Conceptual design and optimization of a Supersonic business jet

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Abstract

Keeping in view the current opportunities, the market requirements and assessing the feasibility, a conceptual design of a business jet capable of cruising at supersonic speed is suggested. Special consideration is given to drag reduction and thrust optimization at high altitudes and supersonic speeds by geometric sizing and rubber engine sizing respectively. Range is optimized using the Genetic algorithm. Cost of two prototypes based upon aeronautical manufacturers planning report weight is also predicted.

I. INTRODUCTION

Since the early 1980's many studies have been done to establish an economically successful and environmentally harmless supersonic business jet. These studies have been carried out both at industry and academia to establish the technology for carrying passengers at supersonic speed but has not yet been employed and assessed practically, since it's considered an unchartered territory. The Anglo-French joint venture of Concorde (large supersonic transport) was shut down after a few years (early 2000's) of service due to technical issues and crashes, concluding that there is an urgent need to do research more in the supersonic regime along with feasible engines.

Supersonic transport aircraft pose extraordinary design challenges. Tight requirements on a low boom, low drag aircraft coupled with the desire to optimize efficiency, noise, range, and other factors create a lot of challenges at the conceptual design level. But the technology is now available to put the research to test practically. Also the growth of international markets as well as business partnerships between U.S. and Asian-based firms has led to an increased interest in an economically viable business jet capable of supersonic cruise Such an aircraft would reduce the travel time to these regions by as much as 50% by increasing cruise Mach number from roughly 0.85 to 2.2.

II. MISSION REQUIREMENTS

The aircraft must be designed to complete supersonic trans-oceanic flight so a cruise range of 3200 nm is taken as a target for design.

Various segments of the mission profile are:

0-1 Taxi and Takeoff.

1-2 Climb and Accelerate.

2-3 Cruise at Mach 2.2 at 60000 ft for 3200 nm.

3-4 Loiter for 20 minutes at 6000 ft.

5-6 Landing.

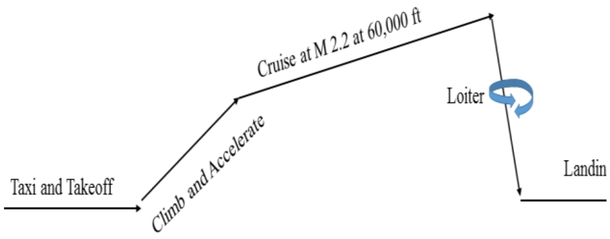

Fig. 1. Mission profile segments.

III. DESIGN CONSIDERATIONS

For better mission performance in the supersonic regime, importance is given to aerodynamics and configuration layout. But foremost consideration is given to takeoff gross weight calculations.

A. *Gross takeoff weight.*

Gross takeoff has been calculated using an iterative process and by using the fuel fraction for each mission segment along with an estimated weight of the same type of supersonic cruise aircraft from historical data. Gross takeoff weight is the sum of Payload weight, Crew weight, Fuel weight, Empty weight of the aircraft. Aircraft is designed for 2 crew members and 8 passengers.

$$W_{\text{Gross takeoff}} = W_{\text{crew}} + W_{\text{payload}} + W_{\text{fuel}} + W_{\text{empty}} \qquad (1)$$

Using (1), gross takeoff weight is calculated.

Table 1. Take of gross weight calculation.

PAYLOAD + CREW WEIGHT	**3000 lbs**
FUEL WEIGHT	30276 lbs
EMPTY WEIGHT	47994 lbs
GROSS TAKEOFF WEIGHT	**81270** lbs

B. Wing design

A low aspect ratio double delta wing with an arrow planform is designed with leading edge sweep ($\wedge_{LE}$) of 68 degrees to reduce drag due to formation of Mach cone at supersonic speeds. At 60% of the planform, second panel of the wing has an edge 63 degree sweep. This wing gives best tradeoff between subsonic and supersonic speeds [4]. An aspect ratio of 2.3 is chosen with span of 43.45 ft.

Based upon distance of the minimum pressure area and range of lift coefficient, NACA 64A204 airfoil is chosen for the wing. The airfoil was also analyzed in a virtual subsonic wind tunnel, with the help of DesignFoil, to confirm its parameters. Wingtip devices increase the lift generated at the wingtip and reduce the lift-induced drag caused by wingtip vortices, improving lift-to-drag ratio. This increases fuel efficiency in powered aircraft which in turn increases range. So a cut off forward swept wing tip is selected for this supersonic wing [1]. Low wing configuration with a dihedral of 4 degree is chosen [1].

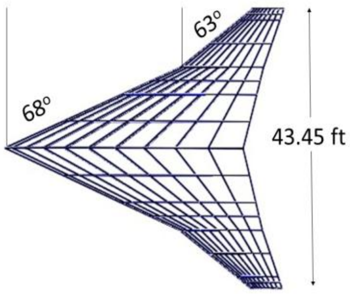

Fig. 2. Wing planform.

C. Fuselage, Nacelle and tail.

The thickness to chord ratio of the supersonic wing is quite low so the wing can't store much fuel, fuselage is designed so that maximum fuel is held in it. In doing so, the fineness ratio came out to be 15. The extra fuel requirement was integrated in fuselage by giving it an elliptical shape rather than a circular one [6]. The length was also increased from 85 to 103 feet. Elliptical fuselage also is spacious for the passengers. Nose droop is used for ground operations and while in flight the fuselage camber line is aligned with cruise free stream vector for less drag [6] and [11].

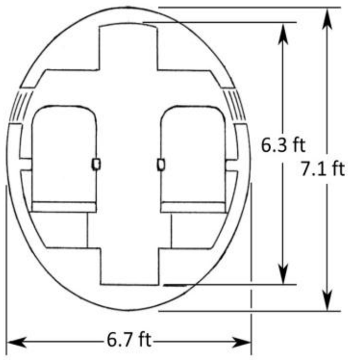

Fig. 3. Fuselage

Engines are placed on the aft fuselage, behind trailing edge of the wing. This placement of nacelle helps in low sonic boom and doesn't require boundary layer diverter. Wake free air enters the engine inlet [6] and [12].

T tail configuration is employed for tail effectiveness since it's free from the wing wakes [1] and [4].

Table II. Dimensions and Areas

Fuselage Length	103 ft
Fuselage diameter.	6.7 ft
Wing span.	43 ft
Wing reference area (S_{ref}).	820 ft^2
Horizontal tail reference area	225 ft^2
Vertical tail reference area	55 ft^2
Nacelle length	12.8 ft
Nacelle diameter	3.41 ft

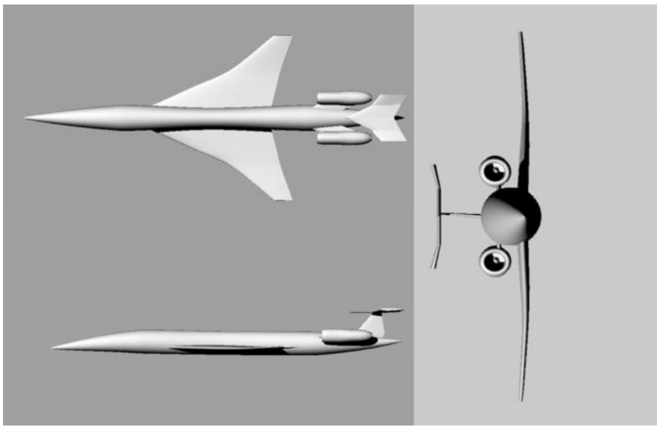

Fig. 3. Three views of the aircraft.

The exact Computer Aided Design (CAD) model is generated using NASA's open source Vehicle Sketch Pad (OpenVSP).

IV. AERODYNAMICS

A. *Drag*

Generally the most important parameter in supersonic regime is drag. Drag arises mainly due to configuration and propulsion. Estimation and minimization of wave drag is of significance here.
Supersonic drag is calculated as:

$$C_{DO}= \Sigma C_f (Re, M) (S_{wet}/S_{Ref})_{+} C_{Dmisc}+ C_{DL\& P}+ C_{Dwave} \qquad (2)$$

All possible drags were calculated and summed up in the final calculation. Final drag plot contains Parasite drag (C_f), supersonic wave drag (C_{Dwave}), interference drag, leakage and protuberance drag ($C_{DL\& P}$), nacelle drag, landing gear drag and miscellaneous drag (C_{Dmisc}).
To reduce wave drag build up on fuselage, area ruled body is designed with Sears-Haack body's volume distribution as ideal for the aircraft.

The wave drag on the area ruled fuselage is determined by (3).

$$C_{Dwave}= 9\pi/2(A_{max}/l)^{2} \qquad (3)$$

Here A_{max} is maximum cross sectional area and l is the longitudinal dimension.
The overall wave drag is calculated by (5)

$$C_{Dwave}=E_{WD} [1.0.386(M-1.2)^{0.57}(1-\pi (\Lambda_{LE})^{0.77}/100)]\, C_{DSears\text{-}Haack} \qquad (4)$$

E_{WD} is the empirical wave drag efficiency taken here as 1.8 and $C_{DSears\text{-}Haack}$ refers to the drag on the idealized body after applying Sears-Haack's volume distribution methodology.
Final drag, after adding C_{Dwave} from (3) and (4), is calculated and plotted against Mach number in Fig. 4.

Fig. 4. Drag variation with Mach No.

Maximum time will be spent in cruise by the aircraft so drag polar at cruise height of 60,000 feet at Mach 2.2 and with starting cruise weight of 72944 pounds is calculated.

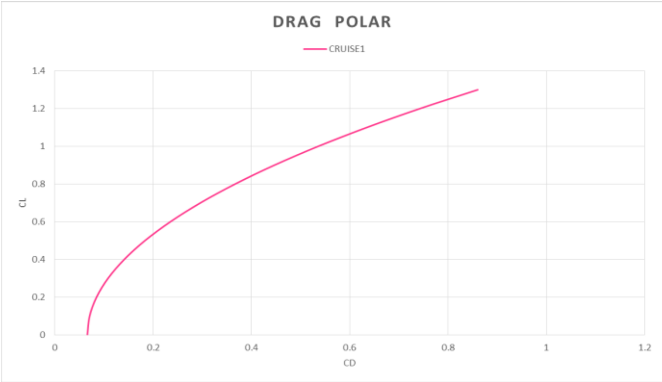

Fig. 5. Drag polar curve.

NASA's SSXJET drag polar curve was taken as the baseline. Comparing the baseline curve and the new curve depicts a significant increase in C_L and also a decrease in C_D at the cruise Mach number of 2.2 [2].

B. *Lift*

The maximum clean lift for the low aspect ratio wing, C_{lmax} of airfoil and the reference ΔC_{Lmax} were used in calculating the C_{Lmax} of the aircraft at different Mach numbers. Triple slotted flaps are employed on the wing to increase the overall lift.

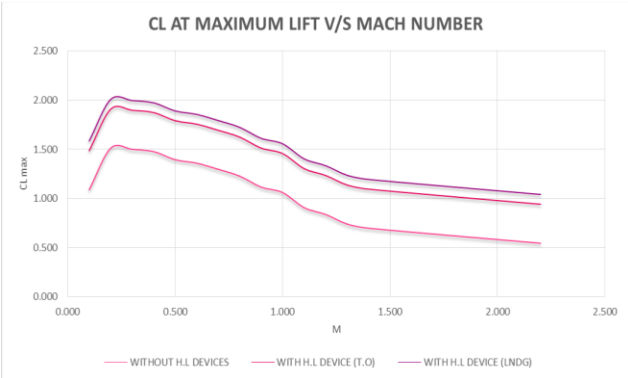

Fig. 6. C_L at different Mach No.

V. PROPULSION

The propulsion system must work efficiently in all mission segments. Supersonic travel highly depends on propulsion system due to high performance requirements both in subsonic and supersonic flight regimes.

For the changing flight regimes in a single mission, a variable cycle engine is required. A high bypass engine is desired for ground and subsonic operations while a low bypass engine is desired for high speed travel.

Keeping in view the above mentioned traits, the General Electric GE/J11-B10 variable cycle double bypass engine is selected as the reference engine, also the baseline engine for NASA's SSXJET [2]. Rubber engine sizing technique is used to scale the engine according to requirements [1].

Thrust matching and statistical estimation technique is used to calculate the maximum thrust to weight ratio (T/W) [1]. With takeoff gross weight already known, thrust is obtained through T/W. The GE/J11-B10 engine has thrust greater than the required thrust for the aircraft. Using a scale factor of 0.82, the engine is scaled down.

Table III. Scaled down engine dimensions.

Length	12.8 ft	8.1% reduction.
Diameter	3.4 ft	10.1% reduction.
Weight	9807 lbs	18.5% reduction.

The bypass ratio and mass flow rate are same as that of the original engine. The reference engine's thrust data corresponding to Mach number and altitude is corrected according to the scaled down engine. An inlet pressure recovery of 0.94 is considered [1] and [2]. Knowing the bleed correction factor, bleed and inlet mass flow rate, a 10% thrust loss is calculated.

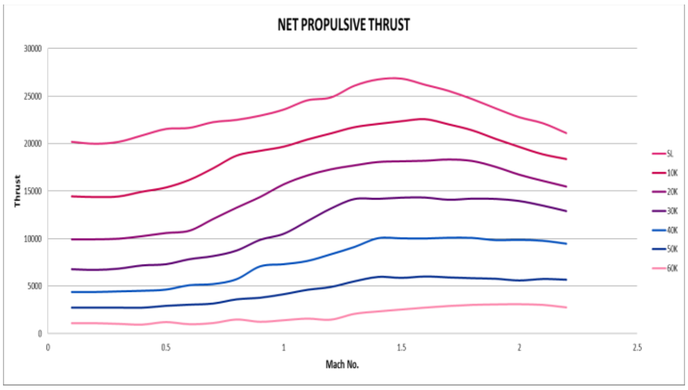

Fig. 7. Corrected thrust.

Fig. 7 shows the optimized thrust for each Mach number at all altitudes.

VI. OPTIMIZATION

The main aim of any transport jet is to maximize range with minimum fuel usage. Supersonic business jet is no different.

$$R = (V/C)(L/D)ln(Winitial/Wfinal) \qquad (5)$$

Range of the aircraft is calculated using (6). Here c is the specific fuel consumption and $W_{initial}$ and W_{final} are the cruise segment weight before and after cruise respectively. L/D is the lift to drag ratio. Aircraft was designed to achieve a range of 3200 nm. The desire to achieve large range without changing the major physical design parameter was achieved by using Genetic algorithm. PALISADE's Evolver module was used to employ the algorithm.

A model on spreadsheet was created that linked all the design variables and constraints. A target range of 3500nm was given to Evolver and it was achieved by adjusting an L/D= 5.7 and also by adjusting the appropriate altitude settings for Mach 2.2 (2140 ft/s).

VII. COST PREDICTION

Although supersonic air travel is desirous but very costly. Even if the aircraft is fuel efficient, many other areas of development and maintenance will make it expensive. First and foremost issue is the cost incurred in development of the aircraft.

Using Advanced Aircraft Analysis software by DAR Corporation, cost of manufacturing two prototypes is predicted. The cost is calculated based upon aeronautical manufacturers planning report weight. This report entirely depends upon the aircraft's empty weight. The empty weight of the aircraft is summation of avionics weight, landing gear weight, installed engine weight, generators weight, hydraulics weight, electrical system weight and weight of wing, fuselage and empennage. The predicted cost for producing two prototypes of supersonic business jet is 44 million dollars.

REFERENCES

[1] Daniel P. Raymer, "Aircraft Design: A Conceptual Approach."

[2] Vincent R. Mascitti, "A Prelimnary study of the performance and characteristics of Supersonic executive aircraft", NASA TM 74055.

[3] Cornelius Driver, "Progress in Supersonic cruise aircraft techonology", NASA TM 78695.

[4] Dr. Dimitri N. Mavris and William T. Hayden, "Formulation of an IPPD methodology for the design of a Supersonic busniess jet," 1st World Aviation Congress, Los Angeles, CA, October 1996.

[5] Kenji Yoshida, "Supersonic drag reduction technology in the scaled Supersonic experimental airplane project by JAXA."

[6] Robert J. Mack, "A Supersonic business-jet concept designed for Low Sonic Boom," NASA/TM-2003-212435.

[7] Sriram. K. Rallabhandi and Dimitri N. Mavris, "Design and analysis of Supersonic business jet concepts," 6th AIAA Aviation Technology, Integration and Operations Conference, Wichita, Kansas, September 2006.

[8] Laurent Daumas, Nicolas Héron, Zdenek Johan, Gilbert Rogé and Sébastien Vigneron, "Aerodynamic design process of a Supersonic business jet," 24th Applied Aerodynamics Conference, San Francisco, California, June 2006.

[9] Leon L. Phan, Yohei Yamaoka, and Dimitri N. Mavris, "Implementation and benefits of variable geometry wings for Supersonic busniess jet," AIAA's 3rd Annual Aviation Technology, Integration, and Operations Tech, Denver, Colorado, November 2003.

[10] Bakar O. Bey, Stephen C. Pace, Zach D. Parson, Raul Telles, "The Javelin concept," Aerospace & Ocean Engineering Dept., Virginia Tech.

[11] General Description Boeing 2707-300 Supersonic Transport, The Boeing Company, September 1969.

[12] Hyoung-Seog Chung, Seongim Choi and Juan J. Alonso, "Supersonic Business Jet Design using a Knowledge-Based Genetic Algorithm with an Adaptive, Unstructured Grid Methodology," Stanford University, "unpublished."

[13] J.J. Thibert and D. Arnal, "A review of ONERA aerodynamic research in support of a future supersonic transport aircraft."