MULTI-POINT OPTIMIZATION STUDY OF HYDROGEN FUELED LOW BOOM SUPERSONIC TRANSPORT

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Keywords: ***Supersonic Transport, Hydrogen Fuel, Low-Boom, Multi-Point Optimization***

Abstract

Many projects have made efforts to realize commercial supersonic transports (SST). These trials have revealed many barriers for the successful completion of various necessary project goals, related to supersonic cruise efficiency, sonic boom annoyance, economical viability and also the development of solutions for avoiding environmental problems. The time to shift the fuel of an aircraft from kerosene to liquid hydrogen (LH_2) will come in the near future. The purpose of this study is to discuss the feasibility of a hydrogen fueled low boom SST (low boom LH_2-SST) designed to carry 50 passengers for a range of 3500 nm at a Mach 1.6 cruise speed by a method which considers the effects of hydrogen and incorporates the sonic boom minimization theory. Multi-point optimization was utilized and it was found that there is a trade-off relation between sonic boom minimization and weight in designing a low boom LH_2-SST. A kerosene fueled low boom SST (low boom Kerosene-SST) was designed by this method for comparison with the low boom LH_2-SST. As a result of this comparative discussion, it was confirmed that LH_2 fuel can reduce the take-off weight (W_{TO}) by 25 % because of its high heat level during combustion. Accordingly, the sonic boom intensity was reduced by 33%, from 0.67 to 0.44 psf.

Nomenclature

A_E	=	Equivalent area distribution
ΔA_E	=	Difference from target A_E
BFL	=	Balanced field length
C.G.	=	Center of gravity
C_L	=	Lift coefficient
DOC	=	Direct operating cost
L/D	=	lift to drag ratio
LFL	=	Landing field length
LH_2	=	Liquid hydrogen
SFC	=	Specific fuel consumption
SSBJ	=	Supersonic business jet
SSC	=	Second segment climb
SST	=	Supersonic transport
T/W	=	Thrust to weight ratio
W/S	=	Wing loading
W_E	=	Empty weight
W_F	=	Fuel weight
W_{TO}	=	Take-off weight
q	=	Dynamic pressure

1 Introduction

Concorde retired in 2003. Still, many projects have made efforts for the realization of a commercial SST since then. In Japan, the former National Aerospace Laboratory of Japan (NAL) which is now the Japan Aerospace Exploration Agency (JAXA) successfully launched a scaled supersonic experimental airplane in Australia in 2005 [1], and validated computational design methods as well as retrieving flight data. JAXA has been promoting the Silent Supersonic Technology Demonstrator (S^3TD) project [2] which puts emphasis on low sonic boom, noise reduction and the integration of the advanced demonstration system. Now, as part of it, they are planning a project known as Drop Test for Simplified Evaluation of Non-symmetrically Distributed sonic boom (D-SEND project) [3] in 2011.

Many projects including the studies of JAXA have indicated there are many barriers for the successful completion of various necessary project goals such as supersonic cruise efficiency, sonic boom annoyance, economical viability and also environmental problems. According to a report of ICAO in 2008 [4], CO_2 emissions from aircrafts to the total CO_2 emissions will increase at an average annual rate of 4.6 % between 2005 and 2025. Furthermore, a stable supply of oil is becoming difficult to maintain. Some projects have been carried out to analyze the feasibility of hydrogen fueled aircrafts. An idea using the LH_2/BWB Configuration SST was proposed by Horinouchi [5], JAXA. Of course, its environmental friendliness captures a lot of attention. One of the other notable advantages of this concept is a potential to reduce the weight of an aircraft due to the high heat of combustion of hydrogen.

Reference 6 discusses the comparisons of two concepts, a kerosene fueled SST (Kerosene-SST) and a LH_2 fueled SST (LH_2-SST) both of which were designed to carry 234 passengers for a range of 4200 nm, at a M2.7 cruise speed . This result indicates that the LH_2-SST could be nearly 50% lighter than the Kerosene-SST.

It is hypothesized that the sonic boom overpressure of less than 0.5 psf on the ground is considered as an environmentally acceptable value. It could be achieved by using the small-sized Kerosene-SST (Super Sonic Business Jet class, or SSBJ). This is because the sonic boom intensity is affected by the size of an aircraft, and especially by its weight. However, it is expected that a LH_2-SST could meet this sonic boom criterion of less than 0.5psf while carrying more passengers than the SSBJ class since LH_2 fuel can reduce the take-off weight.

The purpose of this study is to discuss the feasibility of a low boom LH_2-SST designed by the method which considers effects of hydrogen and incorporates the sonic boom minimization theory. Multi-point optimization is used to find trade-off relations. A low boom Kerosene-SST is designed by this method for comparison with the low boom LH_2-SST.

2 Some Features of LH_2-SST

2.1 Effects of Hydrogen on Aircraft Design

Table 1 lists the properties of hydrogen and the effects on aircraft design [6].

The combustion of hydrogen molecules will provide water vapor principally. It is usually thought to be clean. However, an investigation suggested that condensation trail made by the exhaustion of water vapor could contribute to global warming [7].

The lower molecular weight of hydrogen indicates leakage risk.

Hydrogen has the higher heat level of combustion than kerosene by a factor of 2.8. In other words, it lowers specific fuel consumption (SFC). Accordingly, the fuel weight required for a LH_2 fueled aircraft to fly a given mission would be only be 1/2.8 times as much as would be required by Kerosene fueled design, supposing that all other considerations remain equal.

The lower density of LH_2 requires a larger fuel tank. Furthermore, the cryogenic preservation of LH_2 requires constant tank pressure to minimize the boil-off (loss of vaporization). Therefore, the LH_2 tank would have a cylindrical form for a practical design (however, from the perspective of structural design, a spherical shape would be optimal). These requirements for the fuel tank would cause an aircraft to have a lower lift to drag ratio (L/D).

The higher specific heat of hydrogen gives an aircraft a cooling capability. It will be helpful on chilling the engine and vehicle parts exposed during aerodynamical heating. Notably, the laminar flow control by cooling the surface is expected to be an available technology for reducing skin friction drag [8].

Currently, the prices of both hydrogen and kerosene per gallon [9] [10] are almost the same. However, the price of LH_2 per weight is about ten times higher than that of kerosene. Therefore, it will raise direct operation costs (DOC).

2.2 Early Studies of LH_2-SST

Table 2 presents the comparisons of two concepts, the Kerosene-SST and the LH_2-SST, both of which were designed by Lockeed in the mid 1970s to carry 234 passengers for a range of 4200 nm, at a M2.7 [6]cruise speed. The take-off weight (W_{TO}) of the LH_2-SST was estimated to be much lighter than that of the Kerosene-SST by nearly 50% because lower SFC reduces the ratio of fuel weight to take-off weight (W_F/W_{TO}), although the LH_2-SST has lower L/D. Wing loading (W/S) was determined by the landing constraints in this comparison. Because of this constraint the LH_2-SST had lower W/S. Subsequently, lower W/S requires lower dynamic pressure (q) to meet a given value of lift coefficient (C_L) of cruise (see equation (1)).

$$C_L \; at\, cruise = \frac{W_{CRUISE}/S}{q} \tag{1}$$

Lower dynamic pressure indicates a higher altitude if the cruise speed is constant. At a higher altitude, an aircraft is required to have a higher take-off thrust to weight ratio (T/W) because of the lower engine thrust lapse. Commonly, take-off T/W is determined to meet either balanced field length (BFL) or second segment climb (SSC). However, the difference of the take-off T/W in this comparison may suggest a possibility that a cruise constraint would determine the take-off T/W of the LH_2-SST.

Figure 1 shows the plan view of the LH_2-SST [6]. The fuselage contains two large cryogenic integral tanks fore and aft which are nearly cylindrical in shape. Note that in spite of its lower W/S, the wing is relatively small.

2.3 Take-off Weight Trends of LH_2-SST

As mentioned above, the results obtained by Lockeed show a potential for reducing the weight of an aircraft due to the high heat level of the combustion of hydrogen. The authors have also conducted a preliminary conceptual study of LH_2-SSTs [11] which were designed to carry less than 100 passengers for a range of 3500 nm, at a M1.6 cruise speed, although the design method wasn't incorporated with any sonic boom minimization or optimization process. The study reveals LH_2 fuel can reduce W_{TO} by 40~50% at the most for the purpose mentioned above. It also predicts the weight trend of a LH_2-SST with respect to the number of passengers referring to the past SST projects, as shown in figure 2.

2.4 Other Considerations of LH_2-SST

Generally speaking, the management of cryogenic LH_2 fuel is difficult and some weight penalties are expected due to insulation, tank structure and boil-off. Table 3 summarizes the weight penalties assumed in the design of a LH_2-SST performed by Lockeed.

3 Design Method

3.1 Design Method

Figure 3 shows the flow chart of the design method. First, the preliminary sizing (§3.2) provides a baseline model for a given mission. Next, the geometry generator (§3.3) gives several input files to the subsequent modules. The mass module (§3.4) calculates weight and balance. The aerodynamics module (§3.5) designs wing camber, estimates drags and so on. Last, the evaluation module (§3.6) receives some output files to analyze. The results are iterated and optimized by using commercially-available software called Isight [12].

3.2 Preliminary Sizing

In this design process, preliminary sizing provides a baseline model for a given mission. Specifically, W/S, T/W and some dimensions of a baseline model are estimated here. The allowable region of W/S and T/W is narrowed down by some constraints with respect to BFL, landing field length (LFL), SSC and cruise [13]. In this preliminary sizing, BFL, LFL and SSC requirements give W/S and T/W.

3.3 Geometry

The fuselage is defined to be an axis-symmetrical circular body. Non-Uniform Rational B-Spline (NURBS) determines the radii distributions of fuselage (figure 4) while the maximum length and diameter are fixed.

The wing planform is determined by using the result of reference 14. In this reference, the multi-point optimization of wing planform was carried out at the supersonic cruise condition of M1.6 and C_L =0.1 with two objectives being: 1.)

minimizing the bending moment around the quarter location of the mean aerodynamics center and 2.) reducing induced drag. Among the results as shown in figure 5, the plan form Type 2 on the pareto frontier is chosen to be used as a main wing configuration in this paper.

The horizon tail and vertical tail is defined by an aspect ratio, wing area and a swept angle both at leading and trailing edges. The engine nacelle is assumed to be cylindrical in form. The locations of the tail and engine are properly chosen considering the equivalent area distribution due to volume or Center of Gravity (C.G) location.

The dimensions of the cabin including the cargo space are calculated from the volume required by the number of passengers. The fuel tanks of a conventional kerosene-SST are expected to be located in the wing and aft fuselages to shift the C.G location for trimming In designing a LH_2-SST, the fuel tanks are deployed in the fore and aft of the fuselage similar to the configuration shown in figure 1.

3.4 Mass Estimation Tool

The tool for estimating each component weight of an aircraft is based on the equations used in WAATS [15], which employ an empirical approach. Following the four conceptual design results of SST [16] ~ [19] are referred to update the equations.

1 SSXJET (M2.2, 3200nm, 8-pass.)
2 Low Boom HSCT (M2.0, 4000nm, 10-pass.)
3 M2.4 HSCT (M2.4, 6500nm, 251-pass.)
4 M3.0 HSCT (M3.0, 6500nm, 251-pass.)

Figure 6 shows the equation estimating wing weight as an example [11]. According to an investigation on the current technology used in a turbofan engine with low noise devices for a SSBJ [20], the thrust to engine weight ratio is supposed to be about 3.0 in this paper.

In designing a LH_2-SST, the weight of the LH_2 fuel tank is assumed to be 24% of fuel weight. The penalty due to the fuel supply system is assumed to impose an 85 % increment of the weight in this paper. (see table 3)

At supersonic speeds, the wing aerodynamics center typically moves aft and it leads to trim drag. To minimize it, a C.G. control is needed. Therefore, the allowable extent of C.G. by shifting fuel is calculated here.

3.5 Aerodynamics Estimation Tools

Aerodynamics estimation tools used in this paper are listed in Table 4. These tools are based on linear theories because a low fidelity method will be useful for multi-point design and conceptual design phases where large numbers of calculation cases are required. D2500 [21] [22] is a tool for the estimation of wave drag and it also evaluates the equivalent area due to volume. SEEB, which utilizes the low boom method of Seebass and George [23] and Darden [24], provides the target equivalent area for a given sonic boom signature, either ramp type or flat-top type. This tool was freely distributed for participants of the NASA Fundamental Aeronautics Student Competition 2009 [25]. WARP which was first developed by Yoshida [26] and modified by Higuchi [14] designs optimum wing cambers to reduce a drag due to lift under supersonic conditions by the method of Carlson [27]. FRICTION [28] estimates frictional drag.

3.6 Evaluation Module

In the evaluation module, some output files from the previous module are analyzed to evaluate performances of an aircraft such as take-off weight, L/D in cruise and sonic boom performance. The way to evaluate the sonic boom performance is by estimating the difference ΔA_E of the equivalent area A_E from the target given by SEEB shown in figure 7. The horizontal axis shows the axial distance of an aircraft and the vertical axis shows the equivalent area A_E in figure 7. Note that the ΔA_E is nondimensionalized by a representative area.

4 Design Results

4.1 Baseline (Result of Preliminary Sizing)

The mission requirements were chosen as shown in Table 5 referring to JAXA's Quiet Small Supersonic Transport concept (QSST) [29].

Figure 8 and 9 show the plan views of the baseline model obtained by preliminary sizing and its equivalent area distribution. The pressure signature of the sonic boom is expected to be N-wave (see figure 16) because the ΔA_E is significantly large.

4.2 Design of Experiments for Low Boom Design

The reason for the big gap of the ΔA_E (see figure 9) is because the volume obtained by the integration of the target equivalent area distribution is too small for the baseline. This volume is determined by the following equation (2) concerning the terminal value of a target equivalent area distribution (see figure 7). This is given in the low boom theory.

$$A_E(L) = \frac{\beta W}{\rho U^2} = \frac{\beta W}{2q} \tag{2}$$

According to this equation, increasing weight or decreasing dynamic pressure (q) makes this value larger. Note that decreasing q affects C_L at cruise, as mentioned in §2.2. In order to cruise around the maximum value of L/D, proper W/S or cruise altitude should be chosen.

Design of Experiments (DOE) was performed to find contributions of design variables. The wing area and 10 control points of fuselage radii distribution were set as design variables and C_L =0.1 at cruise was chosen as a constraint. (The value of C_L was determined empirically to cruise around the maximum value of L/D) This constraint means that as the wing area or W/S changes, cruise altitude and also dynamic pressure varies to meet C_L =0.1. Figure 10 shows the result with respect to wing area and ΔA_E . It can be seen that the ΔA_E decreases as the wing area increases and it plateaus around 3,800 ft^2.

4.3 Optimization for Low Boom Design

Multi-Point Optimization was performed by Neighborhood Cultivated Genetic Algorithm (NCGA). The wing area and 10 control points of fuselage radii distribution were set as design variables and C_L =0.1 at cruise was chosen as a constraint. The objective was minimizing ΔA_E and W_{TO}. The calculation was implemented through 10 generations and figure 11 shows the result at the 10th generation. The convergence was not enough. However, it was confirmed that there is a trade-off between ΔA_E and W_{TO}.

To reduce ΔA_E much closer to zero, single-purpose optimization was performed by using the Downhill Simplex method. 10 control points of fuselage radii distribution were chosen as design variables and C_L =0.1 at cruise was set as a constraint. The wing area was fixed at 3,800ft^2 from the result of DOE (see §4.2). The objective was to minimize ΔA_E . Figure 12 shows the convergence history. Figure 13 and 14 presents the plan view of the low boom LH_2-SST obtained and its equivalent area distribution.

4.4 Comparison with Baseline model

Table 6 compares both the specification of the baseline and the low boom LH_2-SST. Each of the cruise altitude is different to meet C_L =0.1 at cruise. This is because of the difference of W/S. The pressure rise from the sonic boom is reduced from 1.87 to 0.44 psf as shown in figure 16. The L/D is also improved from 6.13 to 7.39. Although W/S decreases from 69 to 41 psf and T/W increases from 0.46 to 0.53 drastically, this improvement of L/D is considered to suppress the growth of W_{TO} to only 7%.

4.5 Comparison with Kerosene-SST

The low boom Kerosene-SST (figure 15) was also designed for comparison with the low boom LH_2-SST. Table 7 lists both SST's specifications. The comparison shows that LH_2 fuel could lead to a 25% W_{TO} reduction. With this help, the pressure rise by sonic boom is decreased from 0.67 to 0.44 psf as shown in figure 16.

As another notable difference, the higher price of LH_2 fuel per weight raises DOC from 0.36 to 0.90 $/nm/pass.

4.6 C.G. of Low Boom LH_2-SST

The LH_2 tank was divided into two segments in forward and aft of fuselage (see figure 1). As a result, the C.G. of the low boom LH_2-SST was predicted as shown in figure 17. Note that the forward and aft C.G. lines in figure 17 do not indicate actual C.G. travel, however, they do represent the attainable range of C.G..

5 Considerations

5.1 Optimization

Multi-point optimization was performed in this paper. However, the convergence was not successful (see figure 11). There seems something wrong with the fuselage geometry model. In this paper, NURBS was utilized. Figure 18 shows the B-Spline basis function used. Well-weighted control points and proper choices of the knot vector will improve convergence.

5.2 Take-off Weight of Low Boom LH_2-SST

It is confirmed that there is a trade-off between W_{TO} and ΔA_E in designing a low boom LH_2-SST. That is, minimizing ΔA_E leads to lower W/S and higher T/W comparing with those of the baseline because a higher cruise altitude is required (see §4.2). However, the growth of W_{TO} is suppressed by the improvement of L/D. One of the reasons for this improvement is that the wave drag is decreased because the equivalent area due to volume becomes smoother as shown in figure 9 and 14.

Brewer's report [6] and our former study [11] indicated that LH_2 fuel can reduce W_{TO} by 40~50 % at the most because of its high heat level of combustion. However, W_{TO} of the low boom LH_2-SST in this study is 25% lighter than the low boom Kerosene-SST. It is expected that the advantage of the weight reduction will weaken a little when a LH_2-SST is designed for low boom.

5.3 Sonic Boom Intensity of Low Boom LH_2-SST

It is hypothesized that the sonic boom intensity of less than 0.5 psf on the ground is considered as an environmentally acceptable value. In the case of a kerosene-SST, the SSBJ class most ideally satisfies the criterion for sonic boom. However, the value of the low boom LH_2-SST was 0.44 psf even though it was designed to carry 50 passengers for a range of 3500nm at Mach 1.6. That is, the low boom LH_2-SST meets this sonic boom criterion, which is less than 0.5psf, carrying more passengers than the SSBJ class. This is because of the weight reduction by LH_2 fuel.

5.4 Other considerations

There are some other considerations about a LH_2-SST.

a. Engine

In this paper, the LH_2 fueled engine was assumed to be the same specification with conventional kerosene fueled turbo-fun engine (see §3.4). According to reference 6, it is expected that there are few problems in a turbo jet engine fueling LH_2. It is necessary to study a LH_2 fueled engine in detail.

b. Cost

As above mentioned in §2.1 and §4.5, LH_2 fuel would raise DOC drastically supposing the cost of LH_2 in 2010. At present a LH_2 fueled aircraft may be not realistic for commercial purposes. Now, many Fuel Cell Vehicle (FCV) concepts have been announced. Therefore, there is now a possibility that LH_2 fuel will grow in popularity and come down in price in the future.

c. Safety

Safety is one of the biggest problems. Especially, a LH_2 fuel tank is expected to be stored under a severe, low temperature and high pressure environment. Sufficient measurements for this situation should be taken. Accordingly, if regulations of a LH_2 aircraft are established, there will be a trade-off between the safety and weight penalty.

d. Cooling capability

Hydrogen has the high specific heat (see §2.1). There is an expected available technology for reducing skin friction drag that uses the cooling surface to control laminar flow.

Although it was not taken into account in this paper, it is worth considering.

6 Conclusions

A design method which considers the effects of hydrogen and incorporates the sonic boom minimization theory was developed. By using this method, a low boom LH_2-SST was designed to carry 50 passengers for a range of 3500 nm at a Mach 1.6 cruise speed. The multi-point optimization process was utilized and a trade-off relation was found between sonic boom minimization and weight while designing a low boom LH_2-SST. A low boom kerosene-SST was designed by this method to compare with the low boom LH_2-SST. As a result of this comparative discussion, it was confirmed that LH_2 fuel can reduce take-off weight by 25 % because of its high heat level of combustion. Next it was found that the sonic boom intensity can be reduced by 33%, from 0.67 to 0.44 psf, by the use of LH_2 fuel because of the weight reduction.

Acknowledgement

The authors would like to thank Dr. Akira Murakami, Dr. Kenji Yoshida and Dr. Yoshikazu Makino of JAXA, and to give special thanks to Mr. Shigeru Horinouchi of JAXA for his advice in the present SST design.

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Table 1: Effects of LH_2 on Aircraft

	LH_2	Kerosene	Effects due to LH_2
Composition	H_2	$CH_{1.93}$	Zero CO_2 emission
Molecular Weight	2.016	168	Leakage risk
Energy Density [kJ/g]	120	42.8	Lower Specific Fuel Consumption
Mass Density [kg/m^3]	71	811	Large fuel tank required
Specific Heat [kJ/kg/K]	9.69	1.98	Cooling capability
Price [US$/gallon]	2.4[10]	2.2[9]	Raise direct operation cost

Table 2: Comparisons of Kerosene-SST and LH_2-SST resulted from Lockeed [6]

	Kerosene-SST	LH_2-SST
W_{TO} [lb]	762,000	395,000
W_F/W_{TO}	0.52	0.25
SFC [lb/lb/hr]	1.501	0.575
L/D cruise	8.65	7.42
W/S take-off [psf]	68.7	49.7
W/S landing [psf]	38.9	38.9
T/W take-off	0.456	0.535
Thrust per engine [lb]	86,900	52,800

Table 3: Weight Penalties assumed in the design of LH_2-SST performed by Lockeed [6]

Cause	Weight Penalty	
Fuel system	Added 80~85% to weight of comparable Jet A fuel system for insulation and vacuum tubing around all fuel lines	
Integral LH_2 tank	Added 9.58% of weight of LH_2 fuel to account for tank ends and related support structures	Total 20~24% of LH_2 fuel weight
Tank heat shielding and insulation	Added 13.49 % of LH_2 fuel weight	
Unusable fuel and boil-off	4.1 % LH_2 fuel weight	

Table 4: Aerodynamics Estimation Tools

Tools	Comments
D2500	Evaluate wave drag due to volume
SEEB	Find minimum overpressure, generate the target equivalent area
FRICTION	Evaluate frictional drag
WARP	Design wing camber, Evaluate drag due to lift

Table 5: Mission

Cruise Speed [M]	1.6
Range [nm]	3,500 (target)
Passenger	50
BFL [ft]	7000
LFL [ft]	7000

Table 6: Comparison between baseline and low boom LH_2-SST

	Baseline	Low boom design
Cruise Speed [M]	1.6	
Passenger	50	
Range [nm]	3540	3550
Altitude [ft]	43000	53000
W_{TO} [lb]	148000	158000
W_E [lb]	104021	116000
W_F [lb]	31700	29600
W_F/W_{TO}	0.21	0.19
W/S [psf]	69	41
T/W	0.46	0.53
Length [ft]	220	
Wing area [ft^2]	2150	3800
Thrust×2 [lb]	34000	41900
CL at cruise	0.1	
L/D at cruise	6.13	7.39
Sonic Boom intensity [psf]	1.87	0.44

Table 7: Comparison between Kerosene-SST and LH_2-SST designed for low boom

	Low boom Kerosene-SST	Low boom LH_2-SST
Cruise Speed [M]	1.6	
Passenger	50	
Range [nm]	3420	3550
Altitude [ft]	42000	53000
W_{TO} [lb]	210000	158000
W_E [lb]	95400	116000
W_F [lb]	102000	29600
W_F/W_{TO}	0.48	0.19
W/S [psf]	87	41
T/W	0.46	0.53
Length [ft]	155	220
Wing area [ft^2]	2300	3800
Thrust×2 [lb]	48300	41900
C_L at cruise	0.1	
L/D at cruise	7.04	7.39
Sonic Boom intensity [psf]	0.67	0.44
DOC [US$/nm/pass.]	0.36	0.90

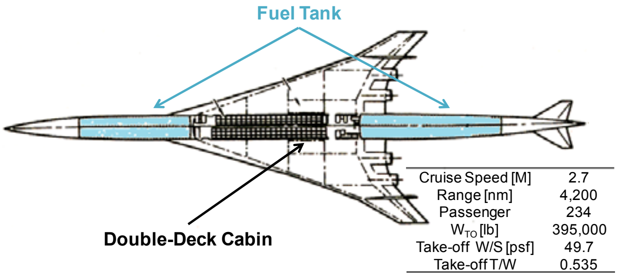

Fig. 1. Plan View of LH_2-SST Designed by Lockeed [6]

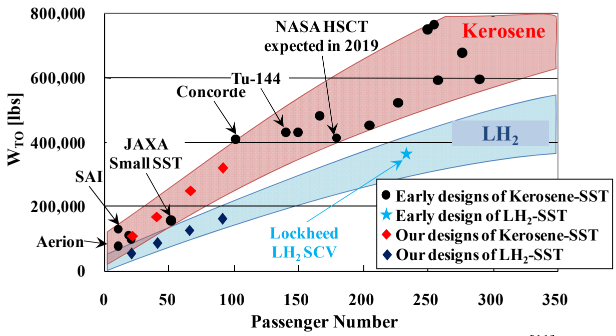

Fig. 2. Predicted Weight Trend of LH_2-SST [11]

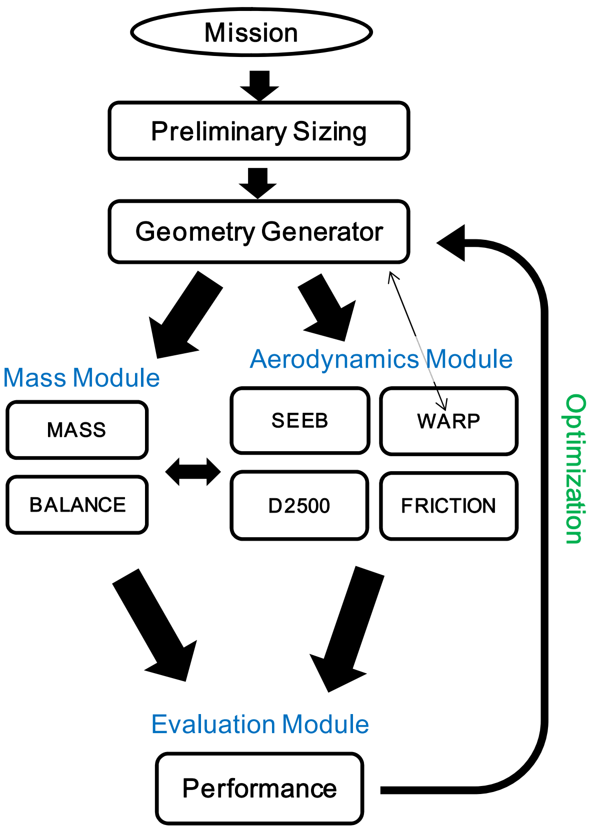

Fig. 3. Design Routines

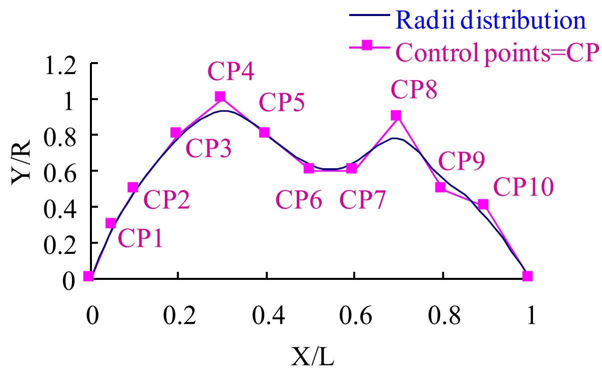

Fig. 4. Radii Distribution of Fuselage Determined by NURBS

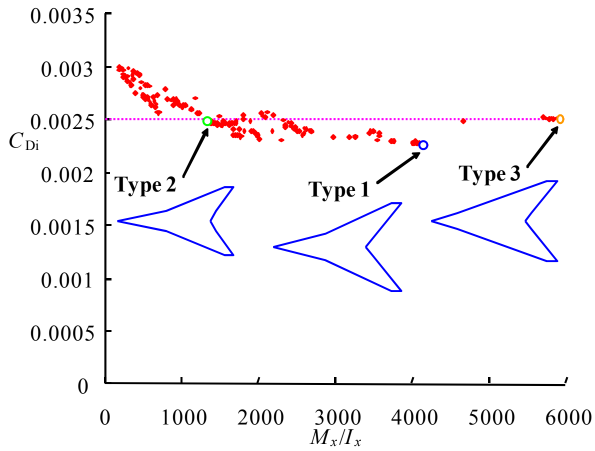

Fig. 5. Multi-Point Optimization of Wing Planform at Supresonic Cruise Condition (Induced Drag vs. Bending Moment) [14]

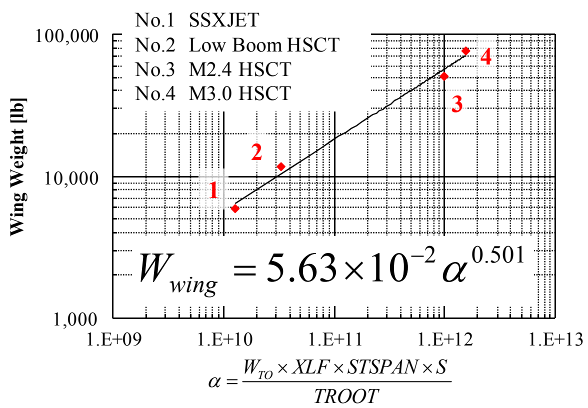

Fig. 6. Wing Weight Estimation [11]

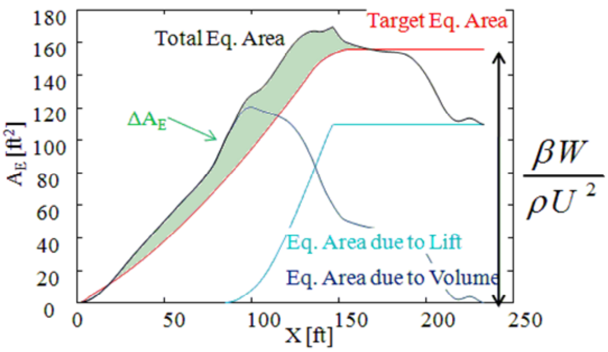

Fig. 7. Equivalent Area and Definition of ΔA_E

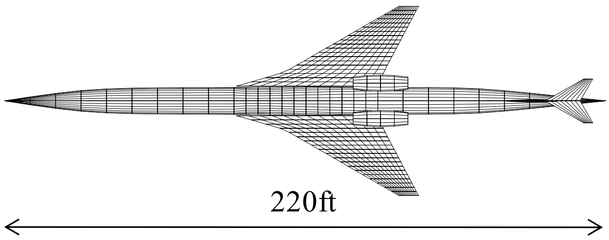

Fig. 8. Plan View of the Baseline

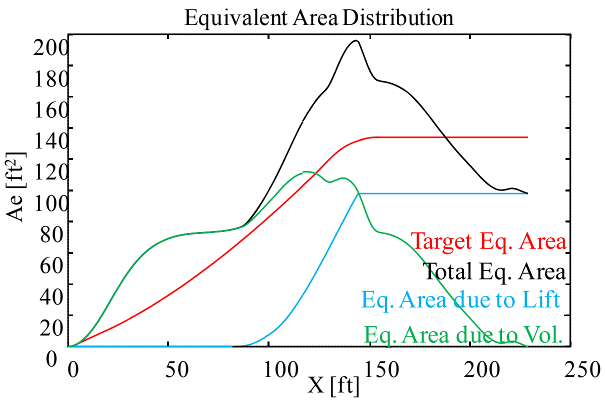

Fig. 9. Equivalent Area of the Baseline

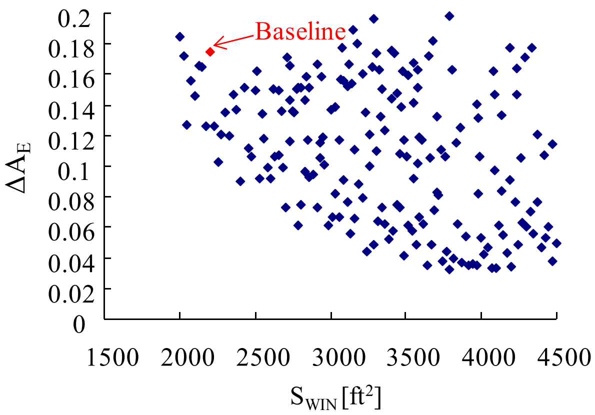

Fig. 10. ΔA_E vs. Wing Area Resulted from DOE

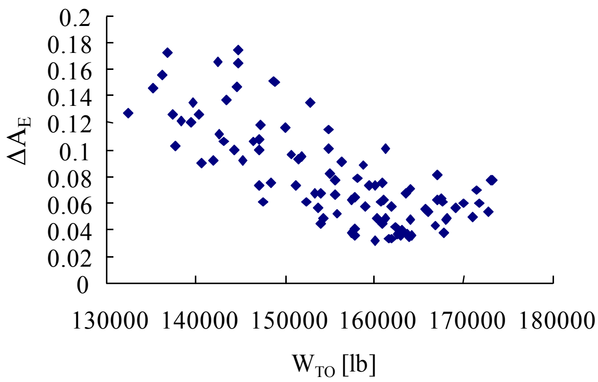

Fig. 11. ΔA_E vs. Take-off Weight Resulted from NCGA at 10th generation

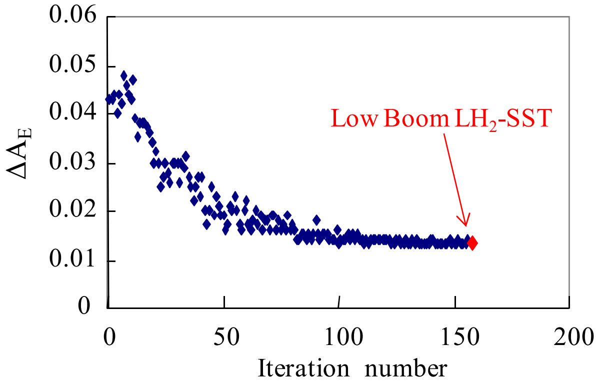

Fig. 12. Convergence History of Downhill Simplex Method

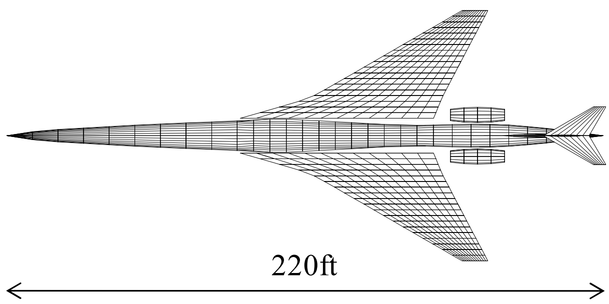

Fig. 13. Plan View of the Low Boom LH_2-SST

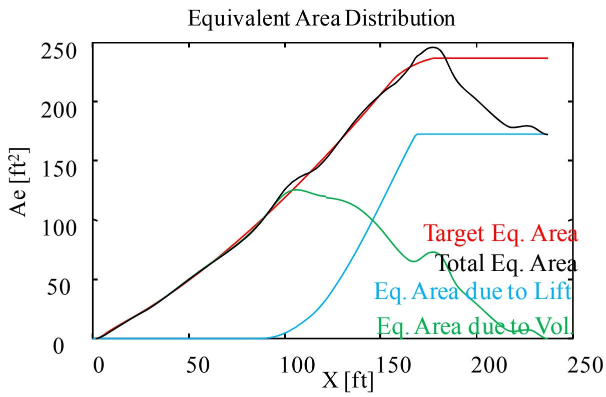

Fig. 14. Equivalent Area of the Low Boom LH_2-SST

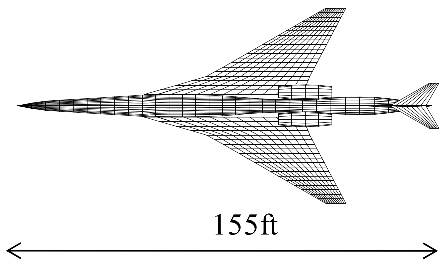

Fig. 15. Plan View of the Low Boom Kerosene-SST

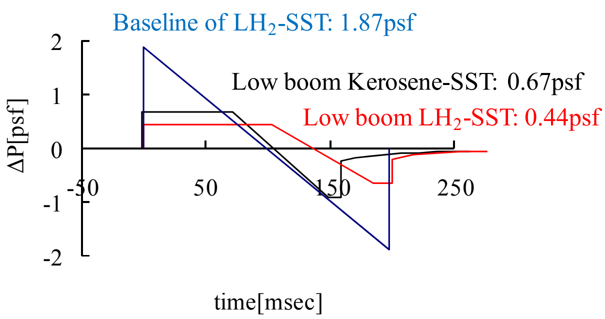

Fig. 16. Overpressure on the Ground

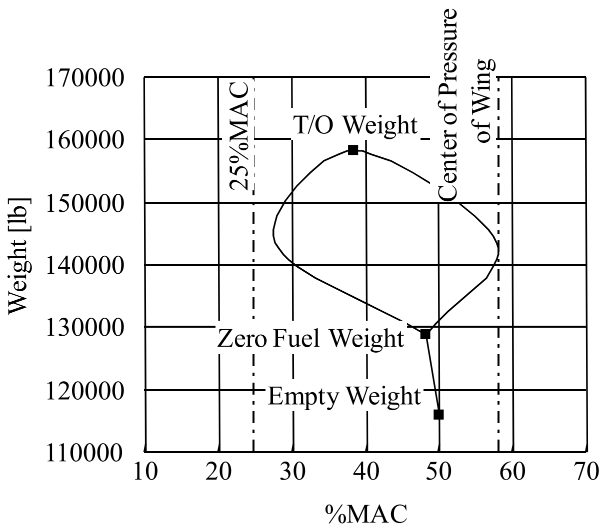

Fig. 17. Estimated C.G. Boundaries of the Low Boom LH_2-SST

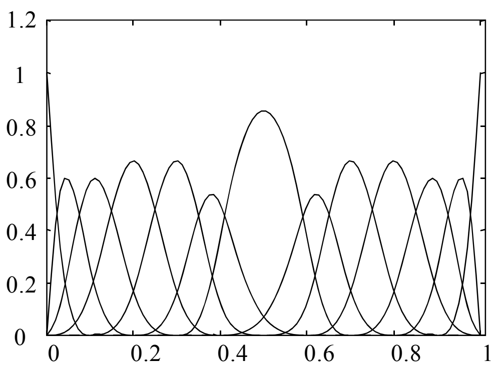

Fig. 18. Rational B-Spline Basis Utilized to Determine Fuselage Radii Distribution