SUPERSONIC BUSINESS JET AIRCRAFT DESIGN

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ABSTRACT

This paper presents a conceptual design for a supersonic business jet based on a design requirement for an 8000 km range, Mach 1.6 cruise, 19 passenger aircraft. Areas investigated in detail include structures, aerodynamics, stability, cabin and cockpit layout, fuel systems, landing gear, engines, performance and multi-disciplinary optimisation. Extensive use is made of work carried out by Professor D. Howe of Cranfield University into conceptual aircraft design and design optimisation methodology. Nearly 8 months of project work by a team of 11 undergraduate Aeromechanical Systems Engineering students has produced a viable conceptual design, though significant noise problems remain regarding sonic boom and engine noise in excess of JAR-36 Stage III requirements.

1. INTRODUCTION

1.1 Background

The recent and well publicised safety concerns and age of the BAe/Aerospatiale Concorde gives rise to a potential gap in the aerospace market. No new replacement supersonic transport is on the immediate horizon, though Boeing's "Sonic Cruiser" may yet partially fill such a void. Meanwhile the trend for larger capacity high subsonic passenger transports continues in the form of the Airbus A380, prompting companies to look at the smaller end of the market for a suitable supersonic transport market. A new business jet therefore seems like the ideal candidate for a future generation supersonic transport.

Such an aircraft would certainly be expensive due to the relatively small production run and would most likely be owned or leased by large international corporations or provided on demand by an agency. The opportunity to charge high fares and leasing charges could, however, make the supersonic business jet (SSBJ) concept tenable.

The specified minimum requirements chosen for the design exercise were as follows:

- Cruise Speed of Mach 1.6.
- 8000 km still air range.
- Cruise altitude between 17 km & 20 km.
- Operation from 2700 m length runways.
- Capable of carrying 19 passengers and 4 crew.
- Compliance with JAR-36 Stage III noise requirements.
- Must have more than 2 engines (ETOPS requirements).

Existing similar concepts in the public domain are the Dassault SSBJ, carrying 8 passengers 7400 km at a speed of Mach 1.8, and the Sukhoi SSBJ, carrying 8 passengers 8000 km at Mach 2.0. Costs for these concepts have been estimated at $83 million and $60 million respectively. The following paper will present a slender body cranked delta configuration with canards and three engines, one mounted in the tail and one mounted under each wing. In the foregoing design process, much use was made of work carried out by Professor D. Howe of Cranfield University, detailed in his book, *Aircraft Conceptual Design Synthesis (Professional Engineering Publishing, 2000)* [1].

2. INDIVIDUAL STUDY AREAS

2.1 Fuselage

In this part of the design, a semi-analytical approach was used to combine supersonic aerodynamic considerations with passenger comfort and compliance with JAR requirements. Fuselage fuel storage also had to be accommodated since the range requirement could not be met with wing tanks alone. A fineness ratio of 19 was found to provide a good compromise between reducing wave drag whilst still minimising overall length.

The cross section was of a double bubble design, with 9.5 tonnes of fuel capable of being stored in the bottom bubble. The passenger compartment has an internal diameter of 1.9 m, and the bottom bubble has an internal diameter of 1.6 m. The effective external diameter is 2.2 m. A headroom of 1.8 m is provided in the aisle by the use of a sunken well in the floor.

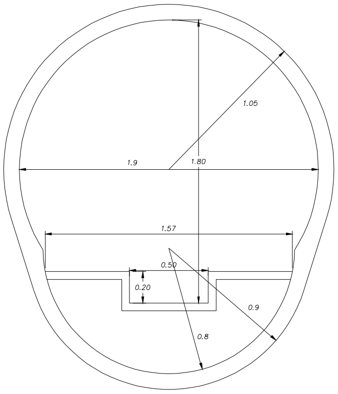

Fig. 1 - Fuselage Cross Section

A fineness ratio of 19 gives an overall aircraft length of 41.8 m, with the main cabin length being 19.8 m long. However, installation issues regarding pressure losses on the tail engine eventually resulted in the overall length being shortened to 35.9 m, giving a fineness ratio of 16.3.

2.2 Cabin

The cabin interior can accommodate either an 8 passenger or 19 passenger configuration in a two-seat across with central aisle layout. The 8 passenger case will also feature tables between facing seats and a group of side-facing divans at the rear. The cabin has been designed to accommodate a fully featured entertainment suite, office equipment and satellite communications, galley and mini-bar.

2.3 Avionics

To reduce costs, the SSBJ makes use of a modern, yet well established, integrated Honeywell avionics package. Along with standard equipment, it also features a Traffic Alert and Collision Avoidance System (TACAS) and a modern colour weather radar that can detect oncoming turbulence, resulting in a more comfortable ride for the passengers. As with the Gulfstream V, the SSBJ has a Head-Up-Display (HUD), which can improve safety by keeping the flight crew's concentration outside of the cockpit whilst still keeping them informed of critical data, and will also aid approach visibility, negating the need for a heavy and complex droop nose as used on Concorde.

2.4 Wings

As the aircraft was required to have good supersonic and subsonic performance, it was decided from an early stage that a subsonic leading edge was required. This was achieved by sweeping the wings behind the shock wave. The wings have been designed to accommodate Mach 1.9 travel, so that the structural aspects of the aircraft would not limit its development potential.

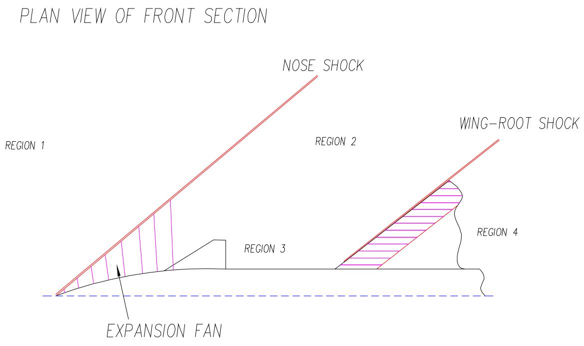

Fig. 2 - Shockwave Analysis

Using a free-stream Mach number of 1.9 and a nose-cone semi-vertex angle of 10°, the Mach number behind the oblique shock wave is 1.72. Using this and a critical Mach number of 0.9, the required wing sweep angle to maintain a subsonic leading edge was found to be 60°.

The planform shape and size were determined by the required wing-loading. An initial estimate of 5500 N/m^2 was found from a constraint diagram, limited by 4 factors; take-off, landing, subsonic and supersonic turns. First stage optimisation however, using more factors, led to a refined value of 3720 N/m^2 for maximum range.

Using a multi-variable optimisation and iteration process involving fuel mass, thrust, drag and wing loading, a wing loading of 3200 N/m^2 was finally reached. However, this wing loading did not provide enough fuel storage room for the range required, so the thickness to chord ratio (t/c) was increased from 3% to 4%, and the iteration process was run again. This then gave a wing loading of 3920N/m². This value was then fixed, and the planform finalised. The maximum span possible was determined from the shock angle from the nose. The final figures were an area of 110 m², a span of 15.73 m and a t/c of 0.04 (4%). This gave a root chord of 14.5 m, a mean aerodynamic chord (MAC) of 10.66 m, and a tip chord of 1.6 m. The wing tips were modified to reduce the possibility of tip stalling. This included the addition of a leading edge crank of 3.5° and wingtip curvature.

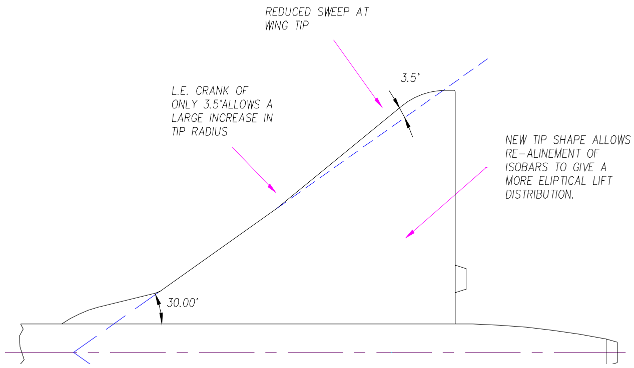

Fig. 3 - Wing Tip Modifications To Reduce Tip Stall

As delta wings have notoriously bad high angle of attack lifting characteristics, Leading Edge Root Extensions (LERX) were added to utilise the benefits of vortex lift. These provide up to 31% of the lift during the landing/take-off phase, and increase the effective wing area up to 125 m². To aid confidence in the design, a 1:80 scale model of the final design was built and tested in the low speed wind tunnel at RMCS. This was used to visualise the conical vortices over a range of angles of attack using smoke flow.

The wing section was difficult to finalise due to a lack of suitable data for 4% t/c sections. As a result, a commercial CFD program (Fluent) was used to design a supercritical airfoil of 4% t/c. The CFD model results were used for the lift and drag estimation. A C_{MO} value of –0.033 was found for this aerofoil design.

2.5 Mass Estimation

The mass of the aircraft and its individual major components were calculated using iterative methods described by Howe [1] and Roskam [2]. A starting mass was first found from basic Level 1 calculations, and then percentages of the overall mass were used to estimate the masses of major components such as the wings, fuselage and systems. A similar iteration procedure to that used to find the wing loading (see above), was then used to find the optimum mass for the stated range requirement.

The total take-off mass with 19 passengers is 44.9 tonnes, with 21 tonnes of this being the empty mass of the aircraft. In approximate terms, this is made up of 7 tonnes for the structure, 1 tonne for the landing gear, 6 tonnes for the systems, 2 tonnes for cabin furnishings, and a total powerplant mass of 5 tonnes. The fuel capacity of the aircraft is 19.5 tonnes, and the maximum passenger payload (including baggage) is 2 tonnes.

The centre of gravity position and variation during flight were also calculated. It is a well-known fact that Concorde moves fuel during transonic acceleration to counter the changing position of the aerodynamic centre, so this was a concern for the fuel system design and for aircraft stability as a whole. The acceptable range of centre of gravity movement for a supersonic aircraft with canards was found to be between 40% and 50% MAC.

At take-off, the centre of gravity was calculated to be 43% of the wing MAC, which equates to 21.7 m from the aircraft nose.

During transition from supersonic cruise to subsonic speeds at the end of the flight, it was found that the centre of gravity moved to 39% MAC. It was therefore decided to allow movement of fuel to the rear of the aircraft during transonic deceleration to aid stability. This changed the centre of gravity position to 41% MAC, falling within the specified boundaries.

The moment of inertia of the aircraft was also calculated for the take-off condition only, in both the x and z planes by considering the individual masses of the components. These came to 9×10^6 kgm^2 and 2.8×10^5 kgm^2 respectively.

2.6 Lift & Drag Estimation

The lift and drag was primarily reliant upon the mass and wing calculations, but was an important consideration for the powerplant design, and feedback was given for both wing design and mass estimation. The analysis of lift and drag was broken down into five main stages of flight. These were: take-off, climb out to subsonic cruising altitude, subsonic cruise, climb out to supersonic cruising altitude, supersonic cruise, descent to subsonic cruising altitude, subsonic cruise and descent before landing.

For subsonic cruise the lift coefficient required was 0.235, and for supersonic cruise, which was considered to be the design point, the lift coefficient required was 0.16. The lift curve slope of the wing was calculated to be 1.95 per radian (0.034/°) for the subsonic case, and 2.6 per radian (0.0455/°) for supersonic cruise. C_{Lmax} was calculated to be 0.95, which takes into account the LERX generated vortex lift.

The drag polars for the aircraft at various stages during the mission profile were also calculated. These are given in the table below.

Initial subsonic cruise	$0.0106 + 0.209C_L^2$
Start of supersonic cruise	$0.012 + 0.356C_L^2$
End of supersonic cruise	$0.012 + 0.356C_L^2$
Final subsonic cruise	$0.0103 + 0.215C_L^2$

Table 1 - Drag Polar Equations

The maximum drag force was encountered during initial supersonic cruise, being 81kN, with transonic acceleration giving an estimated drag of 54kN. The lift to drag ratios were calculated from the above data, and gave values of 10.6 for subsonic cruise and 8 for supersonic cruise.

2.7 Powerplant Design

2.7.1 Engine Selection

The selection of the engines has been a major stumbling block for other supersonic passenger aircraft concepts. Due to supersonic flight, a low bypass ratio turbo fan is required, falling into the category of military fighter engines. These have a high tsfc, and require frequent maintenance. They are, however, the only feasible solution for ‘supercruise’ conditions, i.e. sustained supersonic cruise.

To this end, a choice of military engines was considered, with the final choice being based on best thrust for minimum fuel consumption. The chosen engine was a Rolls Royce RB199, as fitted to the Panavia Tornado.

As the engine performance was a critical parameter, accurate information was necessary for the rest of the design group. The manufacturer’s released information was inadequate for this, so a fully comprehensive Microsoft Excel spreadsheet was constructed using the limited released data and basic gas turbine theory. This spreadsheet, once completed, was able to give thrust values, sfc’s and other key engine temperatures and pressures for any flight speed and any altitude given certain key input engine parameters such as bypass and compression ratios. The model was validated against known engine performance data.

As the design progressed, the RB199’s use became more marginal, but the use of the much more powerful EJ200 could not really be justified due to its greater fuel consumption. As the RB199 is a fairly old design, it was decided to use the spreadsheet to ‘design’ a more modern version, taking into account advances in engine technology. This led to the production of a hybrid RB199. This version had the compression ratio increased from 23:1 to 26:1, and the TET increased from 1600K to 1700K. These changes seemed reasonable in light of recent blade material developments. For the engine to be economically suitable for the civil market, the service interval will have to be significantly increased from the 16 hours under current military practice.

2.7.2 Intake Design

A supersonic intake was designed in order to reduce the velocity from the supersonic flow down to Mach 0.45, as required by the compressor first stage. Complex variable geometry intakes were discounted due to weight considerations, so the intake was designed for the supersonic cruise conditions only. The intake is a fixed geometry, external compression intake. It comprises a 2-shock (oblique and normal shock) system, which is formed by a protruding conical section (see Fig 4). The cone semi-vertex angle is 23.9^o and the intake throat area is 0.230 m^2. To control the position of the normal shock and prevent the shock system operating sub-critically a single bypass door was incorporated on the wing mounted intakes and two smaller doors on the fuselage intake. The capture area is 0.673 m^2 and this area is complemented with auxiliary doors with an area of 0.150 m^2 for low speed, low altitude operation.

The intake is primarily designed to operate at flight speeds of Mach 1.6 with a pressure recovery of 90 %. The intake has also been designed with growth in mind, and will still operate reasonably efficiently up to Mach 1.9 with a pressure recovery of 88.5%. The intake provides an air mass flow rate of 74.6 kg/s.

The installed engine thrust per engine is 58.4kN (SL Dry), and 125.4kN (SL Wet). This is achieved at a static tsfc of 0.65 Ns/kg. During initial cruise conditions (Mach 1.6 at 17 km altitude), the thrust produced is estimated as 29 kN per engine. The use of the afterburner is not required under normal flight conditions, but is required in the event of an engine-out take-off condition. It is this condition that defines the required engine thrust, calculated to be just over 100 kN per engine.

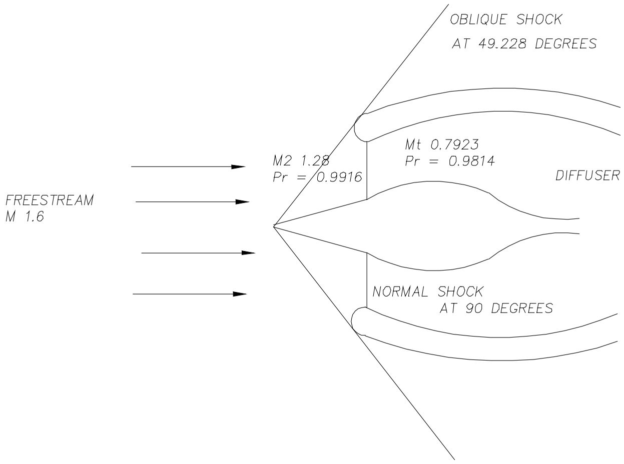

Fig. 4 - The Fixed Geometry Intake

2.7.3 Noise Considerations

One major problem associated with using a military derived engine is the issue of noise. No current military engine would satisfy the latest, stringent, noise measures laid out in JAR 36 stage III [3]. The era of European environmental airline taxes is also thought to be close, making the issue even more critical.

For an aircraft of this size, the maximum noise levels are currently given as:

Take off noise must not exceed	95 dB
Flyover noise must not exceed	90 dB
Approach noise must not exceed	98 dB

The engine noise emitted from the hybrid RB199 has been estimated to be as follows:

At the lateral reference point:	120 dB
At flyover reference point:	98 dB
At approach reference point:	108 dB

Whilst these figures compare favourably with those of Concorde (119.5 dB, 112.2 dB & 116.7 dB respectively), major noise reduction is clearly required. Research suggests that developments in this area have been limited thus far, but potential fixes could include the use of acoustic liners, swept blades and jet efflux mixers, as well as possibly increasing the bypass ratio. A combination of all of these methods (and possibly more besides) would be required to give the necessary 21% maximum reduction. This issue is probably the greatest potential threat to the concept.

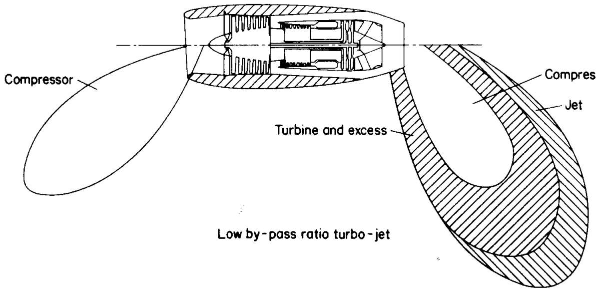

Fig. 5 - Sources Of Noise From A Low BPR Turbofan

2.8 Aircraft Performance

Many of the aircraft's performance characteristics were laid out in the specifications. As such, the aircraft is designed to cruise supersonically at Mach 1.6 at 18 km altitude, with expansion possible to Mach 1.9. The subsonic cruise is at Mach 0.9 at 10 km. Transonic acceleration is assumed to be carried out at 17 km altitude, to take the SSBJ above the flight paths of subsonic aircraft.

The range had been set as a minimum of 8000 km, and as fuel storage was a major problem, it was to this minimum range that the aircraft was designed. A range of 8500 km is possible with a reduced load of 8 passengers. The range does however depend on the route flown, as supersonic and subsonic ranges are different.

For the take-off roll, the aircraft benefits from canards, enabling a reduced rotation velocity of 90 m/s compared to Concorde's 110 m/s. A significantly shorter take-off length was also calculated at 1450 m. The accelerated stop length is 1950 m with a decision speed of 82 m/s. This will enable the aircraft to use runways of only 2 km length, more than satisfying the requirement for 2700 m runway performance.

The approach speed was calculated as 93 m/s, and this is achieved without the use of flaps. The landing roll will take up 1200 m with the use of thrust reversers, fitted as standard to the RB199.

The aircraft was also designed to allow a service ceiling of 20 km, and a maximum normal load factor of 2.5.

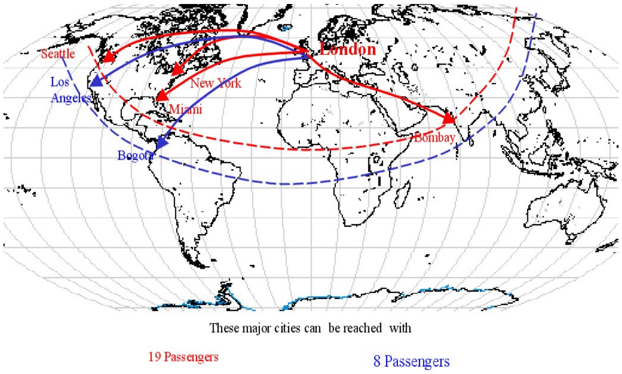

Fig. 6 - The Range Of The Aircraft Under 2 Loading Cases

2.9 Stability and Control

The stability and control was split into two areas for study; longitudinal and lateral. The longitudinal work was mainly concerned with the canard design and positioning, while the lateral studies were mainly concerned with fin and aileron sizing and positioning.

The canards were bounded in their available position by the need for a passenger entry door and cockpit visibility considerations. This called for a long-coupled canard configuration to be used. The canard size was found as a function of the wing size, and was equated to 13% of the wing area (i.e. 14.3 m²). The span is 5 m, and the root chord is 6.15 m. The degree of canard movement is ±25°. Once this design had been completed, the stability derivatives could be found, and these indicated that short period frequency was 0.6 Hz, with a phugoid damping of 0.018.

For the lateral stability and control, fin stalling under full rudder deflection dictated a fin size of $18m^2$. The aircraft was deemed to exhibit positive static stability characteristics, with weathercock stability suggested by the derivative N_v being positive, and roll stability present due to L_v being negative. A Dutch Roll frequency of 1.9 Hz was deemed acceptable, and spiral mode was found to be in subsidence, with a period to half amplitude of 13.5 s. The ailerons span from 5m to 7m from the centreline, and this ensures acceptable roll performance, with a 30° bank achieved in 1.8 s.

Heading change following an engine failure was found to be marginally within regulations. A heading change of 0.33 radians was estimated, compared with the maximum allowable value of 0.35 radians.

2.10 Landing Gear

The undercarriage layout is of a conventional tricycle configuration with twin wheel nose and main gear units. The main gear units are configured as tandem units, wing mounted, retracting sideways into the wing/fuselage structure. The nose gear unit consists of a twin unit, fuselage mounted, folding forwards to locate the wheel ahead of the flight deck.

The main problem facing the design of the landing gear was the positioning under the wings. Lateral stability during engine out dictated the furthest position of the engines, and the space between engine and fuselage was too small for the required strut length. This called for a trailing bogie to be used, similar to that used on the Avro Vulcan. The lateral position provides a track of 3.75 m with a turnover angle of 53^0. This gives a turning radius of 50 m.

2.11 Structure & Material Selection

Due to the kinetic heating effects of supersonic flight, traditional Al 2024 cannot be used due to creep problems associated with overaging at temperatures of around 100°C. Therefore, Al-Cu-Mg-Ag, 2219, will be used for the aircraft skin, and a Ti-6Al-4V titanium alloy converging wing box will be used for the wing structure. The fuselage frames will be constructed from Al-Cu 7075 T76. V-n diagrams were constructed and gust loads were superimposed onto these, indicating that the aircraft was gust sensitive. The main wing structure will consist of 5 main spars, arranged in a converging eggbox layout.

2.12 Auxiliary Systems

This area of study area was concerned with the fuel system, fire system, hydraulic and electrical systems, although only in at a preliminary level. The fuel system was based on the Tornadoin order to aid commonality with the engines. The fuel will be stored in crash resistant bag tanks for the fuselage, and features self-sealing wing tanks to help prevent a recurrence of the tragic Concorde fire.

A standard hydraulic system has been used for the control surfaces and undercarriage, with hydraulic actuators, pumps and reservoirs. The electrical system is fed from 3 VSCF generators producing 75 kVA each, and backed up by an auxiliary power unit (APU).

The fire system is based on fire-wire and heat sensitive/resetting switches, and engine and fuel system two-shot fire extinguishers.

2.13 Design Optimisation

The design was optimised over two levels, the first relating to trade-offs between wing loading and thrust/weight ratio, and the second being the minimisation of aircraft mass. An individual student was assigned this task for the duration of the project, with his output providing top-level guidance to the rest of the team. This was done exclusively from methods devised by Prof. D Howe [1]. The optimisation results were fed back to the other team members on a regular basis and were then used by the others to check their own areas of work.

2.14 Costing

Using a standard costing model (Roskam [2]), an estimate of the aircraft purchase cost and lifecycle cost was made. Many assumptions had to be made due to a lack of information and experience. The aircraft was estimated to cost $73.2 million, assuming an production run of 200 aircraft. Market research indicated a potential demand for 300 to 400 aircraft over 30 years. This cost compares to the $83 million for the Dassault SSBJ, and $60million for the Sukhoi, based upon similar levels of production runs.

3. Conclusions

A group of 11 undregraduate Aeromechanical Systems Engineering students have produced a conceptual design for a supersonic business jet capable of carrying 19 passengers plus associated baggage at a range of 8000 km at Mach 1.6 cruise at an altitude of 18 km. The aircraft total take-off mass is 44.9 tonnes with an operating empty mass of 21 tonnes.

Major issues remain unresolved, however, particularly regarding issues such as costs, powerplant development, noise and other environmental concerns. There are clear benefits for future supersonic business travel, especially in the case of overland supersonic flight. Whether allowances could be made regarding the noise problems, only time will tell, though it appears doubtful at this present moment in time. However, with the present rapid development in aerospace technology and science, it may not be too long before the first supersonic business jets are following in the giant footsteps of Concorde.

4. Acknowledgements

This project was carried out by 11 final year students on the BEng Aeromechanical Systems Engineering degree at the Royal Military College of Science campus of Cranfield University (UK) [4]. This paper is a result of the work completed by the students in the academic year 2000/2001, overseen by the project supervisors (Dr D.Bray & Dr N.Lawson).

5. Notation

C_{Lmax}	Maximum Lift Coefficient
C_{M0}	Zero Lift Pitching Moment
CFD	Computational Fluid Dynamics
ETOPS	Extended-Range, Twin-Engine Operations
JAR	Joint Airwothiness Requirements
LERX	Leading Edge Root Extensions
L_v	Rolling Moment due to Sideslip
MAC	Mean Aerodynamic Chord
N_v	Yawing Moment due to Sideslip
RMCS	Royal Military College Of Science
sfc	Specific Fuel Consumption
SL	Sea Level
SSBJ	Supersonic Business Jet
t/c	Thickness to Chord Ratio
TET	Turbine Entry Temperature
tsfc	Thrust Specific Fuel Consumption
VSCF	Variable Speed, Constant Frequency

6. References

[1] D. Howe, (2001) *Aircraft Conceptual Design Synthesis*. United Kingdom: Professional Engineering Publishing Limited

[2] J Roskam, (1997) *Airplane Design Part II.* DAR Corporation, Kansas

[3] Joint Airworthiness Authority, (2001) Joint Airworthiness Requirements. www.jaa.nl/jar/jar.html

[4] The majority of this paper is based on the individual reports of the students who undertook the project – all RMCS Cranfield 53 Degree ASE (2001).

Wing Aerodynamic Design – R.Cobb & T.Lowing, Intakes, Powerplants & Noise – D.Holmes, Mass Properties & Costings – N.Britton, Lift & Drag – P.Helliwell, Performance & Landing Gear – J.Wilson, Optimisation – G.Dimitriadis, Lateral Stability – T.Lowing, Longitinal Stability & Control – E.Promtun, Structures & Materials – C.Camp, Landing Gear – P.Helliwell, Powerplants & Systems – P.Smith

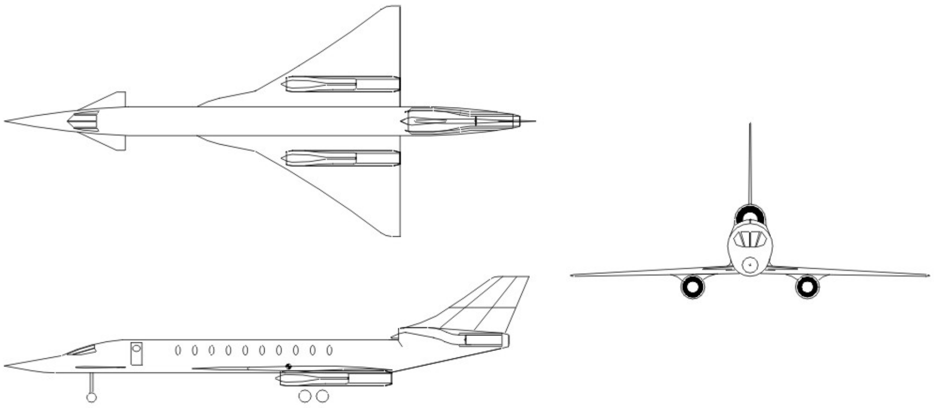

Fig. 7 – A 3-D View Of The Proposed Supersonic Business Jet