Conceptual Study of Separated Core Ultrahigh Bypass Engine

Y. Saito,* N. Sugiyama,† M. Endoh,‡ and Y. Matsuda§
National Aerospace Laboratory, Chofu, Tokyo, Japan

A new concept of ultrahigh bypass turbofan engine is studied and presented. The concept engine, which is composed of a separated high-pressure ratio core engine subunit and a geared fan engine subunit, has many potential merits compared with those ultrahigh bypass engines which are under development. In this article, configuration of the new concept engine, basic performance (design-point characteristics), merits and demerits, as well as an application to an advanced VTOL transport aircraft will be described.

Nomenclature

A = frontal area of nacelle
C_d = nacelle drag coefficient
C_{pl} = pressure loss coefficient of bleed air duct
F = net thrust
F_c = core net thrust
F_d = drag of nacelle
F_f = fan net thrust
F_{sp} = specific thrust
G_b = bleed airflow rate
G_c = core inlet airflow rate
G_{cool} = turbine cooling airflow rate
G_f = fan airflow rate
G_t = turbine gas flow rate
P_3 = bleed air duct inlet pressure
T_c = turbine cooling air temperature
T_g = turbine inlet gas temperature
T_m = turbine metal temperature
T_{4c} = core turbine inlet temperature
T_{4f} = fan turbine inlet temperature
V = flight velocity
W_c = core fuel flow rate
W_f = fan fuel flow rate
ΔP_3 = pressure loss in bleed air duct
η_b = combustion efficiency
η_c = polytropic efficiency of compressor
η_{cool} = cooling efficiency of air cooled turbine
η_f = polytropic efficiency of fan
η_n = nozzle efficiency
η_t = polytropic efficiency of turbine
μ_b = bleed air ratio
μ_{cool} = cooling air ratio
μ_f = fan bypass ratio
π_f = fan pressure ratio
π_{ov} = cycle pressure ratio
ρ = environmental air density
$*$ = corrected value

I. Introduction

MANY concepts of ultrahigh bypass turbofan engine have been proposed and some are under development for the powerplant of high subsonic transport aircraft in the U.S.

or in European countries. These engines have the bypass ratio of about 15–20 and are expected for their capability of fuel saving and noise reduction.

The authors have studied the basic performance and configurations of ultrahigh bypass turbofan engine and found that a new concept engine, which we call "separated core ultrahigh bypass (SCUHB) engine," has various potential advantages over currently proposed engines.

SCUHB engine will also give technical solutions for developing ultrahigh bypass turbofan engines, such as the reverse pitch problem, and will have many applications, including an advanced VTOL transport aircraft.

II. Concept of SCUHB Engine

A. Basic Configuration

SCUHB engine is effective for the large engine with very high bypass ratio and very high cycle pressure ratio. The basic configuration of the engine is composed of two subunits, a core engine and a fan engine, as shown in Fig. 1, and these two subunits are located separately from each other and connected with a high-pressure air duct. A similar concept of the SCUHB engine, remote fan, was studied once by NASA and GE and manufactured for VTOL research aircrafts.[1]

The core engine is composed of a compressor, combustor, and a turbine, similar to a conventional turbojet engine. The core engine supplies high-pressure air, bled from the exit of the high-pressure compressor, to the fan engine through the bleed air duct. The core turbine and the core combustor are smaller in diameter and in volume compared with those of conventional turbofan engines due to the high bleed air ratio.

The fan engine, which is composed of a turbine, combustor, and a fan with reduction gear, is supplied high-pressure air
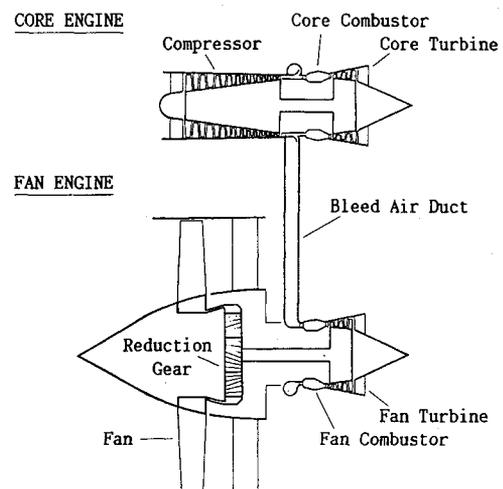

Fig. 1 Schematic concept of SCUHB engine.

from the core engine and produces the major part of thrust in the whole engine system. Due to the high pressure and low volume flow rate of the supplied air, the fan turbine becomes smaller in diameter and operates with very high rotational speeds compared with the power turbines of conventional turbofan engines. Therefore, reduction gear is needed to drive much larger diameter fan.

The sectional area of the bleed air duct, connecting the core engine with the fan engine, is very small relative to that of the fan, even if the flow speed through the duct is made low enough to keep pressure loss to an acceptable level. (This is because the pressure of supplied air is very high.) If the bleed air duct is a simple duct, this engine will be operated like conventional-type engines, but this engine is given higher controllability than other type engines when some flow control device is attached to the bleed air duct.

B. Engine System

The concept of SCUHB engine gives high flexibility to the formation of an engine system, because the whole engines can be operated like a single engine, even if the number of the core engines is different from that of the fan engines. However, if one fan engine is connected with more than two core engines, it is difficult to avoid the interaction among core engines.

Practical engine systems will be as follows:

1) The basic system (Fig. 2a)—one core engine connected with one fan engine.

2) The multifan system (Fig. 2b)—each core engine is connected with more than two fan engines. In this system, it is possible to employ a smaller number of core engines with larger diameter and higher efficiency.

3) The system with a spare core engine (Figs. 2c and 2d)— a spare core engine is added to the system (1) or (2). When the same core engine as other operating core engines is used

for spare, the performance of the total engine system can be kept in a normal operating condition even if one of the core engines fails. A simpler or derated core engine can be employed for the spare core engine for reducing the weight penalty with sufficient safety.

4) The most complicated system with more than two types of fan engines (Fig. 2e)—this concept is especially effective for the VTOL engine system.

III. Features of SCUHB Engine

This engine has merits in many respects, including reliability of operation, flexibility of control, possibility for higher performance aerodynamic design, easier maintenance, lower development and improvement costs, wide variety of application, etc.

A. Reliability of Operation

One of the excellent features of this concept is the reliability of operation.

In the case of conventional-type engines, it is predicted that to keep stable operation when the fan is operating under adverse conditions (such as reverse thrust operation with variable pitch fan) will be very difficult. This is because the core engine is located behind the fan, and the core inlet flow is strongly disturbed or interrupted by the fan operating under off-design condition. But in the case of the separated core type engine, it is easy to keep the core engine in normal operating condition due to the following reasons:

1) The core engine can operate independently from the fan engine.

2) The core engine is not necessarily located in series with the fan engine, and the core inlet can be located where the flow is not influenced by the fan.

3) As the core inlet is relatively small, devices can be easily attached to remove the inlet distortion or to separate foreign objects in the flow.

The fan engine also shows a highly reliable operation, since the high-pressure air to drive the turbine is stable and sufficiently supplied from the separated core engine.

B. Flexibility of Thrust Control

Another excellent feature of this engine is higher flexibility of thrust control.

In the case of conventional engines, the cycle pressure ratio, the turbine inlet temperature, and the engine thrust cannot be changed independently. On the other hand, the separated core type engine has two combustors: 1) the core combustor and 2) the fan combustor, and overall pressure ratio is controlled by the fuel flow rate of the core combustor, while the fan turbine inlet temperature is controlled by the fuel flow rate of the core engine and that of each fan combustor. This feature increases the flexibility of the engine control as follows:

1) The thrust can be varied while the core engine is operated under constant condition. Theoretically, the fan can be stopped while the core engine is operating, if any flow control device is attached to the bleed air duct.

2) The overall pressure ratio can be varied keeping the engine thrust constant. Therefore, the optimum overall pressure ratio can be chosen under the various operating conditions.

3) Fan engine can be accelerated or decelerated very quickly by controlling the fan combustor fuel flow, since the core engine can be kept in the steady-state operating condition free from the surge. It is impossible to control conventional engines in such a way.

To fully exploit these features, some airflow control device must be added to the bleed air duct, adding some complexity to the engine system.

C. Simple and Light Structure

This engine has the high possibility of weight reduction and structural simplification compared with conventional engines.
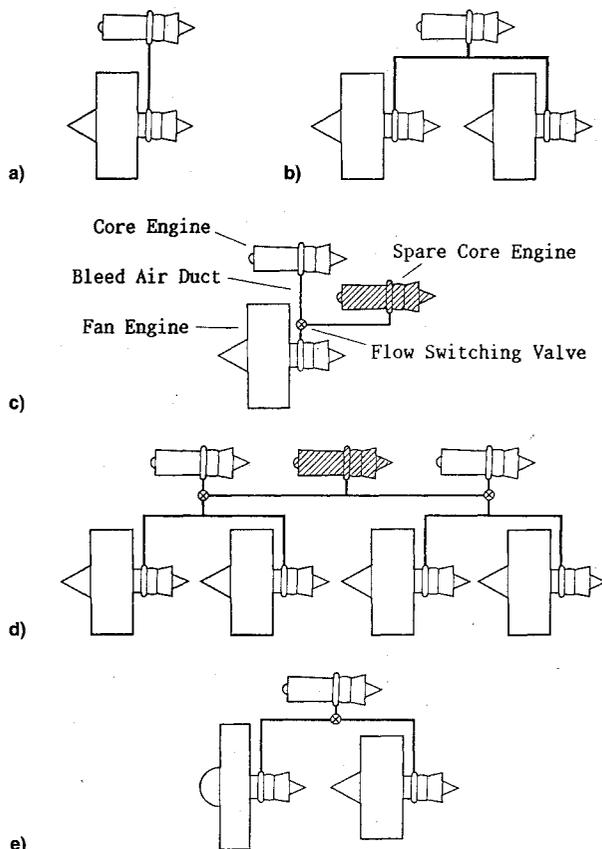

Fig. 2 Practical engine systems are the a) basic system, b) multifan system, c) single-fan system with spare core engine, d) multifan system with spare core engine, and e) multimode system.

In this concept, each subunit of the engine system is simplified in structure, since the core engine and the fan engine are completely separated.

1) The compressor and the turbine of the core engine can be designed to rotate with higher speeds compared with that of conventional engines. This enables the compressor and the turbine to reduce the diameter and number of stages.

2) The fan diameter becomes smaller, because no part of the fan works as the boost stages of the compressor.

3) The casings and the rotational shafts become shorter.

The above features will make it possible to reduce the overall length, diameter, and weight. This engine system has larger number of turbines than the conventional-type engines. However, it will be possible to reduce the total weight and volume of the turbines, because the number of the turbine stages is not increased owing to its high rotational speed.

D. Merits in Aerodynamic Design

Generally, one of the important requirements for engine aerodynamic design is to insure reliable operation under the off-design condition. In this concept 1) it is easy to keep the core inlet flow in good condition; 2) it is not required for core engine, especially for compressor, to work at off-design points for the normal operation within the flight envelope, because the operating point of core engine changes less than that of conventional engines when the fan operating point is changed; 3) less restrictions exist to decide rotational speed of compressor and turbine; and 4) the fan can be designed without considering influences on core engine.

Therefore, the engines based on this concept can possibly be designed to provide for higher performance and efficiency.

E. Development and Improvement

This engine is easier to develop or to improve compared with conventional-type engines, and has great capability of saving costs and time and lowering the risk in development or in improvement, since the mechanical design of the core engine and the fan engine are free from each other. Some engine tests for type certification can be eliminated.

F. Maintenance

This engine has the capability for much easier maintenance, since the core engine and fan engine are relatively small, light, and simple in structure, and can be separately attached to or detached from airframe, assembled or overhauled.
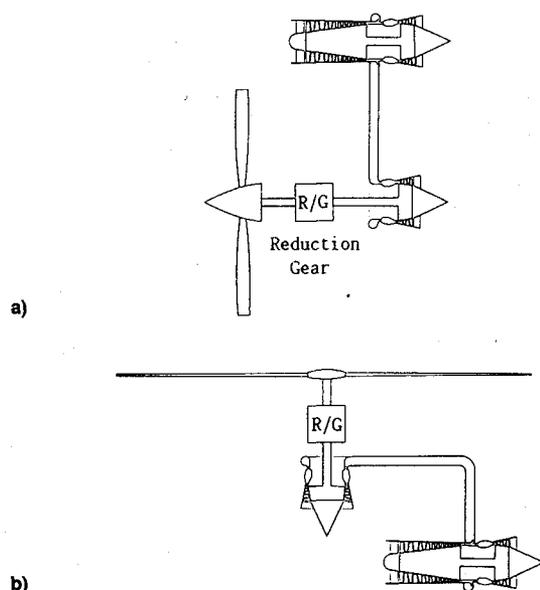

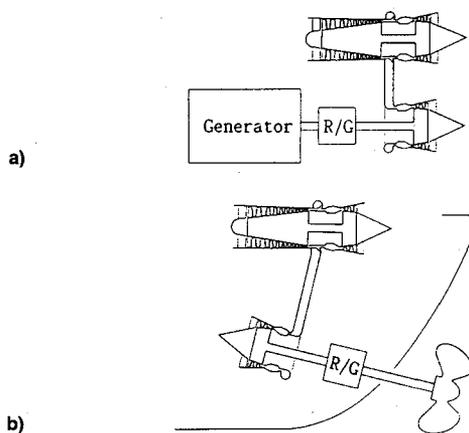Fig. 3 Application of the SCUHB engine to a) turboprop engine and b) turboshaft engine.

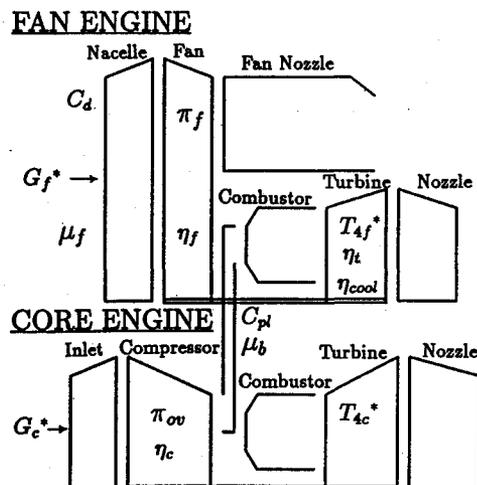Fig. 4 Application of the SCUHB engine to an a) industrial engine and b) marine engine.

Fig. 5 Schematic diagram of SCUHB engine.

G. Applications

The SCUHB engine can be applied to many other uses with small modification. Applications of this concept to aircraft engines are shown in Fig. 3. The original core engine and power turbine can be used with few changes. Though this concept is proposed for the ultrahigh bypass ratio engine, there exists no problem to apply this concept to turboprop engines and turboshaft helicopter engines because these engines have higher bypass ratio than the ultrahigh bypass turbofan engines. Employing this concept, the power system of helicopters can be made simpler and lighter than traditional systems.

Applications to other uses like industrial engines and marine engines are shown in Fig. 4. The power turbine is relatively small and can be located in an adequate place separately from the core engine. The core engine can be used as a high-pressure air supply without any modification.

IV. Basic Performance

Figure 5 shows the configuration of basic-type SCUHB engine in Fig. 2a, along with parameters necessary for the computation of basic performance. The core engine has almost the same configuration with a conventional turbojet engine and supplies a large amount of high-pressure air to the fan engine. The fan engine consists of a combustor, a turbine, nozzles, and a big fan with reduction gear.

Major parameters to define SCUHB engine performance are listed in Table 1. The first three parameters (π_{ov}), (T^*_{4c}), and (μ_b) are related to the core engine and next three parameters (π_f), (T^*_{4f}), and (μ_f) to the fan engine. Two flight conditions, sea level static and cruise condition, are also listed in Table 1. If these six parameters and flight conditions are

Table 1 Major parameters defining SCUHB engine performance and definition of performance

Parameters

π_{ov}	Cycle pressure ratio
T_{4c}^*	Core turbine inlet corrected temperature
μ_b	Bleed air ratio

$$\mu_b = \frac{G_b}{G_c} = \frac{\text{(bleed airflow)}}{\text{(core inlet airflow)}}$$

π_f	Fan pressure ratio
T_{4f}^*	Fan turbine inlet corrected temperature
μ_f	Fan bypass ratio

$$\mu_f = \frac{G_f}{G_c} = \frac{\text{(fan airflow)}}{\text{(core inlet airflow)}}$$

Flight condition

Sea level static:
  Altitude = 0 [m], flight Mach = 0
Cruise:
  Altitude = 10,668 [m], flight Mach = 0.8

Definition of performance

F	Net thrust

$$F = F_c + F_f$$
$$= \text{(core net thrust)} + \text{(fan net thrust)}$$

F_{sp}	Specific thrust

$$F_{sp} = \frac{F}{G_c + G_f}$$
$$= \frac{\text{(net thrust)}}{\text{(core inlet airflow)} + \text{(fan airflow)}}$$

SFC	Specific fuel consumption

$$\text{SFC} = \frac{W_c + W_f}{F}$$
$$= \frac{\text{(core fuel flow)} + \text{(fan fuel flow)}}{\text{(net thrust)}}$$

Table 2 Engine component assumption

Engine component assumption

$\eta_c = 0.9$	Polytropic efficiency of compressor
$\eta_f = 0.9$	Polytropic efficiency of fan
$\eta_t = 0.9$	Polytropic efficiency of turbine
$\eta_n = 0.98$	Nozzle efficiency
$\eta_b = 0.98$	Combustion efficiency
$C_d = 0.03$	Nacelle drag coefficient
$C_{pl} = 0.02$	Pressure loss coefficient of bleed air duct
η_{cool}	Turbine cooling efficiency as a function of cooling air ratio

$$\eta_{cool} = \tanh\left(\frac{\mu_{cool}}{\mu_{cool_d}} \tanh^{-1}\eta_{cool_d}\right)$$
$$= \tanh(14.722\mu_{cool})$$

where, $\eta_{cool_d} = 0.9$, $\mu_{cool_d} = 0.1$,

Definition of parameter

C_d	Nacelle drag coefficient

$$C_d = \frac{F_d}{\frac{1}{2}\rho V^2 A}$$
$$= \frac{\text{(nacelle drag)}}{\text{(dynamic pressure)(frontal area)}}$$

C_{pl}	Pressure loss coefficient of bleed air duct

$$C_{pl} = \frac{\Delta P_3}{P_3} = \frac{\text{(pressure loss in duct)}}{\text{(duct inlet pressure)}}$$

η_{cool}	Turbine cooling efficiency

$$\eta_{cool} = \frac{T_g - T_m}{T_g - T_c}$$
$$= \frac{\text{(gas temperature)} - \text{(metal temperature)}}{\text{(gas temperature)} - \text{(cooling air temperature)}}$$

μ_{cool}	Cooling air ratio

$$\mu_{cool} = \frac{G_{cool}}{G_t + G_{cool}}$$
$$= \frac{\text{(cooling airflow)}}{\text{(turbine gas flow)} + \text{(cooling airflow)}}$$

specified, engine cycle of this engine is defined and overall performance can be obtained. Definitions of overall performance are included in Table 1.

Component performance assumptions, on which cycle analysis of SCUHB engine are performed, are listed in Table 2. Values in the table are assumed considering current component technology level. Nacelle drag coefficient, $C_d = 0.03$, corresponds to approximately 7% thrust reduction at cruise condition. The effect of turbine cooling air is included in the analysis. Cooling efficiency (η_{cool}) is given as a function of cooling air ratio (μ_{cool}), as shown in Table 2. When (μ_{cool}) = 0, 0.05, and 0.1, (η_{cool}) = 0, 0.627, and 0.9, respectively. This is considered to be reasonable.

A. Core Engine Bleed Limit

A large amount of air must be bled from the core engine, but is limited to sustain core engine operation. Figure 6 shows bleed air limits as a function of core engine cycle pressure ratio (π_{ov}) and turbine inlet temperature (T_{4c}^*), at sea level static (solid line) and a cruise condition (dotted line). For example, 35–45% air bleed is possible for (π_{ov}) = 35 and (T_{4c}^*) = 1500–1700 K.

B. Core Engine Performance

To investigate the effect of core engine parameters to overall performance, specific fuel consumption (SFC) at sea level and cruise condition are computed for various combinations of (π_{ov}), (T_{4c}^*), (π_f), and (T_{4f}^*). Bleed air ratio (μ_b) is set to the maximum allowable value defined by Fig. 6, and the fan bypass ratio (μ_f) is set to the value at which (SFC) is minimized. Figure 7 shows an example of core engine parameter effect to (SFC) for a fan engine with (π_f) = 1.3 and (T_{4f}^*) =
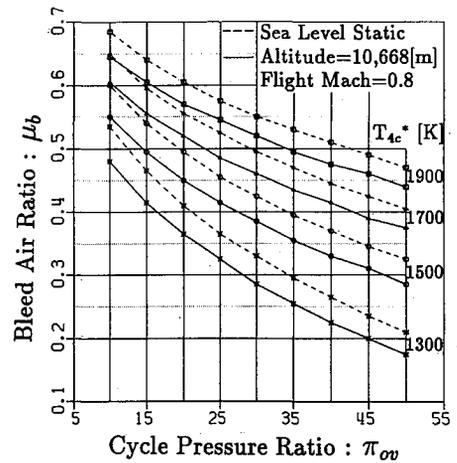
Fig. 6 Core engine bleed limit.

1700 K. It should be noted that (μ_f) is not the same value along the line, ranging 10–20.

C. Fan Engine Performance

Figure 8 shows an example of fan engine parameter effect to (SFC) for a core engine with (π_c) = 35 and (T_{4c}^*) = 1700 K. (SFC) has the optimum point at around (π_f) ~ 1.3. This value is tightly related to flight Mach number and nacelle drag coefficient.

An effect of bleed air duct pressure loss is computed for a typical SCUHB engine with parameters shown in Table 3.
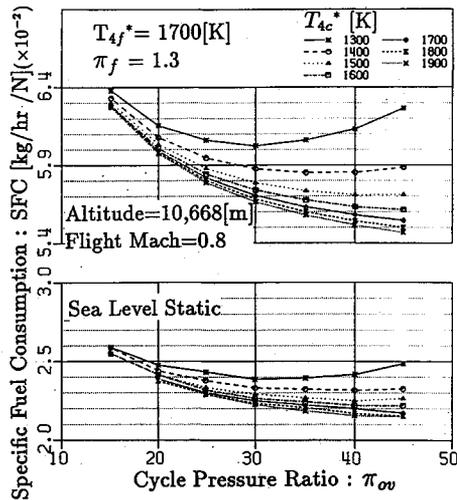
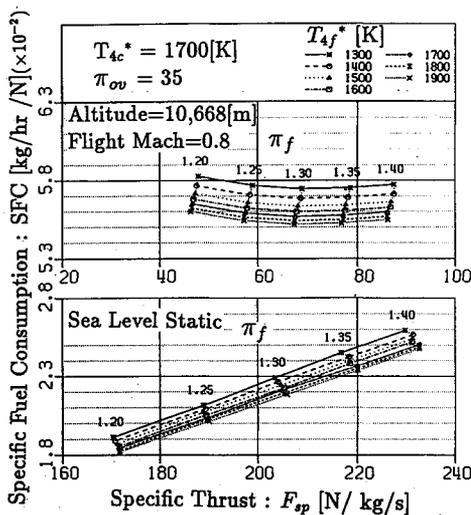Fig. 7 Effect of core engine parameters to overall performance.

Fig. 8 Effect of fan engine parameters to overall performance.

Table 3 Result of design-point performance

	Performance	
	(Cruise)	(Sea level)
SFC	0.0565	0.0223 kg/h/N
F	19.6	151.9 kN
G_c	15.5	40.66 kg/s
G_f	263.5	691.2 kg/s

	Parameters		
π_{ov}	35	π_f	1.3
T_{4c}^*	1680 K	T_{4f}^*	1680 K
μ_b	0.415	μ_f	17.0

	Inlet area
Core	0.226 m²
Fan	3.837 m²

For C_{pl} = 0, 0.02, and 0.1 or 0, 2, and 10% total pressure loss, (SFC) is 0.0564, 0.0565, and 0.0572 kg/h/N at cruise condition, and 0.0222, 0.0223, and 0.0226 kg/h/N at sea level, respectively.

D. Design Point Performance

A promising basic type SCUHB engine with 19.6 kN (2 ton) cruise thrust is summarized as shown in Table 3. Sea level static thrust is 151.9 kN (15.5 ton) and bypass ratio (μ_f) becomes 17. (SFC) is 0.0565 kg/h/N (0.5537 1/h) at cruise and 0.0223 kg/h/N (0.2185 1/h) at sea level static. Good (SFC) is due to very high bypass ratio. 41.5% of core-compressor de-

Table 4 Advanced VTOL engine specification

Core engine	
Length	2,168 mm
Maximum diameter	758 mm
Pressure ratio	35
Inlet airflow	15.5 kg/s (at 35,000 ft, Mach 0.8)
Bleed air ratio	41.5%
Cruise fan engine	
Fan diameter	2,200 mm
Fan pressure ratio	1.3
Thrust	2,000 kg (19,600 N) (at 35,000 ft, Mach 0.8)
Lift fan engine	
Fan diameter	2,400 mm
Fan pressure ratio	1.12
Thrust	10,000 kg (98,000 N) (at sea level)

livery air is fed to a fan-combustor through a bleed air duct with diameter of 84 mm and 2% total pressure loss.

V. Application to an Advanced VTOL Transport Aircraft

The concept of SCUHB engine can most effectively be applied to an advanced VTOL transport aircraft. New engine system, which has been under conceptual study, is shown in Fig. 9. This engine system is composed of three core engines, two cruise fan engines, and six lift engines. Core engines and cruise fan engines have specifications shown in Table 3. Each core engine supplies bleed air to each pair of lift fan engines for vertical flight or for low-speed flight, and to a cruise fan engine for high-speed flight.

Features of SCUHB engine are most effectively used in this engine system. Reasons are as follows:

1) Engine system is light in weight since the same core engine is used in both vertical and transition flight mode and in high-speed cruise mode.

2) Thin lift fan engines enable the VTOL transport aircraft to provide for a highly optimized configuration for high-speed flight.

3) Lift forces are easily balanced without cross shafts connecting lift fan engines, since each pair of two lift fan engines which are connected to the same core engines can be positioned symmetrically over the c.g. of the aircraft.

4) In vertical flight mode, this engine system has higher capability for quiet and high efficiency operation compared with conventional-type lift fan engine system, since bypass ratio of this engine system is very high.

5) For lift fans, it is generally impossible to avoid strong inlet distortion. But these lift fan engines have very high reliability of operation under such condition.

Specifications of this engine system are shown in Table 4. The core engine is composed of a four-stage low-pressure compressor, an eight-stage high-pressure compressor, a two-stage high-pressure turbine, and single-stage low-pressure turbine, and supplies bleed air with pressure ratio of 35. This core engine is smaller and lighter compared with that of current conventional turbofan engines with the same output power.

The cruise fan engine is composed of a geared fan, a combustor, and four-stage turbine, and each cruise fan has about the same specifications optimized for high subsonic cruise as that of ultrahigh bypass engines which are being studied or developed in the U.S. or in Europe.

The lift fan engine has fan diameter of 2400 mm, pressure ratio of 1.12, and produces thrust of 98 kN, and can realize highly quiet operation. Fan pressure ratio is low enough to keep the jet noise in acceptable level. A large number of fan blades (200 and 100) makes fan noise frequency higher, therefore, fan noise is easily reduced and not propagated to far field. This is achieved by the single piece composite fan rotor with tip-shroud and with a midspan shroud. Such configura-
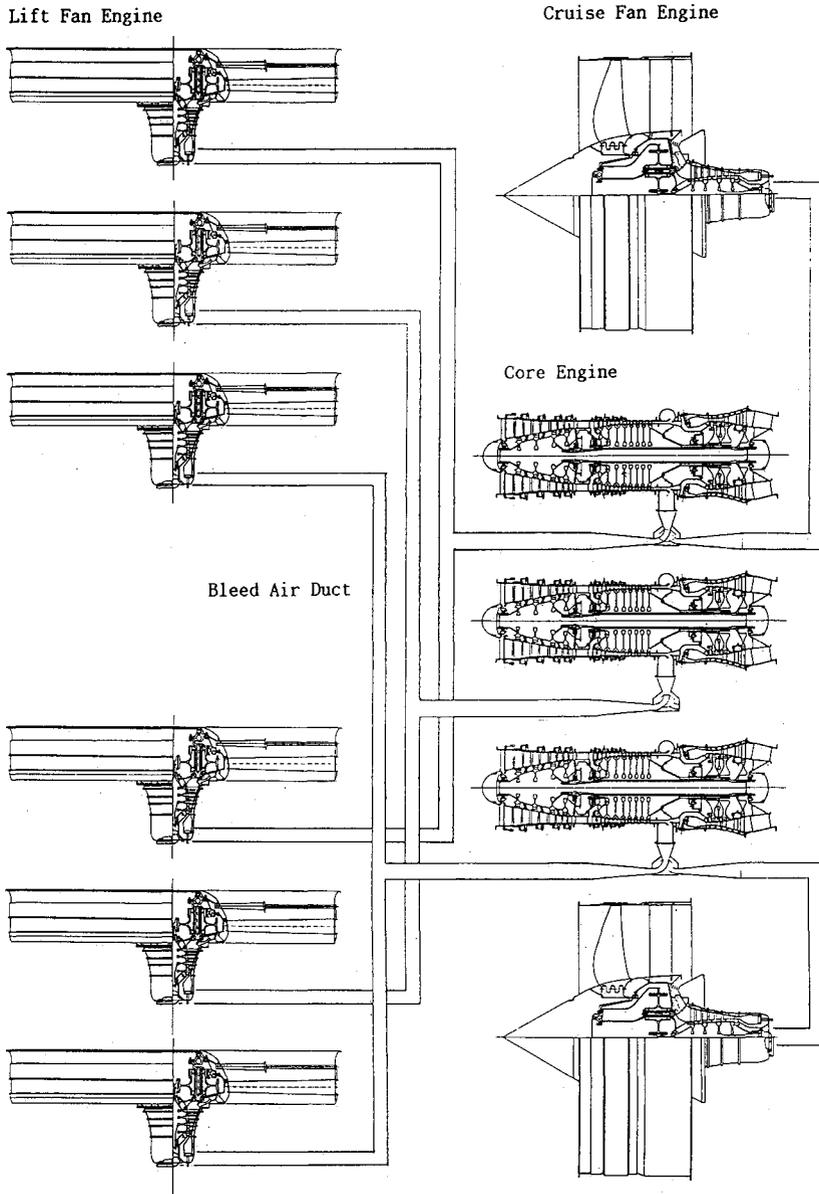
Lift Fan Engine

Cruise Fan Engine

Core Engine

Bleed Air Duct

Fig. 9   Engine system for advanced VTOL transport.

Fig. 10   Advanced VTOL transport.

Core Engine

Lift Fan Engine

Cruise Fan Engine

Bleed Air Duct
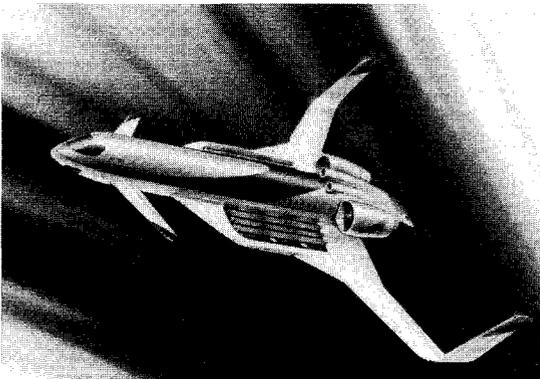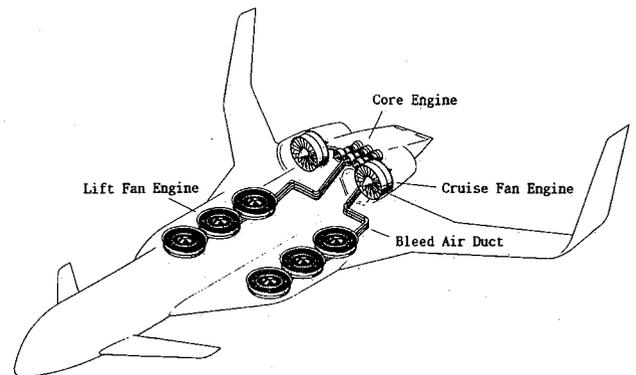
Fig. 11   Engine installation.

tion of the lift fan is also effective for the weight reduction and for the engine height reduction.

The lift fan engine has the reverse flow type combustor and turbine, like cruise fan engine, to reduce its total length and weight, and to make high-pressure air seal easy.

The bleed air ducts, connecting core engines with fan engines, are very small in diameter and pressure loss in ducts is kept very low due to high pressure.

Concept of the advanced VTOL transport aircraft with 100 passengers is shown in Fig. 10. Engine system is illustrated in Fig. 11. The aircraft flies at Mach 0.8 cruise speed, 10,000-m altitude and 25,000-km range. Estimated gross weight of the all composite airplane is about 40,000 kg, but lift fan engines produce 60,000 kg of thrust at design condition. Therefore, the aircraft has sufficient capability for normal vertical flight when one core engine or one of paired lift fan

engines failed. According to a theoretical calculation it is estimated that this transport is much quieter than conventional transports, or even small helicopters.

VI. Concluding Remarks

A new concept of the turbofan engine SCUHB engine is presented in this article. As the result of primary conceptual study, it is confirmed that this engine has many excellent features compared with other concepts of ultrahigh bypass turbofan engines. In this study, no technical problems have been found difficult to overcome for realizing this type engine. This concept will sucessfully be applied to various aircrafts and other vehicles including the advanced high-speed VTOL

transport aircraft. Research of this engine will be continued and the results will be described in other papers.

Reference
[1]Roelke, R. J., and Zigan, S., "Design Studies of Lift Fan Engines Suitable for Use in Civilian VTOL Aircraft," American Society for Mechanical Engineers Paper 72-GT-65, March 1972.