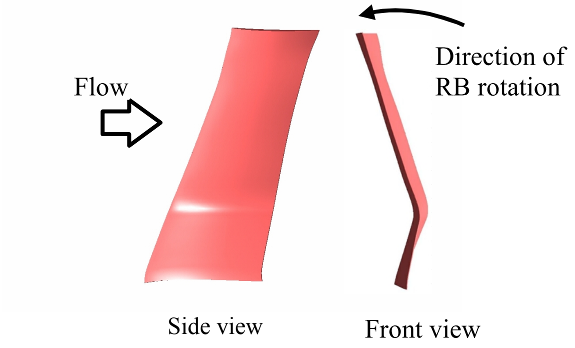
5.3.3 Fan Noise Reduction

The source of the fan noise is the aerodynamic interactions of rotors and stators. In order to reduce the interaction phenomena, leaned/swept FEGV concept are adopted as shown in Fig. 12. Latest CFD technologies are also applied to simulate and confirm such interaction noise.

The unsteady pressures on the stator vanes surface are simulated by CFD, as shown in Fig. 12. The effect of swept and lean of the stator vanes are under study to optimize the fan noise and performance.

On the other hand , the above analysis result was verified by means of model noise test. At present, noise reduction of 1.5dB from ICAO Chap. 3 level has been realized without any reduction of the aerodynamic performance.

This means the intermediate goal of the ESPR project has been achieved. The remaining 1.5dB reduction is set as a goal for the next 2 years of the project, based on the knowledge acquired by the above analyses and rig tests.



Aerofoil shape of swept/leaned SV

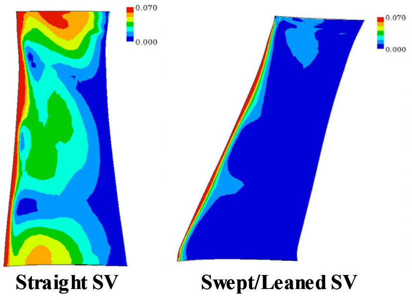


Fig. 12 Low noise swept/leaned stator vane

Unsteady pressure distributions

6. Future Program

In the next 2 years, final goals/targets should be achieved by various rig tests, analyses, and especially engine tests describing below.

6.1. Engine Validation Test

Engine validation test will be carried out to demonstrate the viability of each research. HTCE (High Temperature Core Engine) and Turbo engine which were developed in HYPR project will be used as technology demonstrator engines. The concerned parts which will be assembled into the engine and tested are shown in fig.13 for HTCE and fig.14 for Turbo Engine.

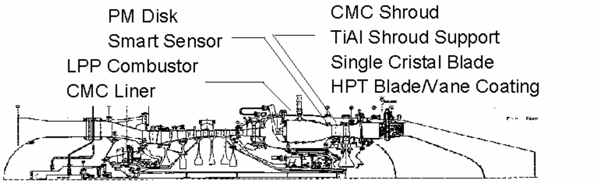


Fig. 13 Parts assembled into HTCE

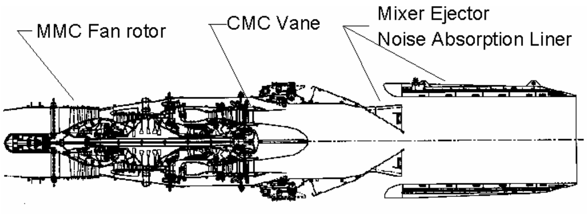


Fig. 14 Parts assembled into Turbo Engine

Generally, high temperature hardware will be validated on HTCE as shown in Fig.18. Not only concerned parts but also neighboring/affected parts will be tested at the same time to confirm whether they have enough design soundness. Test will be carried out in 2002 and 2003.

On the other hand, Turbo engine will be used mainly for noise test in UTC. After noise test is completed, MMC fan rotor and CMC vane will be validated on Turbo engine in Japan in 2003, too.

Acknowledgment

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