Supersonic Passenger Flights in Civil Aviation

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Abstract

For over the last few centuries the transportation industry has grown quite rapidly. But the concept has been there for quite a long time. Starting with the invention of wheel, human civilization has continuously evolved itself to the extent where flying by air is no more a dream. The biggest challenge faced by the industry is to increase the travel distance with reduced time being more economically feasible. The advancement in science and technology, and the invention of the airplanes using those complicated but fundamental laws of physics has made it all seem true. The invention of supersonic planes has breached the speed of sound reducing the travel time by even more than 50%, bringing the world closer. But in the year 1973, the airplane authority in America banned the passenger supersonic flights over the country. As a result of it the supersonic passenger airplane industry is yet to get developed. The time has now come to revisit that ban. More advanced materials, engines, technology and the capabilities to simulate means that it is now possible to manufacture a supersonic civil aircraft which will be far more economical. In this paper, the history of the supersonic flight and some genuine issues related to it are examined first. This then follows up with the brief introduction of the topic, dwelling a little into first successful supersonic passenger plane - 'The Concorde' followed up by the basic engineering principles which made it achieve such high speeds and the challenges to be solved for the success of supersonic passenger flights in civil aviation.

Figure 1

Introduction

Supersonic speed refers to the speed of the object greater than the speed of sound. Basically the speed of an object can fall into one of the four regimes with respect to speed of sound. The ratio of the speed of an object to the speed of sound in the medium is denoted by a non-dimensional number called the mach-number. Based on mach-number the sound speed regimes are classified as subsonic, transonic, supersonic and hypersonic speeds which in laymen term means less speed, nearly equal to, greater than and much greater speed than sound respectively. More precisely supersonic travel is defined as the rate of travel of an object that exceeds Mach 1 (i.e. speed of sound in that medium).For objects traveling in dry air of a temperature of around 25C at sea level, this speed is approximately equal to 343 m/s. An example of supersonic object is bullet fired from gun which travels faster than the sound speed.

i. Sound propogation in a medium

Sound waves are the traveling vibrations in an elastic medium in the form of pressure waves. In gaseous medium sound waves travel longitudinally at different speeds, which mostly depends on the temperature and molecular mass of the gas. Although it also depends on pressure but it has negligible effect on the speed. The speed of sound called acoustic speed given by

$$v = \sqrt{\frac{\gamma * P}{\rho}}$$

where ρ is the density of the gas, P is the pressure and γ is a constant called the adiabatic index.

Now since the temperature and composition of air varies significantly with altitude, which in turn means Mach number for aircraft may change despite the same speed and therefore the regimes of object travel may change at the same speed at different altitudes. This principle gives rise to different aerodynamic characteristics of the airplane in supersonic regime at same speed.

ii. Supersonic Transport(SST)

SST is an aircraft transport system designed to transport passengers at speeds greater than Mach 1. Supersonic transport (SST) was once a dream that became the reality, and then again became a dream . At present supersonic planes are only used in military services with most of fighter jets designed using this technology. But the history speaks something different. It reveals that our current technology is capable of implementing this technology in the application of civil aviation. Till date, there have been planes engineered which have crossed the speed of sound(Mach 1). The only supersonic planes to have been operated on regular basis are - the Concorde and the Tupolev Tu-144. The last flight carrying passengers of the TU-144 flew in June 1978 while that of Concorde in Nov month of 2003. After that there have been no passenger supersonic flight. Around in 1950 SSTs seemed technically possible but economically unfeasible. Methods used for generating lifts at supersonic speed are far less economical than that at subsonic methods, preferably due to the lift-to-drag ratio being half in latter

iii. The Concorde and the Tupolev supersonic planes

The Soviet made Tu-144 flew in 1968 for the first time advancing to supersonic flight in 1969. It started the commercial passenger flight on November 1, 1977 and took its last passenger service on June 1, 1978 after a crash killing two crew members. The Olympus 593 turbojet engine was used in it, along with afterburners for injection of extra fuel into the jet pipe so as to increase thrust during takeoff. The temperatures on surfaces in supersonic flights are generally high due to friction so in order to sustain enough heat, an aluminum formed alloy was used which kept things normal up to around 127 C.

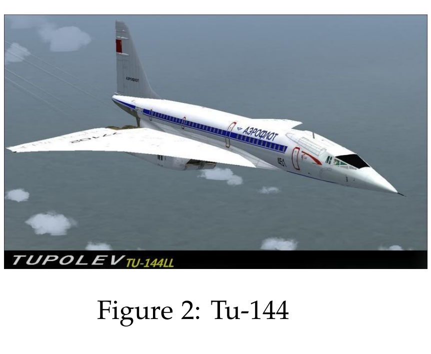


Figure 2: Tu-144

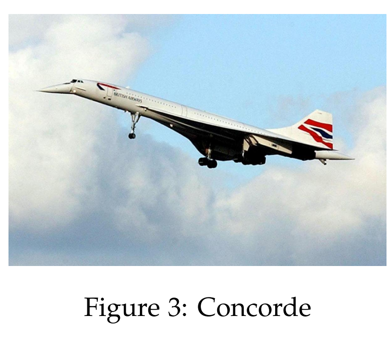


Figure 3: Concorde

iv. Shutting down of Concorde

The Concorde's demise is a complicated tale, but it suffered from two mortal flaws. First, it was a horrendous fuel-guzzler and too expensive to operate. Under the laws of physics, the air resistance or drag that a given object faces in flight increases rapidly as you approach Mach 1. So a plane flying at supersonic speed requires a lot more energy than one flying below the speed of sound.

The Concorde's designers tried to reduce drag by giving their plane a sleek body and short, slender delta wings. Even so, the Concorde required staggering amounts of fuel,about eight times for trans-Atlantic trip compared to present day. That made tickets forbiddingly expensive: $10,000 or more for a New York-London round trip. As oil prices rose, British Airways and Air France (which operated the jets) struggled to consistently fill the jets with 100-125 seats. Bad for profits.

A second problem, meanwhile, is that whenever the speed of Concorde exceeded the speed of sound about 767 miles per hour it created noisy sonic booms in its wake. As the speed of an airplane reaches near Mach 1 at higher altitudes, shock waves know as sonic boom are produced as a result of compression of air waves at plane's nose. In case of the Concorde, the produced sonic boom was as loud as 135 decibels when the boom reached land.

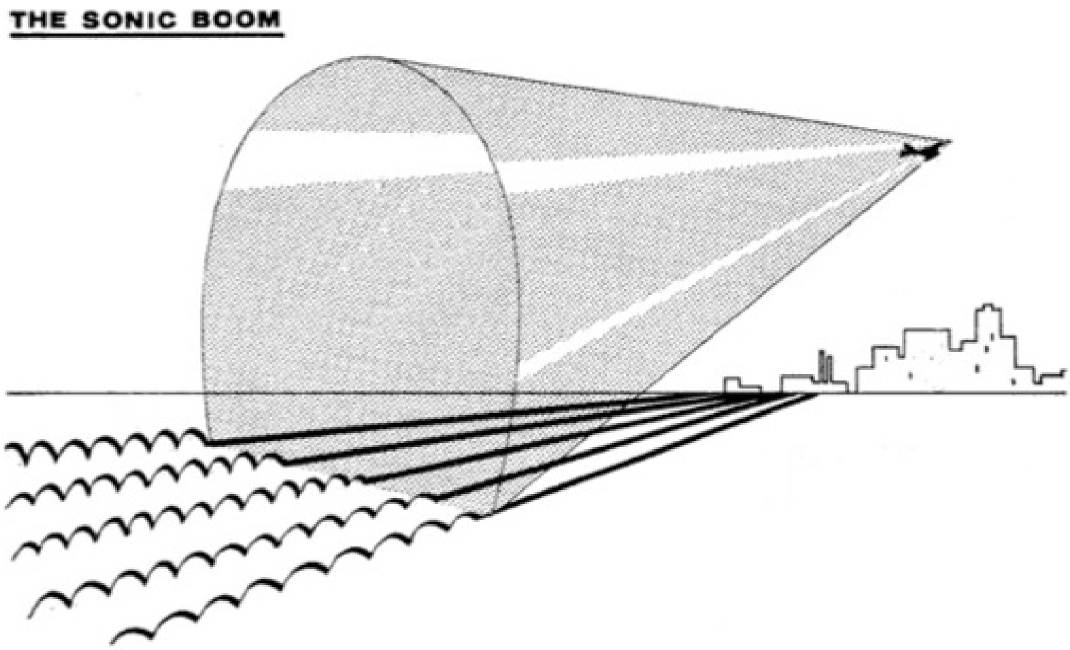


Figure 4: Sonic Boom

To put it simply, the air in front of the Concorde couldn't get out of its way fast enough, so it bunched up into large shock waves in a cone trailing the plane. Wherever those shock waves reached the ground below, they'd be heard as a loud " BANG, BANG that could rattle windows, shake structures, and startle people. After the Concorde went bust, airlines shied away from supersonic flight. The extra speed didn't seem to justify the hassle. After a lot of researches, nowadays new generation of supersonic plane designs are coming up encompassing decades of advances in aerospace engineering, material sciences and simulation techniques in order to reduce the intensity of the sonic boom to a great extent. One more reason for its shut down was the serious environmental concerns a large no. of SSTs traveling at very high altitudes could pose a threat to the ozone layer. There's also the fact transport on Concorde was extremely expensive. Fuel efficiency was also extremely low. When all of these effects are added up, Concorde didn't make economic sense.

Working Principles of Supersonic Aircraft - The Concorde (Case-Study)

The Concorde's ability to fly faster and higher cruising at 1,351 mph equating to 2,172 kph, or Mach 2 at an altitude of 18,300 m made it's engineering more complex and challenging than for the subsonic planes. It's unique streamlined design, Engine design, Main and auxiliary fuel tanks and High-reflectivity paint made it stand apart from major other aircraft.

i. Streamlining

As the plane approaches the speed of sound, a "wall" of air is formed due to the air pressure that builds up in front of the aircraft. Streamlining of the plans is done in order to escape through that wall. For the streamlining of the Concorde, following designs were implemented:

Figure 5: Concorde

- Swept-back delta wing
- Needle-like fuselage
- Vertical tail design
- Movable nose

The Concorde's wing were typical Delta-wing designed having thin, triangular shape. These helped in reducing drag by being thin and provided sufficient lift for take off and landing at subsonic speeds. In order to reduce the drag on the plane when it moves through the air, it had a long, narrow shaped nose. The Concorde used a needle shaped long nose for the air to penetrate which can be tilted up or down during during take off or landing. The windshields were protected using visor when the flight reached supersonic speeds.

ii. Engine in Concorde

The engines that were mounted on the Concorde were capable enough to provide the necessary thrust for takeoff, cruising and landing of the plane. Thrust of 180kN was being produced by each of its four Rolls Royce/Snecma Olympus 593 turbo jet engines. The fuel consumption of all the four engines together was around 25,629 L of fuel/hour.

The engines used on the Concorde were different from those on the other jets. The Concorde's engines were directly attached to the underside of the wing without using the engine struts. This design helped in reducing the air turbulence. At very high speeds the engine struts were likely to break.

In order to reach supersonic speeds the afterburners were used in Concorde's engine to gain additional thrust. Afterburners are used to mix the additional fuel with the outgoing gas and burn it to get more thrust.

iii. Fuel Tanks

The fuel used by Concorde was Kerosene, which is stored in 17 fuel tanks with a capacity of 119,500 litres. These tanks were divided as five on each wing and four on fuselage. Unlike other jets, it used its fuel tanks for aerodynamic stability as well. As supersonic speeds were reached, its aerodynamic center of lift shifted backwards and as a result the nose of aircraft turned downwards. To overcome this instability the fuel is pumped back to trim tanks making its center of gravity match the center of lift.

iv. High-reflectivity Paint

Due the the higher speeds at which the plane operated, the effects of air pressure and friction heats up the body of the plane. To engineer its solution, some properties to radiate this heat were needed. Thus the Concorde was covered with high-reflectivity white paint having the reflectivity twice than the paints on normal jets. The heat developed due to pressure and friction effects caused the plane frame to expand as much as 18 cm. This to minimise the stress and to make it more heat tolerant, the Concorde was manufactured using light weight aluminium alloy.

What are the requirements of an ideal supersonic passenger flight??

For a commercially successful and economical supersonic passenger flight, there are lot of hurdles to be taken care of.

i. Range Capability

Supersonic flights are generally preferred to be flown over the ocean on trans-oceanic routes rather than over the land. This is to minimise the sonic boom produced at the ground. Here there are two things to be taken care of:
(i) First to make it possible to fly over the ground.
(ii) Second to make the trans-oceanic flights possible and economic.C
Considering the second case first, the trans-pacific and the trans-Atlantic routes have to be evaluated for a non-stop flight to operate. The large distances make it a necessity to have one stop for refueling atleast in the Pacific region to have a non-stop flight over the Atlantic region (Pacific barrier is twice as long as the Atlantic barrier). This is the minimum requirement. Fuel fraction is defined as the ratio of fuel weight to the take off weight of the airplane.

$$FuelFraction = \frac{W_F}{W_T}$$

where W_F is the weight of fuel and W_T is the take off weight of airplane. This fuel fraction is an important criteria that influences the range. The Breguet Range equation which predicts the range for a given fuel fraction is:

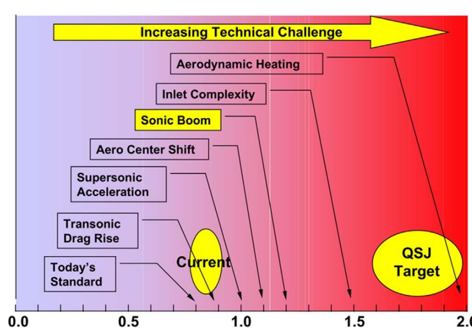
$$R = \frac{Ma \times a}{SFC} \times \frac{L}{D} \times \ln\left(\frac{W_T}{W_T - W_F}\right)$$

where SFC = specific fuel consumption, a = speed of sound, W_T = take-off weight, W_F = weight of fuel. Real value analytics for Ma = 1.6, a = 295m/s, SFC = $1.0/h$ and L/D = fuel fraction for Atlantic range comes out to be 42%. It's been observed that the improvement in lift by drag ratio achieves a range improvement over a considerable range. Today with the current technology the capability of supersonic planes to carry fuel lies somewhat at about 50%. This concludes that for a long range flight higher L/D ratio, high fuel fraction and engine performance are essential factors. The first case is discussed later in the section "Sonic Boom"

ii. Mach Number

With the increasing Mach number, the technical challenges increase in supersonic regime. For a passenger supersonic plane, considering the aerodynamic heating effects it is best to set the upper limit to Mach 2.0. Moreover common material for airspace industry cannot be utilised beyond this speed. Other effects like inlet complexity, aero-center shifting also takes place in that range which needs to be taken care of. These are shown in Fig 6.

Figure 6: Supersonic speed challenges



iii. Flight Altitude

High-altitude emissions

As the supersonic planes fly at higher altitudes, there is a higher chances of ozone layer depletion due to emissions at that altitude. One report by UIUC on the impact of supersonic planes indicated 14.5 km crossover point for the depletion.

High altitude radiation

One of the concerns at higher altitudes is the direct exposure to the cosmic radiation. The Earth's atmosphere protects and shield us from the direct contact of the harmful radiations, but at higher altitudes this is not likely to help. Although various researches have shown that the amount of radiation lies well within the ranges defined by the IRCP but necessary precautions for pilots and crew members have to be taken care of.

Operation Safety

At altitudes higher than 55,000 ft, one of the major challenge is to ensure the safety of the crew members as well as the passengers. The plane must be equipped with the technologies of self healing in case of cabin de-pressurisation.

Passenger Capacity

According to the Seebass-George-Darden (SGD) theory the lift along with the aircraft volume effects the sonic boom intensity directly. Thus the intensity of sonic boom depends on volume which in turn depends on the passenger capacity.

iv. Environmental Concerns

Supersonic flights impacts the atmosphere to a larger extent compared to the subsonic planes as they travels at higher altitudes penetrating the stratosphere. The main global concern from these planes is the emission of oxides of nitrogen (NO_X) and H_2O vapors which alters the atmospheric composition, in particular the ozone layer, affecting the climate significantly. According to a study conducted by NASA on the emission effects on stratosphere and ozone, it concluded that any flight above a specific altitude would effect the ozone layer tremendously. One other major project named SCENIC funded by EU studied the potential climate impacts due to the future supersonic flights. The results obtained, confirmed the previous findings about the climate changing effect of water vapor emission in stratosphere.

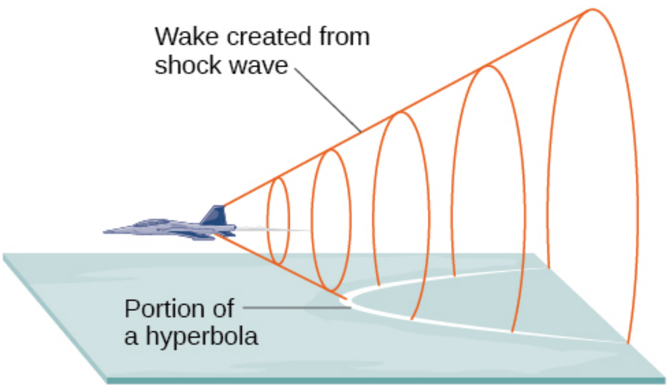


Figure 7: Wake

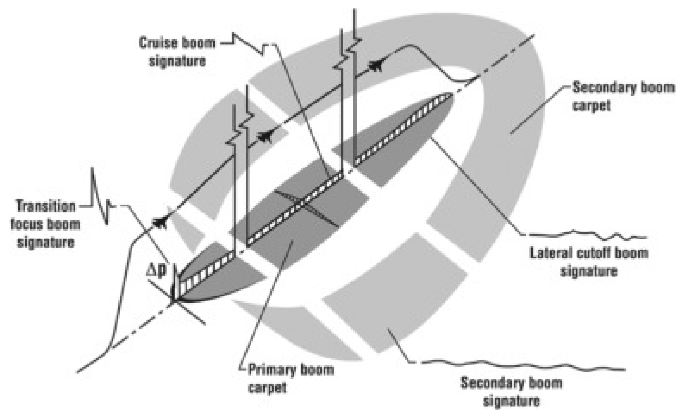


Figure 8: Sonic boom Carpet

Another major environmental issue due to supersonic flight is the sonic boom intensity. Whenever these supersonic planes fly at speeds greater than Mach 1, a carpet of sound waves called sonic boom is formed. The sonic boom intensity has a wide range of effects on the wildlife and marine life. Due the difference in the sensing and hearing capabilities of different organisms the effects are also quite distributed. Humans remains calm at the intensity of 1psf. But above it, it becomes annoying for us. The structures also start to get minimal damages above 2.6 psf intensity. For certain animals, this causes issues in their reproduction cycle. Even thought, sea life is observed to be effected very less due to supersonic planes compared to the land life. It is because about 90% of waves gets reflected back from the water surface minimizing the penetration effect.

Engineering challenges and Solutions

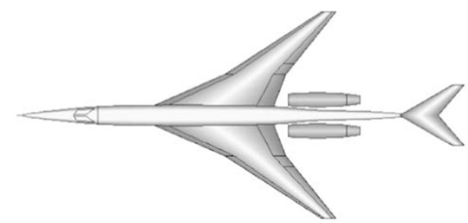
i. Configuration

There have been lot of researches on the configuration of the craft, particular wing configuration. The main goal for this is the reduction in drag, reduction in boom intensity, passenger safety at high speeds.

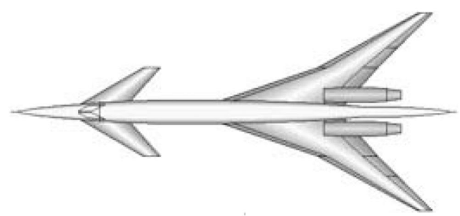
Wing Shape

- In order to lower the wave drag, trim drag and boom intensity, canard wing along with the conventional high-sweep wing is applied. The main function of the high-sweep wing is to reduce wave drag and to augment wing lift by producing vortex at the leading edge. Canard configuration provides two main advantages including lower sonic boom intensity and lower trim drag .This wing configuration also contributes in providing lift reducing main wing's size.
- Another type of wing is called variable geometry wing. It provides low speed performance without compromising high speed potential.It provides improved supersonic efficiency, better aerodynamic performance, lower take-off and landing distances, sweep configuration and better mitigation of sonic boom.
- Supersonic Laminar flow wing. This type of wing configuration has proved to provide the best aerodynamic efficiency. Its ability to supersonic skin friction drag has made it a choice for the Aerion. The limitation of Delta wing for not maintaining laminar flow due to adverse pressure gradients has been overcome by this configuration.

Figure 9: Wing configuration concepts



(a) Generic conventional supersonic configuration



(b) Generic canard supersonic configuration

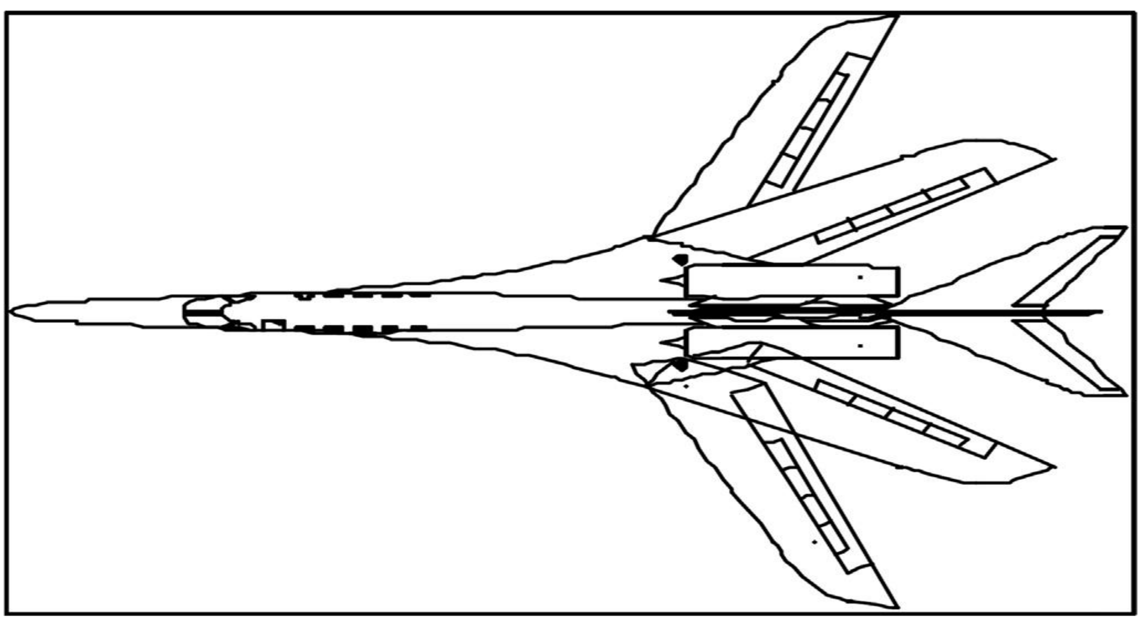


Figure 10: Variable-geometry wing configuration

Fuselage

Designing fuselage involves minimising wave drag and sonic boom . The basic theories helpful in designing of fuselage are the Whitham's theory and supersonic area rule theory to minimizer sonic boom intensity and wave drag respectively.

A possible solution which comes out is changing the circular cross section of cabin to an ellipse for more cabin height.

ii. Sonic Boom

The biggest challenge in supersonic passenger aircraft particularly over the land is the sonic boom. Various big institutes and organizations have done a lot of research for the reduction of sonic boom intensity, its effect on animals and other organisms and its propagation.

- For the analysis of sonic boom, the most predictable method consists of classifying the sonic boom into three different regions.
  (i) The near field region where flow is fully 3-D.
  (ii) The mid field region where, due to atmospheric turbulence, non-linear distortions of the pressure signature occurs
  (iii) The far field region where a continuous region of pressure is developed.

- The near-field over-pressure δp is directly related to the F-function as

  $$\frac{\delta p}{p} = \frac{F(\tau)}{\sqrt{B}}$$

  where F(x) is called F-function which is defined on the basis of Whitham's theory.

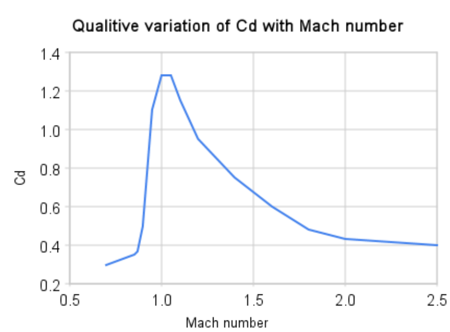
- Concorde used to avoid the sonic boom by not flying at supersonic speeds until over the sea at high altitudes. But in subsonic region, supersonic planes have poorer lift to drag ratio than the subsonic planes. Although this problem is tackled with the technologies like variable-sweep wing. Another solution which comes to mind is reducing intensity of the sonic boom even at land areas. Researches have led to conclusions that changing certain configurations like altering nose cone, or tail can help in reducing the intensity of the shock waves produced by sonic boom. Some research suggests elongating the vehicle may help overcome this problem.

iii. Aerodynamics

The drag force in all aerial vehicles is directly proportional to the airspeed squared, drag coefficient and the air density. As in case of supersonic planes, the speed is quite fast and as the speed rises the drag experienced by the plane also rises. So an engineer's job is to design the plane so as to minimise the drag which at high speeds can be achieved only by lowering the drag coefficient. This requirement leads to a highly streamlined body of the supersonic planes.

Another factor which helps in reducing the drag is the flight altitude. At high altitudes, the air density is low so supersonic planes tackle with higher drag by flying at higher altitudes than the subsonic planes. As plane reaches sonic speed, amazing phenomenon occurs. An additional drag called wave drag appears at speeds near Mach 1. Wave drag typically resides in transonic region which consists of speed range from Mach 0.88 to Mach 1.2. Observations state that peak level about four times the drag coefficient at subsonic level occurs at speed near Mach 1.
The lift to drag ratio of wings in supersonic flights is another important issue. As the speed increases to supersonic regions, the airfoils start to generate lifts in entirely different manner compared to the subsonic speed. Extra thrust has to be provided in order to maintain the speed and altitude at supersonic speeds.

Figure 11: Variation in drag factor with Mach number



iv. Engine

Similar to other features, the jet engines that supersonic planes use also has to be modified. Although, the specific fuel consumption of jet engines is greater at higher speeds, they can provide increased fuel efficiency at supersonic speeds.

Another type of engine which is used in supersonic transport is the Turbofan engine being capable of improving efficiency by increasing the amount of cold-low pressure air accelerated by them. Amongst its features, the design of turboprop, where the jet thrust is used to power a very large fan called propeller is the exciting one. Its efficiency curve depends on the forward speed i.e. the amount of bypass which maximises the efficiency depends on forward speed. The large area taken by the low pressure fan in the front of engine increases drag. which means bypass ratios are limited than on subsonic planes.

v. Take-off noise

One of the main problems faced by the first of the passenger supersonic planes, the Tu-144 and the Concorde was the high noise levels in engines, produced due to high jet velocities at the time of take-off. And this noise was annoying particularly for the communities near the airport. Specific thrust is defined as the net thrust per unit air flow. In case of supersonic transport planes, the engines require a high amount of specific thrust during supersonic flight. In order to reduce drag, engine cross-sectional area needs to be reduced and this implies increasing jet velocities, which in turn makes the engine noisy and causes problems specifically at the lower speeds and altitudes. The possible solution to this problem is design of a variable cycle engine, in which the specific thrust is low during take-off and high in supersonic range.

vi. Operation over a wide range of speeds

Since the supersonic airplanes flies from rest to speed as high as Mach 3, therefore the design should consider the fact that the planes are operable under all speed ranges. So in order to achieve optimal performance, the aerodynamic characteristic of the plane must change with speed and altitude. Such type of engineering would probably increase complexity and thus increasing maintenance needs , safety concerns and operation costs.

vii. Skin temperature

Supersonic aircraft when flying above Mach 1 compresses the air in front of it adiabatically. As a result the temperature of air increases and this air hits the aircraft. This in turn creates problem for supersonic planes. Subsonic planes are generally manufactured using aluminium. But aluminium being light although strong, is not suitable for higher temperatures. This brings out the requirement of materials which have the ability to withstand higher temperatures. The materials like stainless steel and titanium can be used and have been also deployed in some fighter supersonic planes. But these materials come at higher economic expense and their properties make the manufacturing more difficult. The latest research in year 2017 led to the discovery of a new carbide ceramic coating material having the ability to resist temperatures as high as 3000deg occurring at Mach 5 or above.

Model	Passengers	Cruise	Range	MTOW	Total Thrust	Thrust/weight
Concorde	120	Mach 2.02	3,900 nmi (7,200 km)	185 t (408,000 lb)	676 kN (152,000 lbf)	0.37
Boom Technology	55	Mach 2.2	4,500 nmi (8,300 km)	77.1 t (170,000 lb)	200–270 kN (45,000–60,000 lbf)	0.26-0.35
Aerion AS2	12	Mach 1.5	4,500 nmi (8,300 km)	54.4 t (120,000 lb)	201–228 kN (45,000–51,000 lbf)	0.38-0.43
Spike S-512	18	Mach 1.6	6,200 nmi (11,500 km)	52.2 t (115,000 lb)	177.8 kN (40,000 lbf)	0.35

Figure 12: Comparision of different concepts of future SST

The future of Supersonic passenger flight

The future of supersonic passenger flight is near than we can imagine. Many start-ups have come forward with the idea of supersonic flight in the civil aviation industry. Major companies like Boeing, JAXA and NASA are working towards the solutions for a perfect passenger supersonic plane.

Figure 13: Boom's new supersonic XB-1 model

Among the most talked about is the Boom, an aviation company founded by Blake Scholl. His realization of the recent advances in the aerodynamics, engine modeling, simulation and technology has turned him towards building a successor of Concorde. Boom headquarters are located in Denver, Colorado. Boom is said to have advanced itself in terms of fuel efficiency, economy, material strength, sonic boom, and its maximum speed. Fascinatingly, 76 Boom XB-1 supersonic planes have been pre-ordered according to Business insider article.
Not only Boom, but there are other competitors in the market working towards bringing back the supersonic pace. Aerion, founded by Robert Bass aimed for a much more efficient plane by harnessing a new-drag reducing technology. It made its partnership with the giant Airbus for this project. Similarly Gulfstream started working with NASA on its own design for supersonic flight. A simple comparison of Concorde and the upcoming supersonic passenger planes is given in the figure 12.

Figure 14: Aerion

So What is that which brings out the confidence in these companies that they can design better than Concorde

All these companies with their giant partners have gained the confidence majorly over three facts.

- With the advancement in computer technologies, computer aided designing and computer simulations have made it possible to compare different models of planes without actually manufacturing them. Genetic algorithms have made it possible to make these different models in computers and test them.

- Newer researches in the material science field has revealed better materials like carbon fiber which is lighter and strong making it way advanced than the then used aluminium in Concorde. With technologies like 3-D printing complex components can be easily manufactured.

- And thirdly, today's high-tech jet engines are way more efficient then the engines used in Concorde.

According to Scholl, these factors will enable the Boom's supersonic craft to reach as high as Mach 2.2 with an increased fuel efficiency. On the other hand, Aerion along with NASA is working on drag-reducing technology by harnessing Supersonic Natural Laminar Flow which is a concept developed to reduce the turbulent air flow around the plane wings and to reduce the drag.
But inspite of all these improvements one major problem still remains unsolved and thats where NASA steps in - The sonic Boom problem. For last 45 years NASA is continuously working towards solving the complicated maths of the pressure waves that create booms in order to figure out the way to reduce them. Over the last decade, NASA's engineers have finally cracked it. They are designing a prototype X plane with reduced sonic boom. According to their project manager Peter Coen, the simplified explanation of engineering behind this is that when a plane like Concorde travels at supersonic speed, the extrusions from it comes in contact penetrating the air ad thus creating a bunch of invisible shock waves. As these shock waves of different strength travels through air, they gets converted into just two very powerful waves - one strong positive wave at the nose and other strong negative wave at the tail. This forms what is called N-Wave configuration which is quite stable. As this reaches ground, it hits people and structures registering noisy sharp Boom sound in our ears. So NASA scientist came out with a beautiful technique to keep those N shaped shock waves from forming. They designed the plane so that when waves reach ground they will be some gentle pressure waves rather than two pressure disturbances creating loud boom.

Figure 15: QueSST X-plane artistic conception by NASA

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