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Concorde and the Future of Supersonic Transport

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Commercial high-speed flight at supersonic speeds poses major technological challenges that were resolved during the 1960s and early 1970s and that led to a unique vehicle in the history of air transportation. The demonstration of sustained supersonic flight has been made on a regular basis by operating the Concorde over a period of more than a quarter of a century. It has also served to show the limitations of this remarkable aircraft. Commercial operation of Concorde ceased in 2003. It is timely to look back at this adventure and review how this aircraft evolved from a project to a vehicle, identify some of the lessons learned from this experience, and possibly dwell on these lessons for future development of a new supersonic aircraft program. From this viewpoint, it has become clear that no new supersonic transport could be designed without first breaking many fundamental and technical barriers. A new project will benefit from the modern tools devised by aeronautical science and technology during the last period, but advances will have to be made to resolve many difficult challenges. The main areas of progress are related to the environmental impact of the vehicle, to its global performance, and to operational considerations. Meeting the challenges will require fundamental progress in aerodynamic optimization for sonic boom and drag reduction, combustion management for emission reduction, engine design to comply with noise regulations, and propulsion integration to improve performance. The environmental impact of a fleet of supersonic airliners will have to be carefully evaluated and compared to that of an all subsonic air transportation system.

Introduction

SINCE the first supersonic flight achieved on 14 October 1947 by Charles (Chuck) Yeager in the Bell X-1 rocket-powered prototype, considerable progress has been made in aeronautics. A supersonic transport project was boldly initiated about 10 years after this event in the late 1950s and was carried to completion jointly by the French and British aeronautical industries during the 1960s and early 1970s. The Concorde 01 prototype flew for the first time on 2 March 1969 with André Turcat at its command.[1] Concorde 02 took off one month later from Filton with Brian Trubshaw as test pilot. On 1 October 1969, the aircraft flew above Mach 1 and it cruised at Mach 2 for 53 min on 4 November 1970. Static tests were completed by 1974 and by mid-1978, 18 Concordes had flown (including 14 production aircraft). Supersonic flight has been exploited since the mid-1970s by this unique type of aircraft and two airline companies, Air France and British Airways. Operation of the Concorde over a period of more than 27 years has shown that supersonic travel was accessible and had commercial potential but was limited by technology.[2,3] The dramatic Concorde accident on 25 July 2000 near Gonnesse in France led to a halt in operation. After a careful investigation of the causes that led to this catastrophic event, a set of modifications were devised and applied to the fleet of aircraft. The certificate of navigability was attributed on this basis, and Concorde was back in service by 7 November 2001. However, this was discontinued by both Air France and British Airways during the later part of 2003 because of nonprofitable commercial operation resulting from growth of maintenance cost, drop in passenger traffic in relation with the uncertain economic and political situation, and soaring fuel prices. Whereas the Concorde has been a remarkable vehicle with unequaled performance, the first aircraft to use fly-by-wire control, featuring some unique solutions such as fuel transfer for trim management, its design dates back to the 1960s. It is timely to look back, learn the lessons from this development and subsequent operation, and discuss the conditions that could lead to a new supersonic airliner or business jet. Aeronautical science and technology has progressed to a great extent, and much experience has been accumulated. One may, thus, envision the development of a new supersonic vehicle, but it is clear that such a project will not be led to completion if solutions are not found to many scientific and technical challenges.

This paper gives a brief account of how Concorde evolved from a project to a real vehicle. It summarizes many issues that were facing the design and development teams and focuses on the selection of the aerodynamic configuration, the specification and development of

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the propulsion system, the choice of the air inlet geometry and mode of operation, and the definition of some key systems. The outlook for a new supersonic transport is discussed in the final part of the paper. Performance objectives are reviewed, and the many problems facing scientists and engineers are listed. It is concluded that much effort will be required to develop solutions to these problems and that this will require an extensive program of research and development.

Early Projects and Historical Background

Early plans for the design of a supersonic transport date back to 1957,[4,5] but the program was initiated on 19 January 1962 when Lucien Servanty from Sud Aviation (later to become part of Aerospatiale) and William Strang from Bristol Aircaft Corporation (BAC) (later to become part of British Aerospace) reached an agreement on the characteristics of the future vehicle (see Ref. 6). A further agreement was signed later that year by the French and British governments, providing a fair division of the workload between the manufacturers : 60% to Sud Aviation and 40% to BAC for the aircraft, 60% to Bristol Siddeley Engines and 40% to SNECMA for the engines.

At that time, supersonic flight had been achieved by a small number of military aircraft such as the Mirage 3, which had reached $M = 2$. A larger plane, the B58 Hustler was to fly at $M = 2.4$ in 1964, whereas commercial subsonic jet planes (B707 and DC 8) were just getting into service.

The story of the initial design phase is well told by Cormery,[5] former technical director of Aerospatiale. The initial objective of Sud Aviation engineers was to carry 80 passengers over a range of 3000–4500 km at supersonic speed and under conditions of comfort and profitability. Variable geometry was considered but soon discarded when it was found that the choice was between carrying a payload or carrying the pivoting gear and system. One may remember at this point that variable geometry was also envisioned by The Boeing Company in its B2707-200 design. This project won the competition organized by the Federal Aviation Administration FAA in 1966 against the Lockheed L2000-7A and the North American NA-60, which both featured a fixed wing. However, Boeing was facing many difficulties with its initial design, and the variable geometry configuration was dropped by 1969 in favor of a more classical delta wing with a rear tail with a cruise Mach number of 2.7. At this high Mach number, the stagnation temperature reaches values that cannot be accomodated by aluminum alloys, and it was necessary to use titanium. The technical risk was high and the market uncertain. A decision was taken by 1971 to abandon the project.[7]

Systematic parametric studies were used by the European engineeering teams to determine the cruise Mach number, and it was found that stagnation temperatures in excess of 120°C would introduce great complications with regard to metallic materials such as light aluminum alloys, fuel tank lining, air conditioning and cooling. This led to the choice of $M = 2.2$ as a maximum cruise Mach number.

It was also rapidly discovered that highly swept delta wings were needed to obtain the required wing volume with acceptable aerodynamic characteristics. One problem was the evolution of the aerodynamic center with the Mach number. The solution initially devised to compensate for this shift was to place a variable lift wing as far as possible from the center of gravity in front of the main wing [Fig. 1a (adapted from Ref. 8)]. In this initial layout dating back to 1959, the air intakes were in front of the wing leading edge, the fuselage cross section was reduced near the wing trailing edge (a poor solution relative to area ruling), and three vertical fins were required to avoid a strong lateral instability observed under low-speed conditions in wind-tunnel tests with a single-fin model. It was found that the lateral velocities were caused by the vortices originating from the foreplane and interacting with the central fin arrangement. A double-fin model was tested, but the vertical planes had to be set very far apart from each other and interacted with the delta wing apex vortices. The triple fin was the solution, but the configuration achieved the required characteristics with little margin.

Improvement was obtained by dropping the delta layout and adopting a "gothic" planform [Fig. 1b (adapted from Ref. 8)]. This pulled the apex vortex toward the wing tips, and the twin-fin solution was acceptable. The engine inlets were now tucked under the wing and could profit from the air compression achieved by the wing in this region.

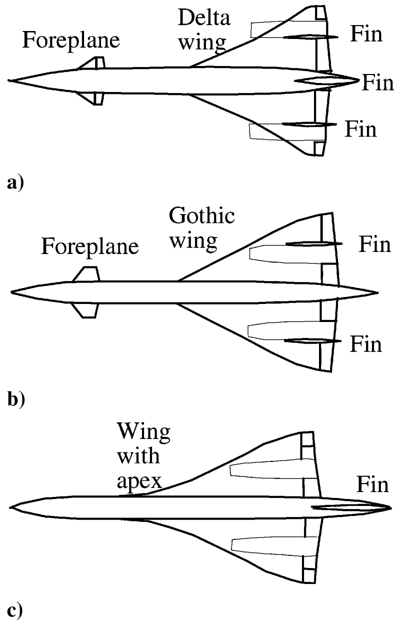

Fig. 1 Three configurations during the preliminary project phase: a) delta wing with foreplane and three fins, b) gothic planform with foreplane and twin fin, and c) Wing with apex with single fin and no foreplane (adapted from Cormery and Negre[8]).

It was then decided to get rid of the foreplane and replace it by a wing apex (an ogival planform) and examine a new configuration with a single central fin [Fig. 1c (adapted from Ref. 8)]. This resulted in a forward shift of the aerodynamic center of the wing fuselage combination. Moment curves were linear with lift allowing a repositioning of the fuselage aft and, thus, improving area ruling and related wave drag. It was then possible to envisage fuel transfer between the reservoir located in the wing apex and a tank located in the aft part of the aircraft. Fuel transfer allowed to achieve an essentially zero trim drag. The aerodynamic layout of the Concorde was defined by 1961 except for the droop nose. The project won the competition initiated by the French government, also involving projects from Dassault and Nord-Aviation.

Similar developments were being made in Great Britain as well, as apparent from informal discussions between Sud Aviation in France and BAC. BAC engineers were initially favoring a highly swept delta wing with six engines grouped symmetrically in two lateral nacelles. The agreement was reached by November 1962 converging on a configuration featuring 1) a modified delta wing low mounted with a continuous spanwise spar, 2) no variable-geometry high-lift devices, 3) a constant cross section tailess fuselage, 4) four engines mounted under the wing and fed by variable-geometry two-dimensional inlets, and 5) a side folding main landing gear with the wheel carriage retracting into the fuselage. A difference of opinion existed on the payload. A compromise was reached on two versions, one being a medium-range and the other a long-range aircraft, but it was decided to use a common prototype. By 1964, the medium-range version was fortunately abandoned, leaving as the objective a single long-range vehicle with 1) transatlantic capability, 2) takeoff and landing characteristics matching existing airports, 3) good flying qualities at all speeds, 4) noise comparable to that of subsonic airliners of the time (B707 and DC8), and 5) no stall or buffet even under lift conditions exceeding those required for airworthiness certification.

These design goals were similar to those of long-range airliners, but with the added complication of a much broader flight envelope with a 60,000-ft ceiling and a $M = 2$ cruise Mach number. The domain included the transonic range with a known evolution of aerodynamic characteristics. The shape of the aircraft with its slender wing and tailess fuselage was also quite distinct from the layouts adopted in subsonic jet airplanes, introducing some difficult handling quality problems. Slender delta wings feature a high pitch inertia, a low pitch damping coefficient, a low value of the lift curve slope, a shift in aerodynamic center in the transonic range, and a reduced moment arm for control flaps. The slender delta wing layout has a high yaw and low roll inertia and a high rolling moment due to sideslip. The vertical fin loses effectiveness in the supersonic range.

Operation of the powerplant over a broad range of Mach numbers induced additional challenges: 1) cruise efficiency at transonic and supersonic speeds, 2) reduced installation drag, 3) engine integration, 4) takeoff performance, and 5) acceptable operation after an engine failure.[9,10]

Layout and Vehicle Characteristics

The many successive steps leading to the final wing and fuselage layout are well described by Rech and Leyman[4] in their informative case study of the Concorde, and they will be briefly outlined here.

The layout selected during the preliminary project phase (1959–1962) was further refined during the prototype definition phase (1962–1965) and optimized during the production aircraft definition phase. Design methods were initially based on slender-body theory, conical flow calculations, and area-rule application for supersonic wave drag reduction. Analytical methods were used for lift and camber/twist optimization. The lines of the rear fuselage were improved by combining area-rule and boundary-layer theories. The nacelle geometry was defined by making use of area-rule, shock-expansion methods and corrections for three-dimensional effects. The ogival wing planform selected during the preliminary project phase had many advantages, which are worth noting: 1) The leading-edge sweep is high and the thickness-to-chord ratio at the root is low to provide reduced drag characteristics. 2) The vortex generated by the wing apex is intensified by the high leading-edge sweep. This vortex induces additional lift at low speed and high angle of attack. 3) The amplitude of the aerodynamic center shift with Mach number is lower than that of a standard delta wing. 4) The thickness at the root is high, which is favorable to fuel storage.

Many aspects of the vehicle layout required much design effort. Longitudinal trim was carefully considered to minimize cruise trim drag. This involved suitable design of wing camber and twist and the addition of the fuel transfer system. Improvements in wave drag were obtained by area ruling and configuration modifications to avoid high curvatures in the total area distribution plot. The wing thickness-to-chord ratio was the subject of extensive optimization to obtain the required wing volume for fuel storage, acceptable weight and stiffness, and minimal supersonic drag. The shape of the wing subjected to aeroelastic distortion had to be taken into account to obtain the required characteristics. It was also necessary to consider deflections associated with thermal distortion. The development made use of extensive wind-tunnel testing. Work was also carried out to improve the aerodynamic characteristics beyond those of the production model.

Aircraft Characteristics

The final vehicle (Fig. 2) features a wing span of 25.56 m, a wing aerodynamic reference chord at root of 27.66 m, and an aspect ratio of 1.7. The overall length is 62.1 m, the fin chord at base is 10.59 m, the wing gross area is 358.2 m^2, the elevons total area is 32 m^2, the fin area excluding the dorsal fin is 33.91 m^2, and the rudder is 10.40 m^2. The vehicle has an operating weight empty of 78.7 metric tons, a typical payload of 11.34 metric tons, a maximum takeoff weight of 185 tons, a maximum zero-fuel weight of 92 metric tons, and a maximum landing weight of 111.1 tons. The maximum wing loading is approximately 488 kg $\cdot$ m^{-2}. The takeoff speed is 214 kn (397 km/h), the landing speed is 162 kn (300 km/h). The range with maximum fuel, Federal Aviation Regulations reserves, and 8.8 ton payload is 6580 km (3550 n miles). Operational noise characteristics [measured according to Federal Aviation Regulations Part 36 and expressed in effective perceived noise (EPN) decibels (EPNdB)] are 119.5 EPNdB [takeoff (TO) level], 116.7 EPNdB (approach), and 112.2 (sideline), with a cumulated value of 348.4 EPNdB. It is interesting to compare these numbers with those of the first generation of subsonic turbojet planes (Table 1).

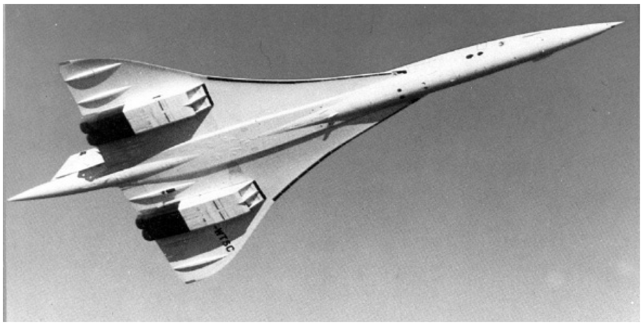

Fig. 2 Concorde viewed from below.

Table 1 Noise levels of early subsonic jet planes and Concorde

Observation point	B707-320B, EPNdB	DC8-50, EPNdB	Concorde, EPNdB	FAA–Federal Air Regulations Part 36[a] EPNdB
TO	114	115	119.5	105
Sideline	108	106	112.2	107
Approach	120	117	116.7	107
Cumulated noise	342	338	348.4	319

[a] Maximum values specified.

This comparison indicates that Concorde was not much noisier than the first generation of subsonic jet planes (just about 6.4 EPNdB in cumulated level above the B707 as pointed out by Forestier et al.[7]). However, by the time it was introduced into the market, the subsonic airliners equipped with new high-bypass turbofans had become quieter and the population had become more aware about environmental issues. It took about two years of difficult negotiations to obtain permission to land at Kennedy airport. Another environmental issue that was raised as the vehicle went in service was the impact of emissions on the upper atmosphere. Some initial scientific reports contained alarming conclusions on modifications of the atmospheric chemistry. Further investigations of the problem carried out by various committees in the United States, the United Kingdom, and France converged on less pessimistic conclusions on this matter. Still, noise and atmospheric impact remain key issues for any new supersonic aircraft, and the problem is now shared by civil aviation in general.

Flight Qualities and Control System

The flight control system on Concorde represented a major advance in aeronautics. Concorde was the first civil transport to fly by wire because it used electric signal transmission with full authority to control roll, pitch, and yaw. A mechanical system provides a backup but was never put in operation during commercial flights. The aircraft features six elevons on the wing and a rudder. Each of these surfaces is moved by a hydraulic twin chamber servovalve controlled by two entirely independent electric circuits.[4,8] To augment performance and passenger comfort while reducing the flight team workload, an autostabilization system is included and operates independently of the autopilot. An artificial feel system provides control efforts back to the pilot and also serves as an authority limiter. The control system may be used to tailor handling characteristics precisely. The fuel transfer system is another unique feature of Concorde. This system not only manages fuel utilization by the powerplants, but also serves to modify the position of the aircraft center of gravity. When the aircraft moves into the supersonic range, the center of pressure is shifted back by about 2 m. This would induce a pitch-down moment, which could be compensated by deflecting the elevons but with an associated increase in drag. Instead, the fuel transfer system fills the aft tank, bringing the center of gravity backward and, thus, establishing a new longitudinal equilibrium. At the end of supersonic cruise, the fuel is pumped from the back tank to the front to shift the center of gravity forward (Fig. 3).

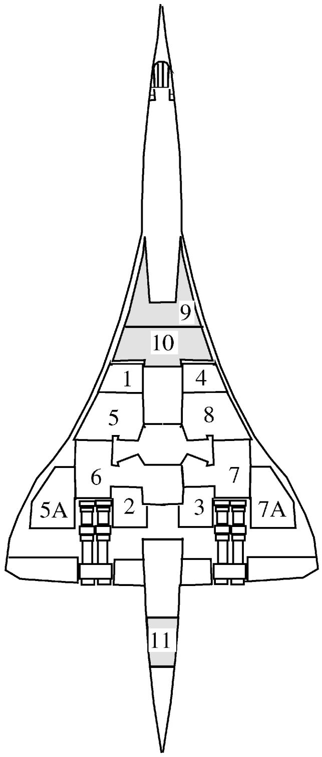

Fig. 3 Tank location; tanks located in the wing apex and in the aft piece serve to change the center of mass during supersonic flight to accompany the shift in aerodynamic center: tanks 1–4:17.72 metric ton, main tanks 5–8: 39.34 metric ton, auxiliary tanks 5A and 7A: 4.5 metric ton, equilibration tanks 9–11: 33.8 metric ton, total capacity: 95.36 metric ton (adapted from Ref. 6).

Engines

The choice of an optimal propulsion system for Concorde was made at a time when supersonic flight was still in its infancy. Engineers had to face difficult problems and find the best compromise allowing operation over a large flight envelope with an engine providing high thrust for TO and transonic acceleration and minimal consumption under supersonic cruise as well as in high subsonic cruise.

Selection of the Olympus 593 (OL 593) produced by Bristol-Siddeley was made by extrapolation from the military engine Olympus 320 (OL 320), which had cycle characteristics close to those required by the Concorde mission. Early in the program it was recognized that four engines were needed to provide the required TO thrust. It was also found that an afterburner (reheat) was needed to provide the level of thrust required at TO and for transonic acceleration. Note that all supersonic transport (SST) projects of the same period were relying on turbojets with reheat with the exception of the Soviet Union TU144 powered by low-dilution-ratio turbofans with reheat in both channels. The additional thrust required by Concorde for TO and transonic acceleration was initially evaluated to lie between 9 and 14%, but the design value was later increased to 18%. Design of the afterburner was carried out by SNECMA. A variable geometry nozzle had to be developed to adapt to the various flight conditions. This was obtained by changing the nozzle cross section as a function of the mass flow rate, pressure, and temperature in the afterburner. A variable geometry diverging section was developed to expand gases to supersonic speed. The nozzle had also to allow for reverse operation at landing.

The nacelle and inlet were to be developed by BAC, whereas the ejection system was SNECMA's responsibility. The first development engine OL 593D derived from OL320 was equipped with an additional low-pressure compressor stage and its testing began in July 1964, providing a thrust of 130 kN with a reheat of 14%. It was rapidly found that additional thrust was needed, and a new engine OL 593B equipped with the SNECMA-type 10 afterburner system was tested in 1965, providing a thrust of 158 kN at 9% reheat.

In 1966 a new version of the afterburner (type 11) was adapted to the engine OL595-602. In December of that same year, the specification was revised with requirements to operate the reheat system for a period of 8–10 min at TO and transonic acceleration. In 1968 the reheat operation was increased to 15 min under transonic conditions. Objectives were set to diminish head losses in the afterburner under dry operation during supersonic cruise to augment thrust at TO and to develop a fuel modulation system. Further improvements were introduced between 1968 and 1972 to reach a thrust augmentation of 18%, a maximum TO thrust of 173 kN, and diminish the nozzle weight. The final series engine OL 593-610 associated with a type 14-28 ejection system brought a payload gain of 1180 kg, allowing a range of 6500 km as specified at the outset.

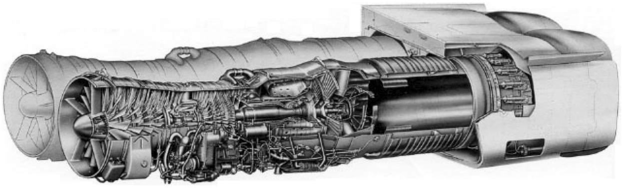

Fig. 4 Cutout view of twin Olympus 593 engines equipped with the variable geometry divergent block, (courtesy of SNECMA).

During the 10-year period of development with a large program of ground and flight testing, much was accomplished to reach the required performance level, improve reliability, and diminish the engine weight. The resulting production engines (Fig. 4) feature a seven-stage low-pressure and a seven-stage high-pressure compressor delivering a mass flow rate of $\dot{m}_a = 186\ \mathrm{kg \cdot s^{-1}}$ with a pressure ratio $\pi_c = 15.5$. The main combustor is annular and comprises 16 vaporizing fuel injectors. A single-stage high-pressure turbine features cooled stator and rotor blading. A single-stage low-pressure turbine with cooled rotor blades drives the low-pressure spool coaxially located inside the high-pressure shaft. The maximum engine diameter at inlet is 1.206 m, the length between the flanges is 3.810 m, and the length between the inlet flange and the final nozzle is 7.112 m. The engine weight with its exhaust system is 3386 kg. The performance ratings are TO [Sea level (S/L), International Standard Atmosphere (ISA)] 169 kN, a contingency thrust (S/L, ISA) of 173.8 kN, and a cruise thrust [$M = 2$ at 16,100 m (53,000 ft), ISA + 5 deg] of 44.6 kN. The cruise specific fuel consumption is rated at $33.7\ \mathrm{mg \cdot N^{-1} \cdot s^{-1}}$.

The Olympus 593 is the first application of full authority control to a civil engine. It uses fuel flow in the main combustor to control the high pressure (HP) spool revolutions per minute and the primary nozzle area to control the low pressure (LP) spool revolutions per minute. An elecrical actuator controls a fuel throttle valve. Another electric actuator modifies the primary nozzle geometry. A simplified view of the control system is shown in Fig. 5. The system takes into account the intake stagnation temperature and air pressure to determine the HP spool rotation speed N_2 compatible with the turbine entry temperature. This provides a protection against rapid changes in atmospheric conditions. The system also controls the engine during thrust reverse. It ensures a positive surge margin by controlling the rate of increase of fuel flow and by reducing the nozzle area to augment the LP spool revolutions per minute. A separate unit controls reheat light up, operation, and shutdown.

Engine elements that are most specific to supersonic flight are examined in the following paragraphs.

Inlets

Critical components of supersonic aircraft, the variable geometry inlets must adapt to different flight conditions, provide a uniform stagnation pressure to the engine, and avoid flow unsteadiness. The Concorde's inlet definition required a considerable development effort. The variable geometry is easily implemented in the rectangular cross section selected on Concorde using two mobile ramps to change the area and move the set of shock waves inside the inlet. The rectangular cross section simplifies variations in geometry but induces complications such as those associated with the secondary vortices originating from highly swept side walls. Also the ramps had a limited capacity to regulate the airflow captured by the inlet. It was necessary to include a bleed door on the lower cowl to spill excess air. The ramps and bleed doors are activated by hydraulic motors. An auxiliary flap integrated in the bleed door is required to capture an additional amount of air during TO and low subsonic

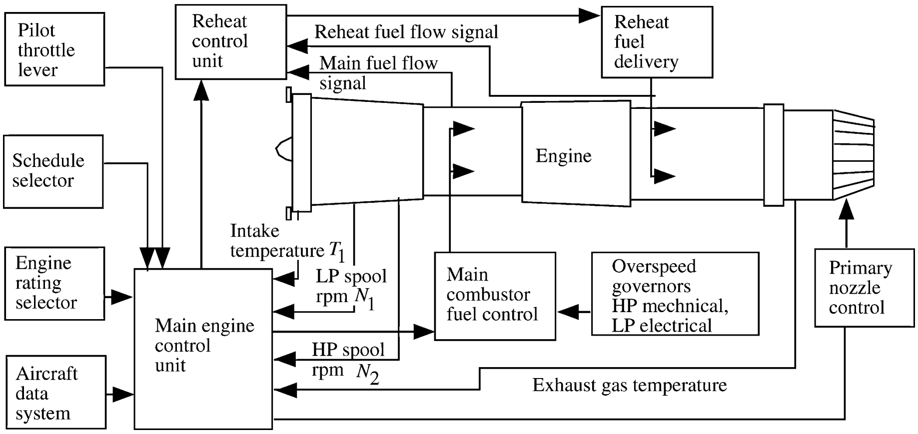

Fig. 5 Simplified block diagram of the Olympus 593-14 control system (adapted from Ref. 9).

flight. This freely floating flap set inside the dump door frame is activated by the differential pressure between diffuser and freestream flows (Fig. 6).

At Mach numbers below 1.3, the ramps are fully open and the bleed door is closed. Beyond $M = 1.3$, the ramps and discharge door are moved between their minimum and maximum positions as a function of the inlet characteristics and engine regime parameters: bleed slot efficiency $\eta_v = p_v/p_i$, where p_v is the static pressure above the ramp and p_i is the stagnation pressure measured by the pitot tube, LP spool rotation speed N_1, and angle of attack.

Under supersonic operation, the inlet uses a mixed compression arrangement with part of the compression provided externally by oblique shock waves. There is a degree of flow turning after the lip, providing some internal compression. One novel and useful feature is a slot, which bleeds the boundary layer (a boundary-layer trap). The flow is turned at this point, and the pressure increases rapidly. The presence of bleed in this region prevents separation that would notably degrade the inlet performance. The shock originating from the cowl is bent toward the diffuser section. The constant pressure condition in the slot produces a rapid flow turning, and a strong Mach number gradient is obtained. The supersonic flow region terminates with a weak normal shock attached to the downstream lip of the bleed slot. On the downstream side of this shock, the flow turns sharply and gives rise to a centrifugal pressure gradient, which compensates the pressure difference between the main diffuser section and the bleed region. By properly choosing the geometry and bleed pressure, one obtains a uniform pressure loss in the upper and lower fluid streams. This leads to a nearly uniform stagnation pressure at the subsonic diffuser entry section.

Another advantage of the inlet system lies in its tolerance to sudden changes in the engine operation regime with variations in the mass flow rate. In the optimal configuration (critical regime), the ramp is positioned to produce a set of oblique shock waves converging on the lower cowl. In this position, excess air is spilled away from the engine by opening the lower discharge door. A reduction of engine demand or an increase in ambient temperature is compensated by lowering the ramps. If the inlet operates in the subcritical regime, the shock waves are displaced upstream of the inlet. This happens when the air flowing in the inlet exceeds the engine demand, and it is remedied by increasing the engine rotation speed. If the inlet operates in the supercritical regime, the oblique waves are swallowed in the inlet, and there is a risk of pumping, which is avoided by reducing the engine rotation speed.

Control of the four separate inlets relies on analog and digital computers receiving information from the aircraft air data computer, from the engine and from the front variable ramp. The inlet geometry is modified to deliver the required mass flow rate to the engines (Fig. 7).

Afterburner (Augmentor)

The augmentor comprises a cylindrical channel bounded by an antiscreech liner. It features a single injection ramp facing an impingement plate to atomize the kerosene jet and to provide a homogeneous distribution of fuel and a single annular gutter for flame stabilization. The blockage is low to minimize head losses under dry operation. The afterburner provides up to 18% of additional thrust for TO and transonic acceleration. A variable area nozzle is required to accomodate the increase in stagnation temperature when the afterburner is operating. Reheat is used for up to 5 min during TO and up to 15 min during transonic acceleration. These extended periods of operation complicated the design of the primary nozzle actuation system.[9]

Variable Geometry Nozzle

Supersonic aircraft nozzles must operate over extended periods at high subsonic speeds, while featuring a maximum propulsion efficiency under nominal cruise conditions. The Olympus engine is equipped with a variable-geometry primary nozzle, which serves to control the LP spool independently from the HP spool. The converging nozzle is used to accomodate the low expansion ratios required for subsonic flight, but a divergent section is needed for the HP expansion ratios required by supersonic flight. It was of course possible to use a fully variable de Laval nozzle, but the weight and complexity were considered to be too high. The selected geometry is that of a nozzle with a throat bleed ejector. The divergent channel is formed by two buckets (also designated as eyelids), which can be made to rotate around their axis (Fig. 8). In subsonic flight, the internal base area is reduced as the buckets are deflected. This yields a passage allowing entrainment of the freestream air. In supersonic flight, the buckets form a divergent channel and the flow is accelerated to high speed. The secondary nozzle is fully open at $M > 1.1$. At lower Mach numbers, the nozzle angle scheduling units (NASUs) are used to position the buckets as a function of Mach number and engine rotation speed. There are two NASUs, one for engines 1 and 4 and the second controlling engines 2 and 3. The primary convergent nozzle is mounted on the augmentor channel. It comprises 36 mobile flaps with 18 pneumatic actuators. The secondary nozzle fixed to the engine nacelle features a single block structure comprising three vertical walls (two side walls and one central wall defining two ejection channels for the pair of engines placed side by side). These walls are connected together by the upper and lower frames, which bear two refractory sandwich pannels. This structure holds the secondary nozzle buckets and the actuation systems for these units.

The bucket deflection is also used to provide reverse flow for aircraft deceleration. The buckets are fully closed in that situation and form an angle of 73 deg, and the gas stream is ejected above and below the nacelles through passages liberated by the bucket rotation.

Thrust Breakdown

The thrust distribution with respect to the various engine components is an interesting aspect of supersonic flight [Fig. 9 (adapted for Ref. 11)]. Considering the first subsonic operation, 82% of the

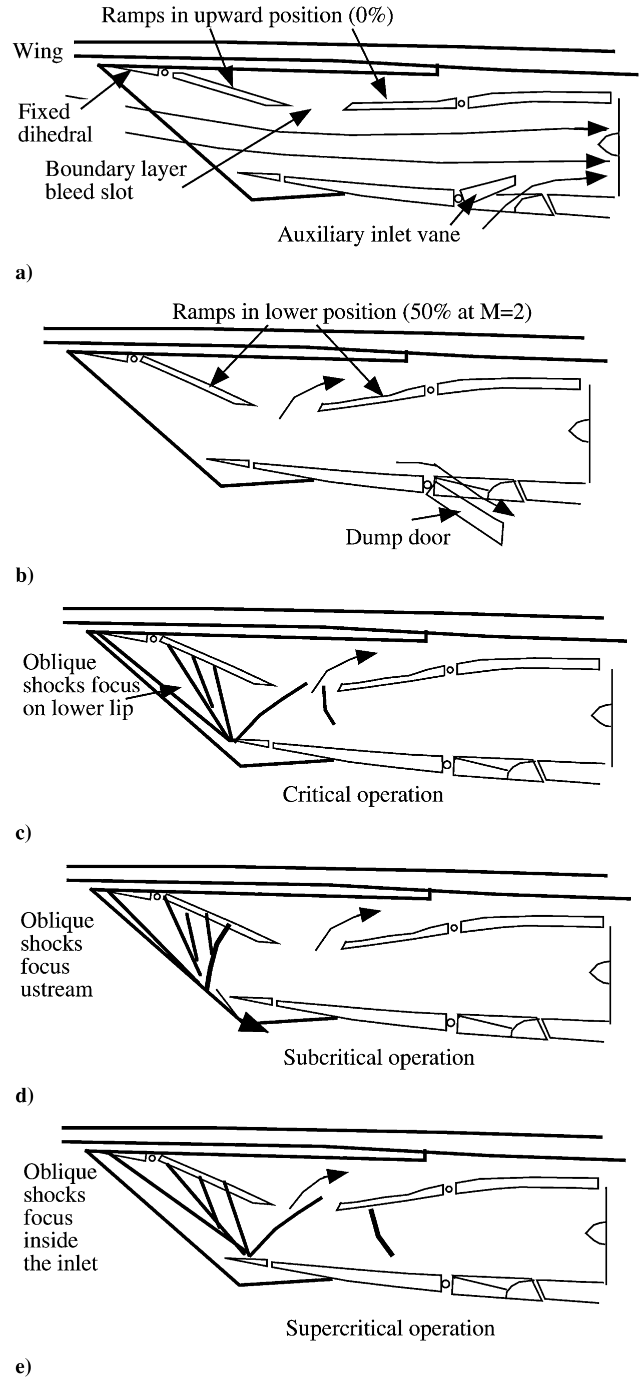

Fig. 6 Inlet geometry corresponding to various Mach numbers and modes of operation: a) geometry at $M < 1.3$, b) geometry at $M > 1.3$, c) critical flow regime under cruise conditions, d) subcritical regime under cruise conditions, and e) supercritical regime under cruise conditions (adapted from the Concorde flight manual).

thrust forces apply to the engine. The resulting force acts through the engines mountings onto the aircraft structure. About 6% is directly produced by the nozzle, whereas 21% results from the diverging part of the inlet. A drag of 9% is generated by the converging part of the inlet. The balance is quite different under supersonic flight conditions. The engine thrust forces contributes to 8% of the total, the diverging section of the nozzle yields 25% of the thrust, but the main part of thrust (75%) originates from the subsonic section of the diffuser. This is because pressure rises in this section produce a net forward thrust contribution. The supersonic section of the inlet yields a drag force of 12%. This indicates that, under supersonic flight conditions, the inlet and divergent section produce the major part of the thrust.

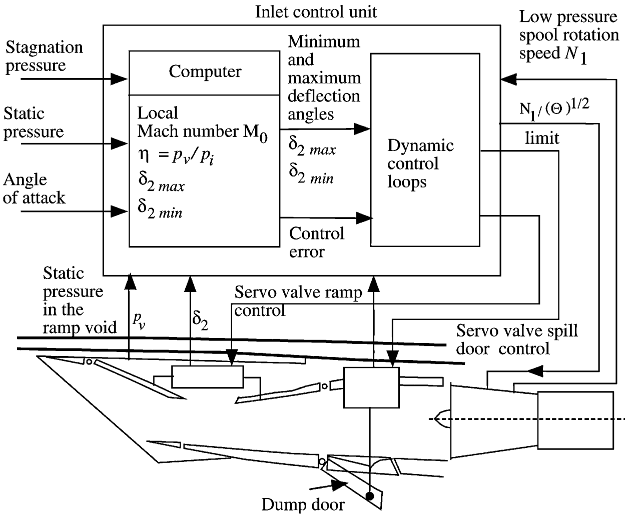

Fig. 7 Inlet control system (adapted from Rech and Leyman[4]).

Powerplant Integration

Integration is a central issue in supersonic aircraft design. The powerplant underwing location was chosen early in the program for a number of reasons. First, an air intake placed below the wing operates in a flowfield with a reduced Mach number and the inlet benefits from the air compression provided by the wing. Second, the pressure field associated with shock waves attached to the inlet can be used in principle to generate lift, thereby, allowing some reduction of the installation drag by properly matching the inlet location with the wing shape. Third, the underwing location has definite advantages with regard to maintenance. There are also some drawbacks because the inlet is more likely to ingest debris and water from the runaway. The nacelle position under the wing is mainly determined by additional constraints : 1) Center of mass must be considered. 2) Distance of the outermost nacelle lip with respect to the wing leading edge must be considered. Note that the lip corner should not be too close to the leading edge and perturb the development of the wing vortex. 3) If the engine nacelle is too far back, it limits the ground clearance at landing at reduced touchdown speeds. 4) Acoustic fatigue of control surfaces requires an aft location of the nozzle to reduce near-field interactions. In the lateral direction, the distance from the centerplane must be limited to allow control in case of engine failure, or under crosswind landing but sufficient to place the landing gear while keeping the nacelle lip away from the wing leading edge. The placement problem was quite constrained and took considerable effort before it converged to a final location.

Many other aspects of Concorde are discussed in the literature and in particular in the case study by Rech and Leyman[4] and will not be reviewed in this paper. We turn instead to the question of the future of commercial or business supersonic flight.

Objectives for Future SST Aircraft

Concorde service was discontinued in 2003, and a question may be asked as to whether the SST adventure will cease with the retirement of this vehicle.

This issue has been extensively discussed in various, specialized meetings and reports.[12–22] The analysis has focused on two types of vehicles: the commercial airliner and the supersonic business jet. The European Supersonic Commercial Transport (ESCT) envisioned by Aerospatiale–Matra Airbus (now Airbus) considers a payload of 250 passengers and a desired range of 10,000 km (5400 n miles). The cruise Mach number is set to 2, but more recent investigations envisage lower cruise Mach numbers. This has distinguished the European vehicle from the U.S. High Speed Civil Transport (HSCT) project characterized by a more ambitious Mach number of 2.4 (Ref. 16). Higher Mach numbers, however, can pose difficult and often unsurmountable challenges, as demonstrated in the past. For example, to cruise at $M = 2.4$, the airframe structure

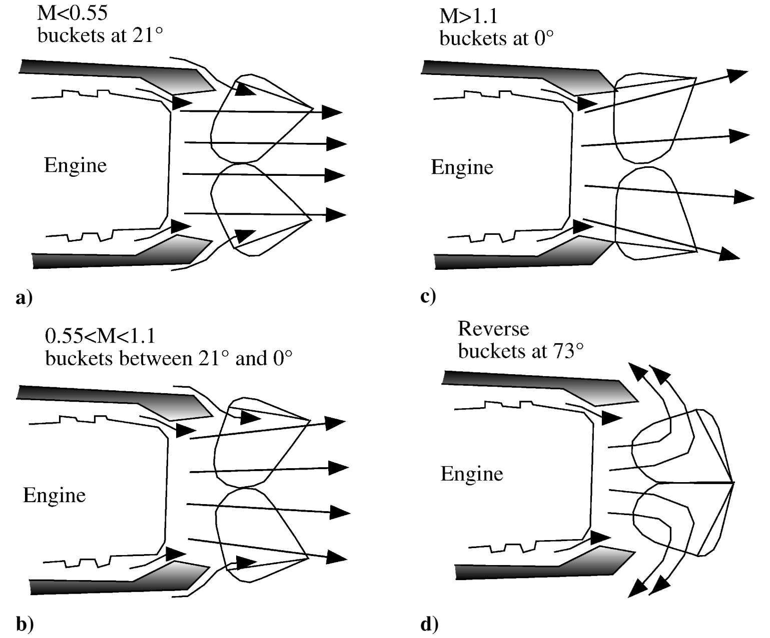

Fig. 8 Nozzle operation: a) TO, b) high subsonic regime, c) supersonic regime, and d) reverse flow (adapted from the Concorde flight manual).

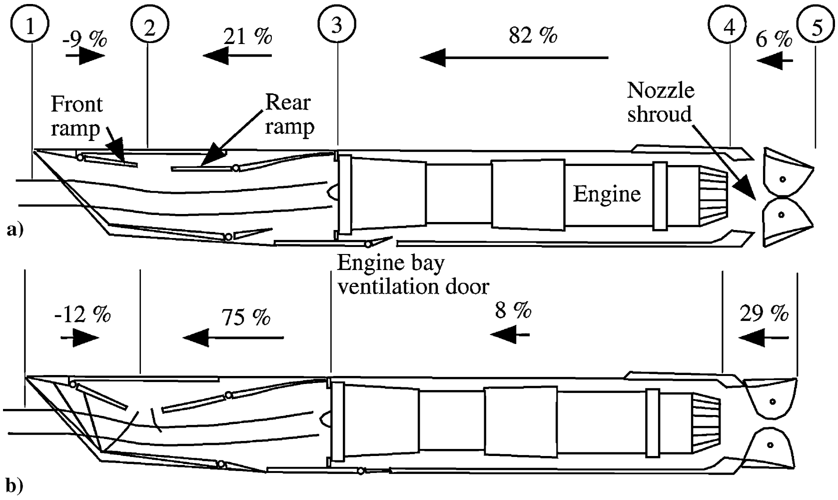

Fig. 9 Thrust breakdown among the various engine and nacelle components: a) subsonic operation and b) supersonic operation (adapted from Huenecke[11]).

should use unproven materials, thus increasing the technical risk. The aircraft will have to cruise at a higher altitude, and the levels of pollutant emissions from its engines will have to be reduced further to lessen the impact on the stratosphere. More recent U.S. projects have converged to a lower value of the cruise Mach number to alleviate the technological challenges and environmental concerns associated with the very high speed initially considered in Ref. 19. Because there are currently no solutions to reduce the sonic boom to acceptable levels, both the European and U.S. projects require that overland flight be subsonic. The possibility of flying at low supersonic Mach numbers overland and at higher Mach numbers over water was, however, reexamined. Table 2 (see Refs. 18, 19, and 23) summarizes the main characteristics of some future supersonic aircraft as compared to Concorde.

In comparison with the Concorde characteristics and performance, the ESCT specifications are relatively ambitious: 1) The payload would be more than doubled. 2) The range of 10,000 km would allow supersonic flight from Tokyo to New York or Paris along appropriate routes. 3) Fuel consumption (per kilometer and per passenger) would be reduced by a factor of two. 4) The total service life would be brought to 80,000 h including 60,000 h under supersonic cruise conditions. The maximum cruise altitude would not exceed 65,000 ft (20,000 m) and this would be advantageous with respect to the environmental impact. An aircraft featuring a lower Mach number is also being considered. Its cruise altitude would be reduced, which would further mitigate the impact of emissions on the upper atmosphere.

Another interesting project and perhaps a more realistic one is the supersonic business jet studied by Dassault (see Ref. 24). This aircraft would cruise at lower Mach numbers of 1.6–1.8. Its range should exceed 4000 n miles (7200 km) to cover missions that would be flown partially or totally at a subsonic Mach number ($M = 0.95$). The approach velocity should not exceed 145 kn, a reasonable upper limit for an airplane that would be flown by a broad range of pilots. The most difficult issue in designing a supersonic business jet (SSBJ) is to derive a propulsion system from existing engines that would satisfy performance requirements in terms of noise, specific fuel consumption, maintenance, service life duration, and the safe operation.

Performance Objectives

To identify areas where progress is required to fulfill the aforementioned specifications, it is worth considering factors that

Table 2 Supersonic aircraft characteristics

Characteristics	Concorde	European SST[a]	U.S. HSCT[b]	Japan second-generation SST[c]	French SSBJ[d]	U.S. SSBJ[e]
Range	6,300	10,000	9,000–10,000	10,100	7,400	7,400
Cruise Mach number	2.05	1.8-2	2–2.4	2	1.8	1.6–1.8
Seats	100	250	300	300	8	8–15
TOGW, tons	185	340	371	373	39	63
Length, m	62	89	95	104	32.6	
Wing span, m	25.5	42	40	41	17	
Wing reference surface, m^2	358	836		938	130	
Consumption, $kg \cdot seat^{-1} \cdot km^{-1}$	0.1	0.043				

[a] Data from Ref. 18.
[b] Data from Ref. 19 (note Ref. 19 quotes TOGW-600,000lb, which is corrected to 800,000lb).
[c] Data from Ref. 23.
[d] Data from Ref. 18.
[e] Data from Ref. 19.

Table 3 Improvement objectives in percent with respect to the Concorde baseline

Parameters	State of the art	Objectives
Overall weight empty	−30	−40
Aerodynamic efficiency	+25	+35
Installation drag	−20	−30
SFC (supersonic cruise)	−10	−15
SFC (subsonic cruise)	−15	−20

determine the range covered by an aircraft cruising at nearly constant speed and constant lift-to-drag ratio. For a given Mach number and payload, this range is well estimated by the Bréguet–Leduc formula,

$$R \simeq v(L/D)(1/C_s g)\,\ell n(W_I/W_F) \tag{1}$$

where v is the cruise speed, L/D is the lift-to-drag ratio and represents the aerodynamic efficiency, $C_s = \dot{m}_f/T$ is the specific fuel consumption (SFC) and is closely related to the engine propulsion efficiency, and (W_I/W_F) is the ratio of the initial (at TO) and final (at landing) aircraft weights and represents the structural efficiency.

This expression clearly indicates that improvements in the three efficiencies are needed to reach the ranges envisioned for future supersonic vehicles. The aerodynamic cruise efficiency (the lift-to-drag ratio) of supersonic vehicles is lower than that of subsonic aircraft. Values in excess of 18 are achieved by current subsonic airliners, whereas the cruise efficiency of Concorde is of about 7.5. Low values of L/D lead to an increased fuel consumption and induce range limitations. The low value of L/D obtained on supersonic aircraft is due to the additional drag induced by supersonic aerodynamics. There is, however, a margin of improvements that could be achieved with respect to the Concorde baseline. Various studies indicate that a 25% gain in cruise efficiency could be obtained by applying state-of-the art methods. The objective is to reach a 35% increase in L/D with respect to the Concorde value. Other performance increases with respect to the Concorde baseline are shown in Table 3.

For the engine, the economic viability is essentially based on supersonic cruise performance. A 1% increase in consumption is equivalent to a 5-ton increase in the TO gross weight (TOGW) or to a loss in payload equivalent to 50 passengers. Another objective is to augment the thrust to weight ratio by 50% with respect to the Olympus engines. For a supersonic business jet, there are additional penalties related to the relative size of the cabin with respect to the wing. The fuselage size determines its drag. The ratio of the fuselage diameter to the wing span defines the respective contributions of the fuselage and wing to the total drag. For the ESCT, this ratio could be increased, thus, decreasing the relative contribution of the fuselage to the total drag. This is not feasible on the SSBJ, and as a consequence, the relative contribution of the fuselage will be in the same proportion as that of the Concorde.

Environmental Issues and Design Objectives

To be economically viable, supersonic aircraft will have to achieve the flight ranges and carry the payloads defined earlier, but their success will depend on the environmental acceptability. This implies that these aircraft will be in conformity with respect to current and future certification standards and regulations. Sonic boom, noise radiation, and emissions are successively considered next.

An aircraft traveling at supersonic speeds produces shock waves, which merge in the near field and eventually propagate to the ground, creating an impulsive change in pressure. The sound wave is intense and provokes a considerable disturbance. Concorde experience has shown that the sonic boom was not well accepted by the public. Commercial flight at supersonic speeds is in fact forbidden in many countries. The design of a supersonic aircraft that would be economically viable and feature an acceptable sonic boom level does not seem to be feasible, at least with the current technological knowledge. It is concluded at this point in time that the ESCT will have to fly at a reduced speed over land and at supersonic speeds only over water. There is, however, some hope to reduce the boom level and shape the waveform to diminish the human response and perhaps allow supersonic flight over ground, for example, for the SSBJ.[25] Sonic boom minimization and shaping must not, however, degrade the aerodynamic performance.

Community noise related to aircraft operation has become a sensitive environmental issue. Commercial aircraft have to meet noise regulations for TO and approach to landing. The standards are currently described by stage 3 of the International Civil Aviation Organization annex 16 volume 1. Future supersonic aircraft must comply with these regulations and the levels that will be set at the date of entrance in service of these vehicles. The trend has been to a reduction of the noise emitted by subsonic aircraft, as shown in Fig. 10. This figure shows the evolution of the cumulated noise level of different classes of aicraft as a function of time. (The noise level is given in EPNdB and is calculated by summing the levels preceived at the three points of observation of the stage 3 regulation.) A reasonable objective for the future propulsion system of the ESCT will be to achieve a noise level of 18 EPNdB below the current stage 3 value. This reduction will not be easy to reach. Further improvements might be needed depending on the entry-into-service date. Note that if the goal is not reached, future SST might face the same difficulties as Concorde did.

Noise abatement requires advanced design that allows a reduction of the high-ejection velocities of supersonic engines. Because the acoustic power radiated by subsonic and moderately supersonic turbulent jets increases with the eighth power of the initial jet velocity, the exhaust speed should not exceed 400 $m \cdot s^{-1}$ at takeoff. The mass flow rate passing through the engine must be increased to obtain the required thrust. At higher flight velocities when the aircraft is away from populated areas, the jet velocity can be increased to obtain the specfic thrust required for transonic acceleration and supersonic cruise, and the mass flow rate will have to be reduced. The dual

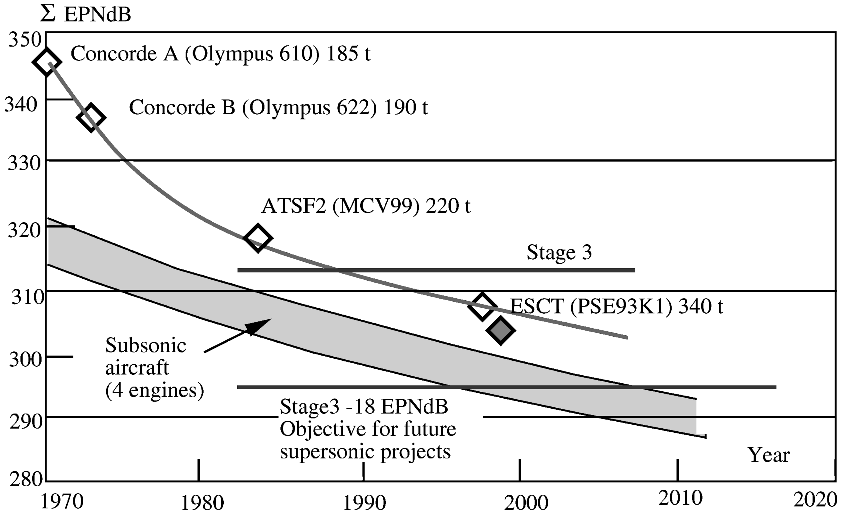

Fig. 10 Evolution of noise level of different types of aircraft.

mode of engine operation implies a variable cycle. Current projects focus on mixer-ejector and midtandem fan concepts, but neither of these engine architectures is, at this point, capable of fulfilling the noise reduction specifications. In addition, improvements in aerodynamic and structural efficiencies of the vehicle will contribute to the reduction in thrust required for takeoff and, hence, contribute to the reduction of the noise level.

The quantity of emissions from the global fleet of aircraft is relatively small compared to that of other sources (anthropic or natural). The contribution of 200 supersonic aircraft would represent about 2–4% of the total CO_2 emissions of a mixed fleet of subsonic and supersonic vehicles. These emissions, however, take place at a high altitude, and they perturb the atmosphere in its upper layers inducing variations in the ozone level, modifying the radiative balance, and influencing the greenhouse effect. It is believed that water vapor emissions from stratospheric aircraft may have an impact on the climate several times greater than that of aircraft flying in the lower atmosphere. Studies of the climate change (Intergovernmental Panel on Climate Change,[26]) indicate that the radiative forcing resulting from the operation of 1000 supersonic aircraft in 2050 would induce a nonnegligible forcing of $0.10\ \mathrm{W \cdot m^{-2}}$ to be compared to a total forcing of $0.27\ \mathrm{W \cdot m^{-2}}$ for the mixed fleet. This forcing would be five times larger than that of the subsonic aircraft it would replace. The same studies tend to show that forcing is essentially related to water vapor in the case of supersonic vehicles, whereas it is controlled by CO_2 and contrail condensation in the subsonic case.

Emissions of nitric oxides NOx has been a concern since the early 1970s when supersonic air transportation was brought to the market. It has been investigated by many groups over the years. It is now known that NOx compounds may have either a positive or a negative effect on the concentration of ozone in the upper atmosphere, depending on the altitude of emission. Studies carried out in the U.S. High Speed Research (HSR) program by assuming a Mach number of 2.4 have led to set a goal of 5 g of NOx emission per kilogram of fuel. This may be compared to the value of 20 g/kg issued from the Olympus engines of Concorde. More recent U.S. evaluations indicated that a goal of 15 g/kg would be acceptable during the subsonic part of flight at a lower altitude, whereas 5 g/kg would be the goal for cruise at $M = 2$ at higher altitudes.[19] Other studies indicate that ozone depletion would be mainly controlled by water vapor emission. In this context, it is important to further evaluate the impact of NOx emissions and of water vapor on the ozone content of the upper atmosphere. The development of ultralow NOx combustor technologies deserves special attention. This sets a major challenge in combustor design and in the related area of material technology.

The preceding discussion highlights areas that deserve sustained research. Efforts should focus on 1) impact of emissions on the upper atmosphere and combustion management to reduce emission levels, 2) innovations in engine design for noise reduction, propulsion efficiency, and service life, 3) sonic boom evaluation and exploration of possible reduction methods, 4) improvement of aerodynamic performance through new concepts and extensive application of optimization methodologies, 5) innovations in propulsion integration to minimize installation drag, and 6) new concepts and related material utilization for structural efficiency augmentation and lifetime extension. There are many other issues that deserve investigations, but those listed are the most critical. Sonic boom mitigation appears most difficult to achieve. Current studies of shape optimization lead to extremely slender geometries,[17] which do not seem compatible with large payloads and current airport constraints. It is still possible to consider that the SST would fly subsonically over land. The next most challenging topic is that of designing an engine with extended service life, reduced noise radiation, low-emissions levels, and enhanced efficiency.

Research efforts along these lines are now being carried out in various countries. One such effort is being made in France by a Supersonic Research Network initiated in the year 2000, a synthesis of which is given in Ref. 21.

Conclusions

This paper contains a short account of the development of Concorde. This aircraft, designed some 40 years ago, has flown for 27 years and demonstrated that supersonic transport at twice the speed of sound was accessible. The aircraft relied on revolutionary concepts for the time of its design: 1) an ogival wing planform with a low thickness-to-chord ratio and a sharp wing appex inducing an intensified vortex that provides additional lift at low speed and high angle of attack, 2) variable geometry engine inlets including bleed doors and variable ramps that allow boundary-layer control and flow bleeding for mass flow rate adjustment, 3) variable geometry nozzles with bucket deflectors accomodating low and high expansion ratios, as well as reverse flow for aircraft deceleration, 4) fly-by-wire controls, 5) fuel transfer for longitudinal stability tuning allowing trim drag reduction under cruise conditions, and 6) first application of full authority control to civil aircraft engines.

Concorde featured unique performance still unmatched by any other vehicle, the most notable being its ability to cruise at Mach 2 with 90 passengers aboard for about 3 h and cover a range of 6300 km. The technical achievement was remarkable, but Concorde did not meet commercial success and service was discontinued in October 2003. It has often been stated that Concorde was launched without a serious market analysis. In fact, commercial evaluation indicated that a few hundred aircraft could be sold profitably and that this was sufficiently attractive to pursue the development. By 1967 there were 74 firm orders from 16 different airlines. However, the downturn came in 1973 when the Pan American Airlines canceled its options and soon after most other airlines abandoned theirs as well.

The remaining orders were those of Air France and British Airways. A compounding difficulty was that of obtaining landing rights. The SST project had been abandoned by the United States, and traffic rights soon became a political issue that was bitterly debated. The airplane was rejected on the basis of environmental considerations. Although the U.S. federal government reached the decision to allow access to a set of airports, the agreement to land at the Kennedy airport in New York took 18 more months to settle, which was at the end of 1977. In retrospect, one can say that the aircraft took too long to get to the market. The initial 1970 entry into service was delayed to 1976 in relation with the many technical difficulties of the project. By that time, the world had changed and the initial assumptions that were made in the early 1960s were not those that prevailed in the mid-1970s. The oil crisis of 1973 induced a spectacular increase in oil prices, whereas environmental awareness had progressed in the public and community noise became a key issue.

In assessing the Concorde program,[5] Cormery advocated a comprehensive evaluation that would also consider the influence that this development has had on later subsonic aircraft projects. Among many examples, he cited the fly-by-wire controls and the sidestick tested as early as 1978 on Concorde, which were later adopted on the Airbus family starting with the A320.

As the only commercial supersonic aircraft that has gone to completion and operation, Concorde will remain as a reference for any new development. From the lessons learned from this adventure, it is clear that the outlook for a future supersonic vehicle will be conditioned by a careful assessment of its marketability, profitable operability, and by our capacity to solve fundamental scientific and technical challenges. The list of issues is quite large, but the toughest challenges are related to propulsion. The objective is to design a powerplant that would generate the required thrust efficiently, feature an extended service life, and produce acceptable noise levels with reduced fuel consumption and emissions. A variable cycle will be required to provide low-ejection speeds and high mass flow rates under TO and subsonic conditions and high-ejection velocities and moderate mass flow rates at high Mach numbers. Entirely new combustor technologies are needed to fulfill the ultralow NOx emission goals. On the technical side, considerable progress is needed to develop engine components and systems capable of operating at near maximum temperature conditions required by sustained supersonic cruise. Research and innovations are needed, and efforts are being made in the United States, Europe, and Japan. One cannot be sure that these efforts will be able to produce the technologies that would bridge the gap between the state of the art and supersonic vehicle requirements, but it is important to invest in this direction.

Acknowledgments

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