



POTENTIAL OF THE RANGE EXTENSION OF SUPERSONIC TRANSPORT

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Abstract

The supersonic transport consumes a large amount of fuel in supersonic cruise, which accounts for about 50% of their takeoff weight. In order to increase the range, the supersonic transport commonly becomes larger, thus results in higher manufacturing costs and fuel consumption. The objective of this study is to investigate the range extension by adopting transonic cruise of flight segments in addition to supersonic cruise within the allowable cruising time. The effects of the combination of supersonic and transonic cruise on the range extension and cruising time were estimated using flight theories. Based on the results, the advantages in flight performance and operational economy were discussed.

Keywords: Supersonic transport, Flight Performance, Range Extension, Sonic Boom

1. Introduction

Extensive research and development efforts have been dedicated to addressing economic and environmental challenges in order to bring about the realization of the next-generation commercial supersonic transport for many years since the last century. Efforts have been made to tackle the most difficult environmental concerns associated with supersonic transport, including low boom, low noise, low drag, and low CO₂ emissions. In terms of economics, it is important to consider the costs associated with development, manufacturing, and operation during the design phase of airplane. The dimensions of the airframe have significant impacts not only on the cost, but also fuel consumption, sonic boom, and noise. Range and endurance, which are major design specifications, are directly related to the operating profit of airlines when they select flight routes, and are also the most important factors in evaluating the business feasibility for air transport. Currently, numerous organizations around the world are conducting research and development of supersonic commercial aircraft. Based on surveys conducted on cost and passenger demand, it appears that a supersonic passenger aircraft with a seating capacity ranging from 50 to 100 holds significant economic potential.

According to a forecast [1], the market for airline travel was projected to experience a 1.7% increase in the number of jet passenger aircraft over the next 20 years. Liebhardt et al. suggested that the airline market holds significant potential for supersonic flight [2]. Supersonic transports offer the advantage of flying faster than the speed of sound, resulting in shorter flight times and enhanced value for passengers. As a result, some airlines expect the introduction of supersonic passenger aircraft to differentiate themselves from existing subsonic jetliners, which typically cruise at around Mach number 0.8. This strategic move aims to attract airline passengers by providing a unique and faster travel experience. In the United States, where air travel demand is particularly high, there is a strong expectation for supersonic passenger aircraft. In fact, several airlines have already contracted dozens of Overture supersonic passenger aircraft, which was being developed by Boom [3].

The authors [4] have conducted conceptual designs for the supersonic transport. In the previous study, the 50-seat supersonic transports with a cruise speed of M1.6, cruise altitude of 50,000 ft, and

the maximum ranges of 3500 NM and 4500 NM were studied using the aircraft conceptual design method. Discussions were also conducted for flight performance with different engine bypass ratio $BPR = 3, 4$, and 5 . The sizing of the wings took into account the reduction in structural weight due to the use of composite materials, as well as the aerodynamic drag reduction achieved through the implementation of a natural laminar flow wing design. Furthermore, the design met all the necessary constraints, including takeoff/landing conditions and onboard fuel capacity. On the other hand, the sonic boom intensity was predicted for the aircraft obtained from the conceptual design, and it led to the conclusion that a lower boom design would be necessary.

The operation and market of supersonic transport are influenced by various factors, including development cost, operation cost, service rate, gas exhaust emissions, sonic boom, and so on. Based on the results of the supersonic aircraft conceptual design obtained in the previous study [4], the focus of this paper is to investigate the aircraft size, engine performance, boom intensity, and cruising capability, and discuss potentials of operational configurations that combines both supersonic and subsonic cruising flight. It is assumed that the supersonic cruising is restricted in the over ocean region with the permitted level of sonic boom, and transonic cruising is permitted over land and near coast where no sonic boom is generated on ground.

2. Sizing of Supersonic Transport

This paper assumes that supersonic flights are prohibited over land and coast, and that oceanic flights are supersonic and land flights are transonic or subsonic. Figure 1 shows some of the possible flight routes for supersonic transports. Actually, a combination of supersonic and transonic cruise is unavoidable for some routes operated by supersonic transports.

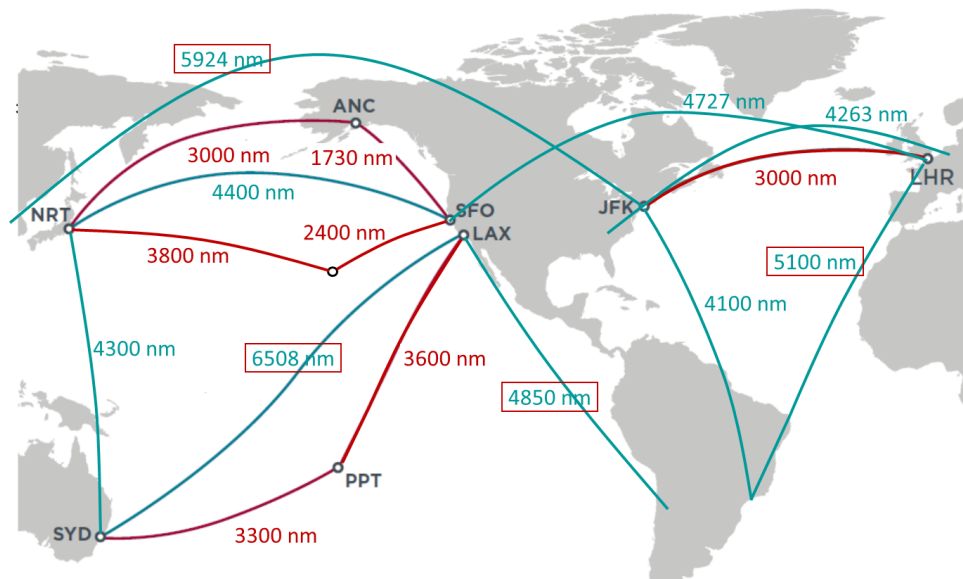


Figure 1. Examples of flight routes of supersonic transports

Several companies are currently engaged in the research and development of supersonic commercial transport, for example, Spike's S-512, Aerion's AS2, Boom's Overture, and Exosonic's Supersonic Jet. Table 1 shows the main specifications and performance metrics of supersonic transports and competing transonic transports. All supersonic transports were designed for supersonic cruise conditions, except for subsonic flight during the takeoff and landing sections. For each specified range, the supersonic cruise is basically assumed, resulting in significantly shorter flight times than subsonic aircraft.

Due to the limited number of operating routes for supersonic passenger aircraft and the high cost of developing and manufacturing airframe systems, it is difficult to consider subdividing the different

POTENTIAL OF THE RANGE EXTENSION OF SUPERSONIC TRANSPORT

Table 1. Specifications of competing supersonic and subsonic transports

Manufacturer	Unit	Supersonic transport						Transonic transport			
		BAC	Spike	Aerion		Boom	Exosonic	Boeing		Airbus	
Model		Concorde	S-512	AS1	AS2	Overture	Supersonic Jet	B737 MAX7	B787-9	A320 Neo	A350-900
Full length	m	61.7	40.8	51.8	44.2	62.4	76.0	35.6	62.8	37.6	66.9
Wing span	m	25.6	17.7	18.6	24	-	27.1	35.9	63.4	35.8	64.8
Wing area	m ²	358.2	104.5	125.4	-	-	-	127	377	122	443
Aspect ratio of wing		1.82	2.99	2.76	-	-	-	10.1	9.59	9.5	9.49
Seats	seat	100	18	12		65-90	70	153	290	165	315
Range	NM	3900	6200	4750	4200	4250	5000	4400	8600	3500	8100
Fuel weight	ton	95.7	25.4	27.4	31.8	-	-	20.7	101.5	19.1	110.8
Empty weight	ton	78.7	21.4	26.2	-	-	-	45	129	42.1	134.7
Max takeoff weight	ton	185	52.2	54.9	63.1	77	-	80	245	79	268
Mach number at cruising		2	1.6	1.4	1.4	1.7	1.8	0.79	0.85	0.78	0.85
Number of engines		4	2	3	3	4	2	2	2	2	2
Thrust per engine	kN	169	89	80	80	156	-	130	320	121	375
Specific fuel consumption	lb/lbf/h	0.245						0.53	0.51	0.51	0.478
Fuel consumption per NM seat	lb/NM/seat	0.540	0.503	1.060	1.391			0.0677	0.0897	0.0730	0.0957

sizes of the aircraft. In this study, two patterns of supersonic transport were examined the cruising performance: the pattern 1 is the 3500 NM-ranged supersonic transport and the pattern 2 is the 4500 NM-ranged supersonic transport.

As shown in Figure 1, these two patterns cover most flight routes. If the supersonic flight is prohibited overland, most of the routes both below 3500 NM of Pattern 1 and below 4500 NM of Pattern 2 have to include a part of transonic flight. Therefore, the next-generation supersonic transport will be necessarily operated for both supersonic and transonic cruising. So the market of supersonic transport is generally classified into two categories, i.e., the range below 3500 NM and the range between 3500 NM and 4500 NM. The range more than 4500 NM requires larger dimensions and weight of supersonic transport, which is hardly considered because the strong sonic boom is generated. In comparison to transonic transport, even if transonic flight is adopted in a part region, the effect of reducing the flight time can still be obtained and a part of advantages can be maintained by supersonic cruising. The range between 3500 NM and 4500 NM should be practically divided into a supersonic cruise section over ocean and a transonic cruise section over land and coast. On the other hand, since the route of over 5000 NM range are very limited and the sonic boom intensity of supersonic flight increases is strongly dependent on the volume and weight of the aircraft. The supersonic transport with a range of more than 5000 NM is difficult to be considered due to significant increases of cost and sonic boom.

If the supersonic transport is partly operated at transonic speeds, the total flight time is increased. Instead, the range will be possibly largely increased and the overall fuel consumption is largely reduced, thereby the flight cost is reduced. For airlines who place importance on operating costs, this allows them to flexibly plan more flight routes with a limited number of aircraft, expend the market to make the business more feasible.

3. Conceptual Design Model

POTENTIAL OF THE RANGE EXTENSION OF SUPERSONIC TRANSPORT

The Japan Aerospace Exploration Agency (JAXA) [5] and the National Aeronautics and Space Administration (NASA) [6], among others, have found that a small SST with a maximum takeoff weight of 70 ton class would enable low-boom supersonic flight over land, however, this would result in a decrease of aerodynamic performance. Figure 2 shows an image of JAXA's 50-seat conceptual supersonic transport.



Figure 2. JAXA's 50-seat supersonic transport [5]

In the authors' previous study [4], conceptual designs of a 50-seat class small supersonic transport were conducted. The results are summarized in Table 2. Figure 3 shows the conceptual design airframes for a range of 3500 NM (Pattern 1) and 4500 NM (Pattern 2). For the basic design, a cranked-arrow wing and side fuselage arranged nacelles were adopted based on the shape of a small supersonic airliner provided by JAXA [5]. Constraints were set as follows: takeoff and landing distance $SFL \leq 6000$ ft for a 3500 NM range aircraft, $SFL \leq 8000$ ft for a 4500 NM range aircraft, climb performance $\gamma \geq 0.024$ at the Second Segment Climb (SSC), and flight distance 200 NM to an alternate airport. Laminar flow was assumed on the wing top surface within 10% of the wing string length from the leading edge, and turbulent flow was assumed downstream. Aircraft weight, aerodynamic performance, and cruising performance were estimated using aircraft flight theories

Table 2. Design results of the supersonic transports

	unit	Pattern 1	Pattern 2
Range	NM	3500	4500
Mach number at cruising		1.6	1.6
Altitude at cruising	ft	50,000	50,000
Max takeoff weight	ton	72.2	119.2
Fuel weight	ton	33.4	60.0
Full length	m	65	70
Wing span	m	26.6	31.5
Wing area	m ²	208	292
Aspect ratio of wing	-	3.45	3.39
Lift coefficient at cruising	-	0.1252	0.1434
Ratio of lift to drag	-	7.36	8.71
Bypass ratio of engine	-	3	3
Total thrust	kN	339	540
Boom on ground	psf	1.09	1.19
Fuel consumption per NM seat	lb/NM/seat	0.421	0.589

POTENTIAL OF THE RANGE EXTENSION OF SUPERSONIC TRANSPORT

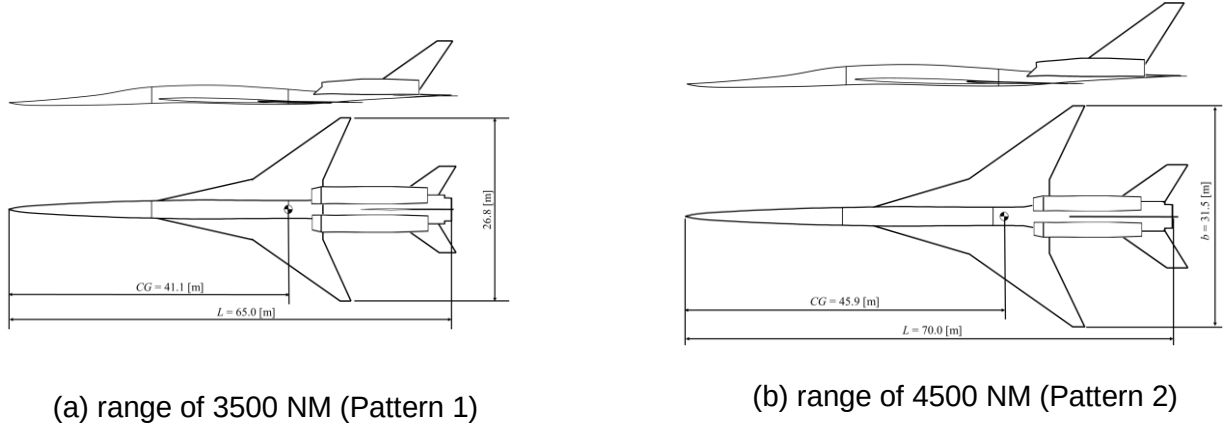


Figure 3. Conceptual design airframes of supersonic transport

and statistical equations [7][8], and the optimal solutions for the main parameters, such as aspect ratio and wing loading, were obtained by sizing the aircraft using carpet plots. The fuselage cross-sectional integral was designed to minimize wave drag, and the fuselage length was adjusted to provide enough fuel capacity to meet the cruising range. In addition, a bypass ratio (BPR) of 3 was adopted for the engine to minimize the fuel consumption rate in supersonic flight.

4. Discussion

Both of the supersonic cruise distance R_{sup} and transonic cruise distance R_{tran} are estimated using the Breguet formula shown in Equation (1).

$$R_{cruise} = V_{cruise} \frac{\eta_j \cdot L}{c_j \cdot D} \ln \left(\frac{W_S}{W_S - W_E} \right) \quad (1)$$

where V_{cruise} : cruise speed [kts], η_j : equipment efficiency, c_j : specific fuel consumption [(lbf/h)/lb], W_S : weight of the aircraft at the start of cruise [lb], W_E : weight of the aircraft at the end of cruise [lb], W_F : fuel weight [lb]. The total cruise distance is the sum of all flight segments.

$$R = R_{sup} + R_{tran} + R_{sub} \quad (2)$$

Excluding fuel used for gliding, climbing, descending, and waiting in the air, the fuel weight used for cruising is divided into supersonic and subsonic cruising to estimate the range of each. Here, a constant value of $R_{sub} = 200$ NM is assumed for the flight distance except cruise.

For supersonic cruise, the speed was set to Mach 1.6, which is twice the cruise speed of the competing transonic transport. The flight speed at transonic cruise was set to Mach 0.98 and the

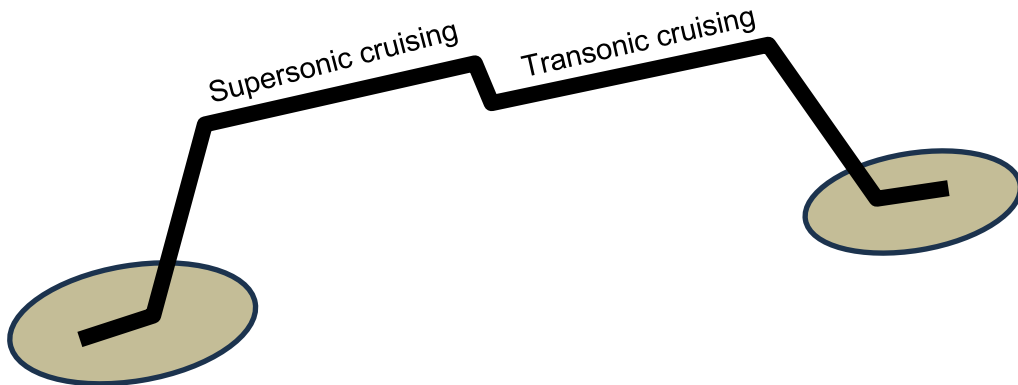


Figure 4. Flight phases of point-to-point with non-stop supersonic and transonic cruising

flight altitude to 40,000 ft, referring to the specifications of the Sonic Cruiser aircraft [9], which Boeing has ever planned. A lift-drag ratio of $L/D = 12$ was assumed at transonic speed.

4.1 Engine Performance

In order to reduce development manufacturing and maintenance costs for engines that can be used in civilian supersonic aircraft, existing turbofan engines could be considered to retrofit. The larger the fan diameter and bypass ratio, the lower the fuel consumption rate and the lower the engine noise during takeoff. The disadvantages are increased airframe weight and aerodynamic drag, especially at supersonic flight speeds, resulting in a shorter range. In other words, a compromise must be reached between low-speed and supersonic flight. Table 3 shows the main performance characteristics of typical jet engines used in air transports: the Olympus 593 used in the Concorde is a turbojet engine with a bypass ratio of BPR=0, and all other engines are turbofan jet engines used in existing transports. The specific fuel consumption(c_j) during cruise commonly takes the value of 0.5~0.8 lb/lbf/h.

Since there is almost no data available on the specific fuel consumption of turbofan jet engines in supersonic cruise, the specific fuel consumption was estimated in this study using the statistical equation [10]. The specific fuel consumption was calculated at takeoff, transonic, and supersonic

Table 3. Specifications of typical turbofan jet engines

Engine model	Olympus 593	CFM56-5C2	CF6-50	RB211-535	JT8D-219
BPR	0	6.6	4.24	4.3	1.72
OPR	15.5/82	31.3	29.2	25	20.1
length[m]	4.04	2.60	4.65	5.03	3.92
Fan diameter [m]	1.212	1.74	2.19	1.88	1.25
Dry weight [kg]	3175	2110	4100	3705	2092
Max thrust at sea level [kN]	169.2	133.5	240	156.7	93.4
SFC at takeoff [lb/lbf/h]	0.7/1.39	0.326	0.385	0.381	0.519
SFC at cruising [lb/lbf/h]	1.195	0.545	0.657	0.598	0.737
Cruise altitude [ft]	65000	35000	35000	35000	35000
Cruise Mach number	2.0	0.80	0.80	0.80	0.80
application	Concorde	DC-8 A340	B747 A300 DC-10	B757	MD-82 B727

speeds by referring to the RB211-535 engine performance data, which is close to the maximum thrust (169 kN) of the Pattern 1 aircraft, and the relationship with the bypass ratio is shown in Figure 5. This estimation shows that the fuel consumption rate reaches a minimum around bypass ratio BPR=3 at an altitude of 5,000 ft and supersonic cruise speed of Mach 1.6. In this study, this data was used to calculate the flight distance assuming an engine with a bypass ratio of BPR = 3.

4.2 Range Extension

As described in the previous section, the cruising performance of a transonic cruise is considered in this section. The altitude and speed are set to 5,000 ft and Mach 1.6 for supersonic cruise, and to 4,000 ft and Mach 0.98 for transonic cruise.

Figure 6 compares the flight time for the different flight patterns. The cruise times of the supersonic transports of Pattern 1 and Pattern 2 were compared with those of the competing B787. It can be seen that the cruise time varies depending on the ratio of supersonic to transonic cruise distance. When using transonic cruise in a part of region, the flight time is longer than the supersonic cruise time for the entire region. The longer the transonic cruising distance, the less the time saving effect.

POTENTIAL OF THE RANGE EXTENSION OF SUPERSONIC TRANSPORT

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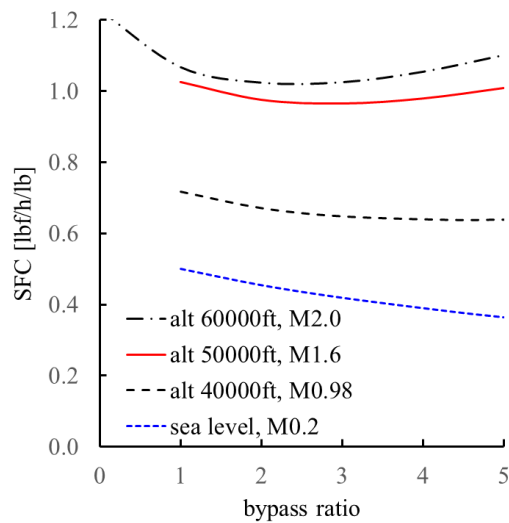


Figure 5. Specific fuel consumption of a turbofan jet engine model

other hand, even if transonic cruise is used, the flight time is still shorter than that of the competing transonic aircraft.

For example, the Pattern 1 operating on the Tokyo-San Francisco route with a flight distance of 4,400 NM will arrive in approximately 6.5 hours, approximately 3 hours less than the 9.5 hours of a subsonic aircraft. A Pattern 2 aircraft operating on the 5100 NM Paris-Saint Baurro route would arrive in approximately 7 hours, approximately 4.5 hours less than the 11 hours and 40 minutes for a transonic aircraft, when operating at transonic speed over land and coast and supersonic speed over ocean. Both patterns have significantly shortened flight time as compared to the competing transonic transport.

Cruising at transonic speed for the entire region, the range can be significantly increased because of the large fuel weight. The Pattern 1 was found to reach a maximum range of 8500 NM, while the Pattern 2 reached a maximum range of 9500 NM.

4.3 Fuel Consumption

Operating costs are strongly influenced by the dimensions of the transport used on the flight route, the range, and the flight time. The longer the range, the more fuel required onboard and the larger

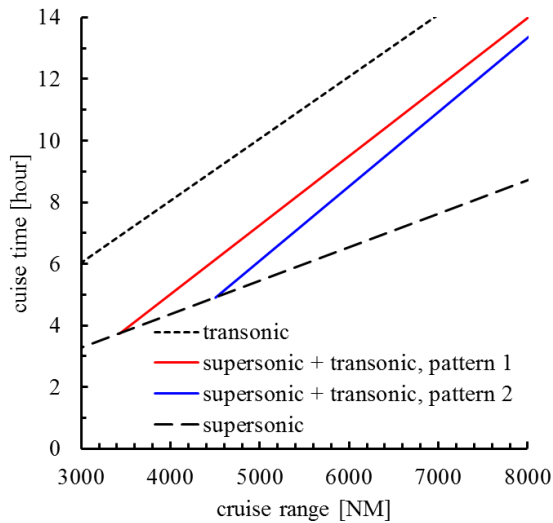


Figure 6: Comparison of cruise times by mode of operation

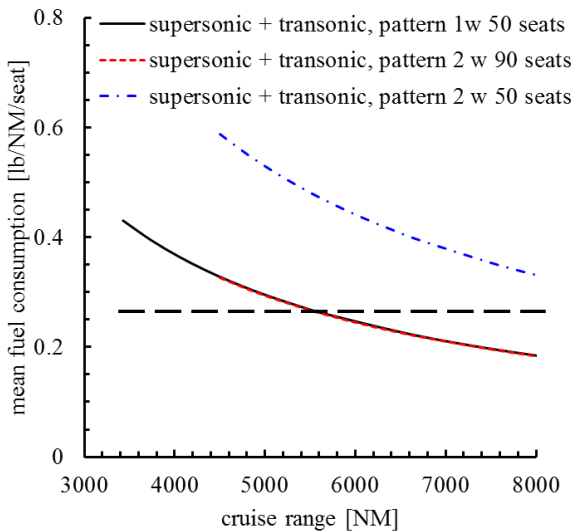


Figure 7: Comparison of operational fuel consumption by mode of operation

the gross weight of the aircraft. Compared to Pattern 1, Pattern 2 improved the lift-drag ratio of aerodynamic performance, but significantly increased the maximum takeoff weight, engine thrust, and ground boom strength. The maximum takeoff weight is 70 tons for Pattern 1 and 120 tons for Pattern 2. Large weight significantly increases manufacturing costs, maintenance costs, and fuel consumption. On the other hand, the specific fuel consumption of supersonic aircraft is approximately twice that of transonic aircraft during cruise. To increase the range, a large amount of fuel must be loaded. For example, in the case of the Concorde, with 100 seats, a cruise speed of Mach 2.0 and a range of 3900 NM, fuel weight accounts for 52% of its maximum takeoff weight of 185 tons. As shown in Tables 1 and 2, for the same range, Concorde halved the flight time compared to the transonic B737MAX, but the fuel consumption per nautical mile per seat was much larger and soared to about eight times.

In addition, the fuel consumption per nautical mile per seat of the Pattern 2 design is even higher than that of the Concorde. The main reason for this is that the Pattern 2 has a small number of seats, so a design with a larger number of seats is required to increase economic profit. Normally, the number of seats is increased as the aircraft size increases in order to reduce the cost per unit operation. As shown in Figure 7, 90 seats for the Pattern 2 is suggested to achieve the same fuel consumption as that of the Pattern 1 with 50 seats.

Due to their high fuel consumption, supersonic transports must operate with all seats in business class. For subsonic aircraft, business class fares are usually about three times higher than economy class fares. Figure 6 compares the fuel consumption per nautical mile per seat for different types of operations. Assuming that the fuel consumption of supersonic cruise is three times that of the subsonic competitors, B787 and A350, the fuel consumption per nautical mile per seat must be reduced to about 0.26 lb/NM/seat, i.e., less than half that of Concorde. Since fuel consumption is highly dependent on the parameters of $(\text{Mach number}) \times (\text{lift-drag ratio}) / (\text{specific fuel consumption})$, large improvements in airframe aerodynamics and engine performance are required. Achieving this level of fuel consumption is seen as very challenging with current and near-term technologies.

On the other hand, if transonic cruise is used in a part region, the longer the cruise distance, the longer the transonic cruise region with lower fuel consumption becomes, and the mean fuel consumption for the entire region decreases. In the case of Pattern 1, the cost that is lower than the business class fares of competing transonic airliners become possible when the cruising range exceeds 5500 NM. The time savings and lower fares make supersonic transports highly competitive if operation combines supersonic and transonic cruising. This is of great interest to airlines, and could open up a new market for business class passengers.

4.4 Sonic Boom

The flow field (Figure 8) was analyzed on a solution-adapted mesh using CFD, and the ground boom intensity was estimated from the Whitham F-Function method [11] using the near-field pressure distribution of CFD at 5 times the full length ($H/L=5$) below the fuselage. As shown in Figure 9, the fuselage of the 50-seat conceptual design had an N-shaped ground profile, which did not provide sufficient sonic boom reduction. However, these values are still larger than the allowable boom intensity of $\Delta p=0.5$ psf (23.9 Pa), which allows supersonic flight over land.

Figure 10 shows the sonic boom intensity of past supersonic aircrafts. The sonic boom intensity tends to increase with the dimensions of the aircraft. Although the conceptual airframe designs studied in this research showed boom reduction effects, neither of them had a low boom design, and the sonic boom intensity must be further reduced to 20 psf or more. A low boom design is expected to reduce the sonic boom intensity.

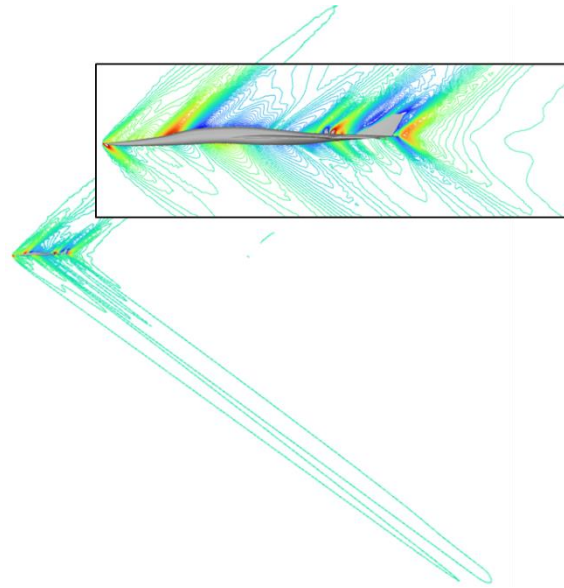


Figure 8: Pressure near-field of CFD analysis during supersonic cruise

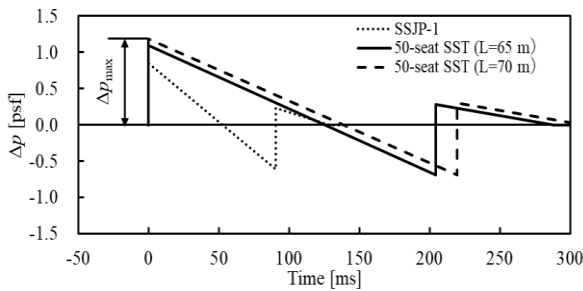


Figure 9: Estimated ground boom intensity

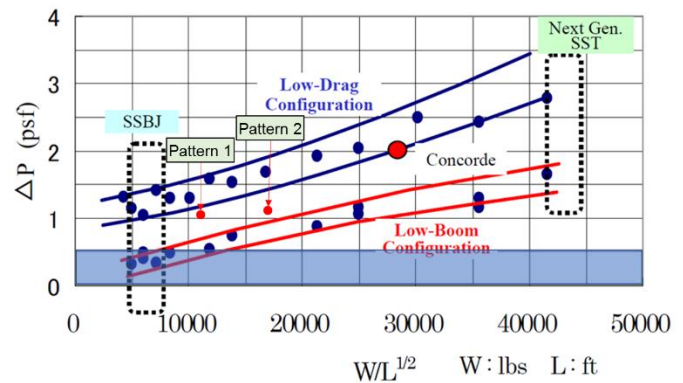


Figure 10: Sonic boom intensity and aircraft size [12]

5. Conclusion

In this study, we investigated the feasibility of the next-generation supersonic transport using the aircraft conceptual design method, examining the aircraft size, engine performance, boom intensity, and cruising performance, and explored the possibility of practical application.

The combination of supersonic cruise and transonic cruise has the following advantages.

- Economic benefit : Reduced cost of aircraft development and manufacturing
- Environmental friendliness : Transonic flight over land and coast
- Speed advantage : Decrease of flight time competing transonic transport
- Increase of flight routes : Market expansion
- Increased range : Expanded routes
- Increase in number of seats : Profit per flight
- Lower fuel consumption : Lower fares, lower emission, more attraction for customer

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