A RESEARCH INITIATIVE ON THE SUPERSONIC AIRCRAFT

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Abstract

Commercial or business high-speed flight at supersonic speeds pose major technological challenges. While the demonstration of sustained supersonic flight has been made by operating Concorde over a period of more than a quarter of a century, it has also served to show the limitations of this remarkable vehicle. Taking into account the lessons learned from the past it is not possible to envisage a new supersonic aircraft program without first resolving the many fundamental and technical barriers of such a project. The vehicle will have to benefit from the modern tools devised by aeronautical science and technology during the recent past but further advances will be needed to resolve the most difficult problems. 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 requires fundamental progress in aerodynamic optimization for sonic boom and drag reduction, combustion management for emissions 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 with an all subsonic fleet. This article summarizes the findings and recommendations of the Advisory Panel on Supersonic Flight formed in France in 1999. The major areas of investigation were identified and methods to set up a collaborative research initiative were proposed. On the basis of a report assembled by the advisory panel over a period of 9 months, a research network has been set-up and has operated since the beginning of 2001. Its organisation is described and selected projects are used to highlight current research efforts.

1 Introduction

Since the first supersonic flight achieved some sixty years ago considerable progress has been accomplished in aeronautics. Commercial supersonic flight has been exploited since the mid-seventies by a unique type of aircraft and two airline companies. Operation of the Concorde over a period of more than 26 years has shown that supersonic travel is accessible, has commercial potential but is limited by technology. While Concorde has been and still is a remarkable vehicle with unique performance, the first aircraft to use fly-by wire control, its design dates back to the sixties and early seventies. Since that time aeronautical science and technology has progressed to a great extent and much experience has been accumulated. It is thus possible to envisage the development of a a new supersonic aircraft but this development will only be reasonable if solutions are found to many scientific and technical challenges. These should be met before launching any new project.

The Advisory Panel on Supersonic Flight (COS : “Comité d’Orientation Supersonique”) was formed to evaluate these scientific challenges and define research priorities for future supersonic air transportation. The objective was to determine the contours of a research initiative in this field. Five working groups were established to identify the critical technologies, assess the state of the art and list research directions which would lead to a reduction of the technological uncertainties and risks involved in future decisions to launch a supersonic transport program.

On the basis of this analysis it was concluded that important scientific and technological advances as well as innovative solutions were needed to allow the development of a supersonic transport

which would be environmentally acceptable and economically viable for users (air-carriers, business aviation and passengers) as well as for aircraft manufacturers.
In certain key areas (noise, emissions, impact on the upper atmosphere, structural life duration, tolerance to damage,...), the success of an eventual vehicle will be determined by advances in research.
The panel also advocated a closely coupled collaboration between all actors from academic laboratories, research organizations, industry and official agencies. It was concluded that novel methods for managing and focusing research were essential to the development of the required technologies. According to the panel the research program on supersonic flight could become a real technological mover for the aerospace industry and play an important role in the competition in a key sector of the economy [1].
This article summarizes some of the findings and recommendations of the panel, explains how the program is being managed and describes the current status of this initiative. Research carried out in the network is illustrated with a selected set of examples. The paper begins with a brief account of requirements and performance objectives of future supersonic transportation vehicles.

2 Requirements and Performance Objectives of Future Supersonic Aircraft

The supersonic commercial airliner envisioned by Aerospatiale Matra Airbus, now Airbus, considers a desired payload of 250 passengers and a desired range of 10000 km (5400 NM) [1]. The cruise Mach number is set to approximately 2 but more recent investigations have considered lower cruise Mach numbers. This has distinguished the European vehicle from the american HSR project characterized by a much more ambitious Mach number of 2.4 [2]. This high value induces many difficult and often unsurmountable problems and in particular requires very low pollutant emissions to reduce the impact on the stratosphere. Current American projects have more recently converged to a lower value of the cruise Mach number to diminish the technological challenges and environmental concerns associated with the very high speed initially considered [3]. The European project considers that the aircraft will fly subsonically overland but it could be useful to reexamine the possibility of flying at low supersonic Mach numbers overland and at higher Mach numbers over water. Table 1 summarizes the main characteristics of some future supersonic aircraft as compared with those of Concorde.
Compared with Concorde, the specifications of the ESCT are relatively ambitious : (1) The payload would be more than doubled, (2) The range of 10000 km would allow supersonic flight from Tokyo to New York or Paris along appropriate routes, (3) Fuel consumption (per km and per passenger) would be divided by two, (4) The life duration would be 80000 hours including 60000 hours under supersonic cruise conditions. The maximum cruise altitude would not exceed 65000 ft (20000 m) which would be advantageous with respect to the impact of emissions on the higher atmosphere. An aircraft featuring a lower Mach number is also being considered. Its cruise altitude would be reduced, thus further mitigating the environmental impact of emissions.
The supersonic business jet would cruise at lower Mach numbers of 1.6 to 1.8 [1]. Its range should exceed 4000 NM (7200 km) to cover missions which would be flown partially or totally at a subsonic Mach number (M=0.95). The approach velocity should not be greater than 145 knots a reasonable upper limit for an airplane which would be flown by a broad range of pilots. The most difficult issue in designing an SSBJ is to derive a propulsion system from existing engines which would satisfy performance requirements in terms of noise, specific fuel consumption and life duration. Artist’s impressions of the ESCT and the SSBJ are shown in Figure 1.

Performance Objectives

The main performance of an aircraft is its range. For a given Mach number and payload this range is well estimated by the Bréguet-Leduc formula :

$$R \simeq v\frac{L}{D}\frac{1}{C_s}\ln(\frac{W_i}{W_f}) \qquad (1)$$

where v is the cruise speed, L/D is the lift to drag ratio and represents the aerodynamic efficiency and C_s is the specific fuel consumption and is closely related to the propulsion efficiency of the engines, $(W_i/W_f$ is the ratio of the initial (at takeoff) and final (at landing) aicraft weights and represents the structural efficiency.
This expression clearly indicates that improvements in the three efficiencies are needed to reach the ranges envisioned for the future supersonic ve-

Characteristics	Concorde	European Sup. Transp.	High Speed Sup. Transp.	Supersonic Bus. Jet (F)	Supersonic Bus. Jet (US)
Range	6300	10000	9000-10000	7400	7400
Cruise Mach number	2.05	1.8-2.	2.	1.8	1.6-1.8
Number of seats	100	250	300	8	8-15
Takeoff gross weight (tons)	185	340	271	39	63
Length (m)	62	89		33	
Wing span (m)	25.5	42		17	
Wing ref.surface (m^2)		836		130	
Consump. (kg seat^{-1} km^{-1})	0.1	0.043			

Table 1 Supersonic aircraft characteristics.

hicles. The aerodynamic cruise efficiency of supersonic vehicles is lower than that of subsonic aircraft. Values in excess of 18 are achieved by current subsonic airliners while the cruise efficiency of Concorde is of about 7.5. Low values of L/D lead to increased fuel consumption and induce range limitations. The low values of L/D obtained on supersonic aircraft are due to the additional drag induced by supersonic aerodynamics. There is however a margin of improvement which 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 2.

For the engine the economic viability is essentially based on supersonic cruise performance. A 1% increase in consumption is equivalent to a 5T increase in the TOGW or to a loss in payload equivalent to 50 passengers. Another objective is to augment the thrust to weight ratio by 50% compared with the Olympus engines. For the supersonic business jet there are additional penalties associated with the size of the cabin relative 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 [1].

Environmental Issues

Supersonic aircraft should be economically viable and for that achieve the ranges defined previously but their success will depend on their environmental acceptability implying their conformity with respect to current and future certification standards and regulations. Sonic boom, noise radiation and emissions are successively considered below.

An aircraft traveling at supersonic speeds produces shock waves which merge in the nearfield and eventually propagate to the ground creating an impulsive change in pressure. The sound signature is intense and provokes a considerable disturbance. Concorde experience has shown that the sonic boom is not well accepted by the public. Commercial flight at supersonic speeds is in fact forbidden over many countries. The design of a supersonic aircraft which 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 moment in time that the ESCT will have to fly at a reduced speed over ground 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 smaller supersonic business jets. The boom minimization and shaping should not however degrade the aerodynamic performance.

Noise radiation by aircraft has become a sensitive environmental issue. Commercial aircraft have to meet noise regulations for takeoff and approach to landing. The standards are currently described by stage 3 of ICAO Annex 16 Volume 1. Future supersonic aircraft will have to comply with

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 %

Table 2 Improvement objectives with respect to the Concorde baseline.

these regulations and the levels which will be set at the date of entrance into service of these vehicles. The trend has been to a reduction of the noise emitted by subsonic aircraft as illustrated in Figure 2. This diagram shows the evolution of the noise level of different classes of aicraft as a function of time (the noise level is given in cumulated EPNdB and is calculated by summing the levels perceived 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 will require advanced design which will allow a reduction of the high ejection velocities of supersonic engines. New variable cycle systems will be needed, equipped with sound attenuation liners. In addition, improvements in aerodynamic and structural efficiences of the vehicle will contribute to the reduction in thrust required for takeoff and hence participate in reducing the noise level.

The quantity of emissions from the global fleet of aircraft is relatively small compared with that from other sources (anthropic or natural). The contribution of 200 supersonic aircraft would represent about 2 to 4% of the total CO_2 emissions of a mixed fleet of subsonic and supersonic vehicles. However, these emissions take place at 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 climatic impact of water vapor emissions from stratospheric aircraft may be several times that of aircraft flying in the lower atmosphere. Studies of climate change (IPCC, 1999) indicate that the radiative forcing resulting from the operation of 1000 supersonic aircraft in 2050 would induce a non-negligible forcing of 0.10 W m^{-2}, to be compared with a total forcing of 0.27 W m^{-2} for the mixed fleet. This forcing is five times larger than that due to the subsonic aircraft that would be replaced. The same studies tend to show that forcing is essentially related to water vapor in the case of supersonic vehicles whilst it is controlled by CO_2 and contrail condensation in the subsonic case.

Emissions of nitrogen oxides NOx has been a concern since the early 1970s and the initiation of supersonic air transportation. NOx compounds may have 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 American HSR program assuming a Mach number of 2.4 have resulted in a goal of 5 g of NOx emission per kg of fuel. This may be compared with the value of 20 g/kg which characterizes the Olympus engines of Concorde. More recent American evaluations tend to indicate that a goal of 15 g/kg would be acceptable for vehicles travelling at Mach 2 at a lower altitude [3]. Other studies indicate that ozone depletion would be mainly controlled by water vapor emission. In this context it will be important to evaluate further the impact of NOx emissions and of water vapor on the ozone content of the upper atmosphere.

3 Research Directions and Selected Investigations

The critical areas which deserve sustained research are clearly apparent from the previous discussion : (1) Impact of emissions on the upper atmosphere, and combustion management to reduce this impact, (2) Engine design for noise reduction, (3) Sonic boom evaluation, and exploration of possible reduction methods, (4) Aerodynamic optimization and propulsion integration for increased efficiency, (5) Structural design and advanced materials for enhanced efficiency and lifetime extension. Many other aspects deserve further work but will not be considered here to keep this article within reasonable limits.

Environmental Impact and Combustion Management

Supersonic aircraft will have to satisfy important environmental constraints. The impact on the stratospheric ozone layer has to be evaluated but it is also necessary to envisage general effects on the atmospheric chemistry at cruising altitude. Research is needed on various facets of this complicated problem (low temperature kinetics and heterogeneous reactions involving soot particles, formation of contrails and interactions with the engine jets, realistic simulations of the atmospheric impact of various fleets of aircraft, sensitivity studies of these global simulations, chemical and radiative impact of water vapor emissions at high altitudes, NOx and water vapor impact on the ozone layer as compared with other sources of emissions).

There are considerable uncertainties which merit further consideration. This is exemplified by investigations carried out by Bedjanian et al. [4] who investigate the impact of HOx and soot on the balance of ozone. The reaction $HO_2 + O_3$ has been studied and the interaction of species like NO_2 and HNO_3 with O_3 and soot is also considered. Another facet of the problem is treated by Garnier et al. [5] who analyze the formation of particles in the propulsive jets and vortex trails of supersonic aircraft.

Reduction of emissions requires advanced concepts for combustion management. New solutions are considered to diminish NOx levels, for example by using lean premixed injectors or staged combustion. These systems operate at elevated pressures and air temperatures which often lead to autoignition, flashback and instabilities. Combustors which deliver very low NOx levels are also sensitive to resonant oscillations and flame dynamical problems. These important aspects are investigated by three groups led by Thierry Poinsot [6], Luc Vervisch [7] and Denis Veynante [8]. Experiments are carried out on a lean premixed combustor, the mixing and combustion of sprays is analyzed with direct simulations while large eddy simulations are developed to describe combustion dynamics. This is illustrated with a full three-dimensional large eddy simulation of the premixed flame formed by a swirl combustor. The calculation uses a specific flame treatment and a subgrid scale model. It has been used to demonstrate the possible transition between a lifted flame formed downstream as in Fig. 3, and a flame attached inside the premixer after flashback. This simulation indicates that it is now possible to envisage LES of combustion instabilities in the relatively complex geometries found in practice.

Engine Design for Noise Reduction

Future supersonic aircraft will have to comply with noise regulations at the time of their introduction into the market. These regulations become progressively more severe and they will not be met by classical solutions. Engines will have to feature a variable cycle [9]. This requirement induces major technical design problems. Current configurations are based on the mid-tandem fan (MTF) concept in which the fan is located behind compressor stages to take full advantage of the larger section available at that level. The fan design is complicated because it has to operate over a broad range of conditions ; this problem is considered by a group led by Georges Gerolymos and Francis Leboeuf [10], [11]. Detailed aerodynamic studies have been carried out to obtain an optimized fan geometry which would feature the required performance and an extended operating range.

Another team led by Daniel Juvé is developing Computational Aeroacoustics methods for jet noise [12], [13]. Figure 4 shows a typical example of large eddy simulation of noise radiation from a subsonic turbulent jet. The lower part of the figure shows the vorticity field in the turbulent jet while the upper part gives the wave radiation pattern. These new tools will allow predictive studies of the acoustic radiation from ejection flow configurations and evaluation of possible control schemes based on synthetic jets or other systems.

Sonic Boom

The sonic boom is a specific problem of supersonic flight. Means of reducing the pressure level at the ground are relatively limited but innovative solutions should be envisaged. Sonic boom studies are also needed to define flight corridors and manoeuvering procedures. It is important to consider focussing effects and the spatial extension of the primary and secondary boom carpets (see Figure 5). A cooperative effort has been set up on these topics. The team led by François Coulouvrat [14] considers the near field shock wave interactions, propagation to the farfield, the computation of focused sonic booms and distorsions of the N-wave induced by turbulence. Simulations of the sonic boom are also being carried out with nonlinear ultrasonic waves propagating in a water tank. This allows detailed studies of focussing effects and an analysis of the caustic region.

A typical example of the effect of turbulence on the initial N-wave is shown in Figure 6. This is obtained by propagating an N-wave in a region of turbulence. The signals recorded after propagation indicate that turbulence may strongly modify the shape of the wave [14], [15]. This indicates that wave shaping techniques could be counteracted by effects of turbulence. This finding has consequences as it may affect aerodynamic wave shaping techniques.

Aerodynamic Optimization

The aerodynamic figure of merit of an aircraft is represented by the lift to drag ratio L/D. This measures the aerodynamic efficiency and which has a fundamental influence on the global performance of the airplane (see equation (1)). Optimization of the vehicle shape should consider low subsonic takeoff conditions, subsonic level flight at Mach 0.95 and supersonic cruise. A high value of L/D is required in the subsonic range to satisfy noise regulations (high L/D requires a lower thrust corresponding to a reduced level of noise at takeoff). The L/D value for supersonic cruise determines much of the performance. A value of 10 at Mach 2 is needed to fulfill the range and consumption objectives. These ambitious goals can only be met with a slender fuselage, thin wings and an augmented wing span. This complicates the structural design as the wing becomes more flexible, inducing enhanced structural loads. Aerodynamic flutter has to be considered early in the design process. It is then clear that multidisciplinary optimization will play a central role in the geometrical definition of the vehicle. It will be important to consider optimization at three flight points (low speed at takeoff, high subsonic level flight and supersonic cruise) while taking into account structural efficiency and aerodynamic flutter. The development of numerical optimization tools thus appears as a central necessity. This is being considered by two groups in the network. The first, led by Hughes Deniau [16], works on the application of genetic algorithms to supersonic cruise shape optimization. The second, animated by Alain Dervieux [17], considers the application of adjoint equation methods to multipoint optimization.

Supersonic flight also requires a careful integration of the propulsion system and detailed studies of the engine inlet aerodynamics. A project led by Jean Paul Dussauge deals with shock/boundary layer interactions occuring inside the inlet duct [18]. A group around Alain Lerat [19] develops advanced tools for inlet design including Reynolds stress turbulence models, higher order Navier-Stokes solvers and Large Eddy Simulation methods. LES methods to deal with compressible boundary layer effects and friction drag are also developed by a group led by Olivier Métais.

Flow control methods are being considered to manage separation (a project carried out by team around Jean Paul Bonnet [20]) whilst active control methods are explored by a team led by Michel Sunyach [12] to diminish jet noise and by a group around Emmanuel Friot [21] to reduce tone radiation from the engine fan.

Materials and Structural Optimization

The slender configurations envisaged for the future supersonic aircraft and the objective of reducing the takeoff weight require new structural solutions and advanced material combinations. One has to envisage titanium for the massive parts of the wing and composite materials for the less heavily loaded components. The structure of the vehicle will be submitted to elevated temperatures associated with kinetic heating and the skin temperature will reach temperatures of 100° C for Mach 2 cruise. The deterioration of composites submitted to cyclic thermomechanical loading is an important ageing aspect. The definition of accelerated ageing procedures for lifetime simulations is an issue of technical importance which is being considered by a group led by Marie-Christine Lafarie [22]. The study includes kinetic modeling of oxidation, thermomechanical cycling and modeling from the microscale processes to the mesoscale behavior of a stratified composite structure. The objective is to account for deterioration and aging.

The high performance engines considered for the supersonic aircraft require materials with improved charcteristics. These engines will have to operate at nearly maximum temperature during the whole flight even during cruise. This distinguishes supersonic engines from subsonic motors, which only operate at maximum temperature for a short period of time during takeoff (see Figure 7).

Rotors will be submitted to creep during periods of a few hours in each flight, for nearly 3000 h per year. To reach five years under the wing without major maintenance, the rotating parts of the engine will have to feature moderate creep after 15000 h of thermal loading. The loading conditions will be less severe for a supersonic business jet cruising at Mach 1.6 than for the supersonic airliner travelling at Mach 2. Improved materials are needed for the combustor (liners and coatings ceramic matrix composites or molybdenum-niobium based alloys), turbine airfoils (single crystal alloys), compressor and turbine disks (superalloys formed by metallic powder processes), nozzles (titanium aluminide), acoustic liners (high temperature CMC, titanium aluminide intermetallic materials). Studies of fatigue and creep of nickel-based superalloys for turbine disks and blades are being carried out by a group around José Mendez [23]. Thermal barriers for turbine blades are being considered by another team led by Luc Rémy [24]. The problem of assembling metallic parts and ceramic matrix composites is explored by Olivier Dezellus and his group [25] with the objective of developing new brazing processes.

4 The Supersonic Research Network

Traditionally, research is aimed at advancing knowledge whilst industry focusses on applications. In many cases technologies have originated from studies carried out in laboratories but for this, research should be tuned to the needs expressed by industry and industry should specify its problems to researchers. Issues raised by supersonic transport cover a broad range of scientific, technical and socio-economic disciplines, offering numerous topics deserving scientific investigation using theoretical analysis, numerical and experimental tools. Starting from this observation, the Advisory Panel on Supersonic Flight ("COS") recommended that a research network should be set up to deal with the critical scientific issues raised by a future supersonic aircraft (see Figure 8). The panel provided an initial roadmap for supersonic research in the form of a report to the French government.

The decision to set up the research network was taken in December 2000 and its operation has now spanned a period of about two years. The scientific board of the network includes representatives from industry, research organisations, academia and government agencies. It defines research orientations, selects research proposals on the basis of an evaluation by independent and anonymous experts and evaluates results obtained by the different teams. Financial support has been provided to 34 research projects involving more than 70 research teams from different laboratories and organizations. A new wave of 18 projects will be launched during the summer of 2002. Four working groups (Aerodynamic Optimization and Systems, Propulsion and Noise, Combustion Management and Environmental Impact, Materials and Structures) have been set up and meet periodically to conduct workshops. A two day colloquium was held in February of 2002 to review the research activities and discuss perspectives and such joint meetings will be held periodically in the future years.

5 Conclusions and Perspectives

The supersonic research network has operated since the begining of 2001. It includes academic teams, research organizations and industrial companies under the aegis of governmental agencies. This network has mobilised the research community and induced a closely coupled collaborative effort focused on the many challenges of supersonic transport. It consitutes an open forum allowing interactions and rapid transfer of research results between different groups and industry and a continuous development of the scientific and technological prospective. The network gathers the distributed competence. It favors partnerships, develops a continuous evaluation of results and encourages the rapid exchange of information among all participants.

Beyond supersonic flight applications, a large number of studies carried out by the network will have an impact in other fields of scientific and economic importance (subsonic air transport, environment, energy...). As an example, progress accomplished in reducing aerodynamic noise will have a direct influence on the development of quieter jet engines for subsonic flight. Work that focusses on low NOx combustors will be useful for heavy duty industrial gas turbines which exploit advanced combustion technologies to comply with more stringent emission regulations. Even studies on the sonic boom which are rather specific to supersonic flight might find implications in the biomedical domain (current non-intrusive techniques to destroy stones in kidneys use nonlinear ultrasonic N-waves). The large number of subjects which needs to be considered, their inherent complexity and interdependence re-

quire new ways of developing and managing research. The network of laboratories set up for this purpose provides a framework for dynamical and interactive cooperations between all participants. The supersonic research network may also serve as an entry point for the development of international collaborations on the supersonic theme.
It is intended to continue this initiative over a period of the order of four years. At the end of this first period, an evaluation will be carried out to measure the progress accomplished in the various areas and define a roadmap for a second term. Results obtained up to now are promising and it is hoped that the effort will be continued and expanded, leading to solutions of the most critical problems.

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Fig. 1 Artistic views of the Supersonic Business Jet and the European Supersonic Civil Transport

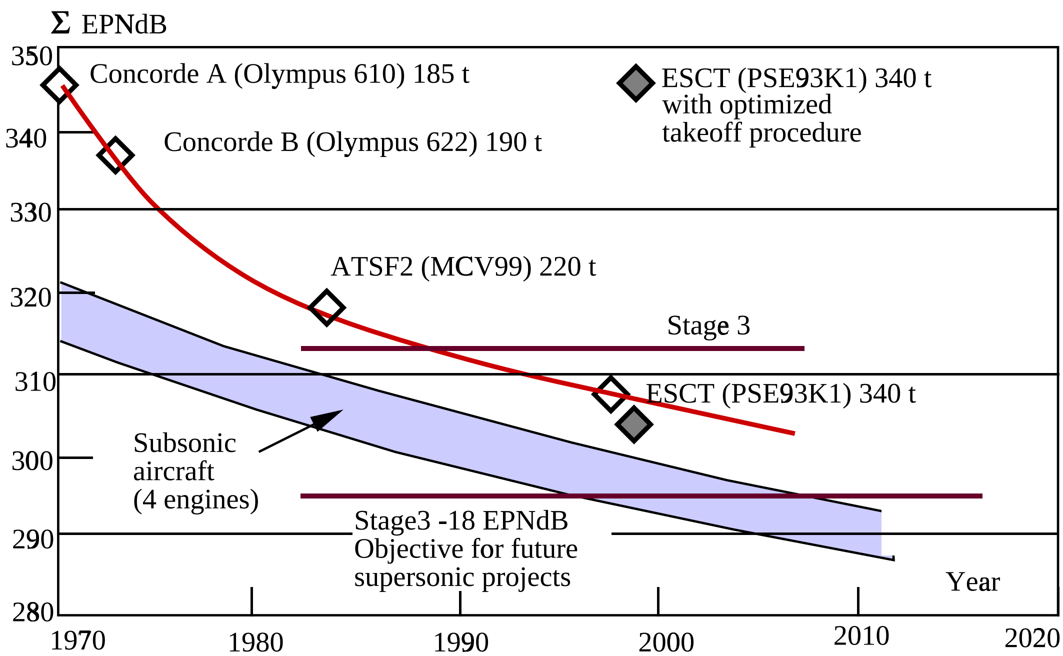

Fig. 2 Evolution of noise level of different types of aircraft.

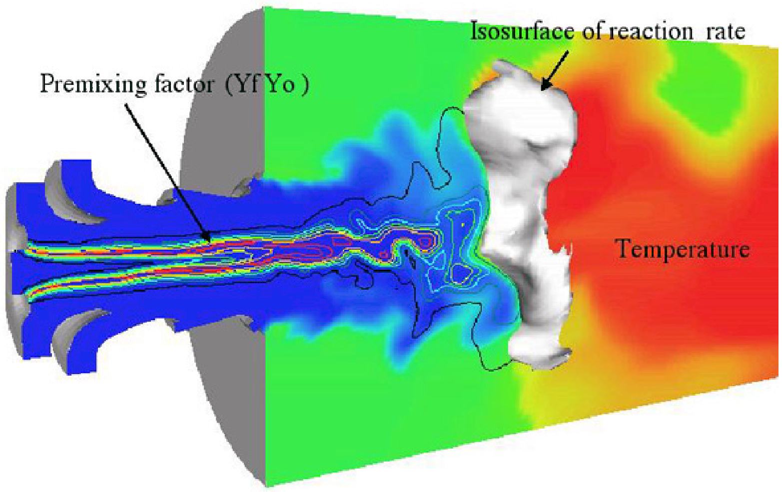

Fig. 3 Large eddy simulation combustion. Air and methane flow through a premixer including two swirlers. The flame formed downstream is displayed on a scale of grey levels. (from T. Poinsot).

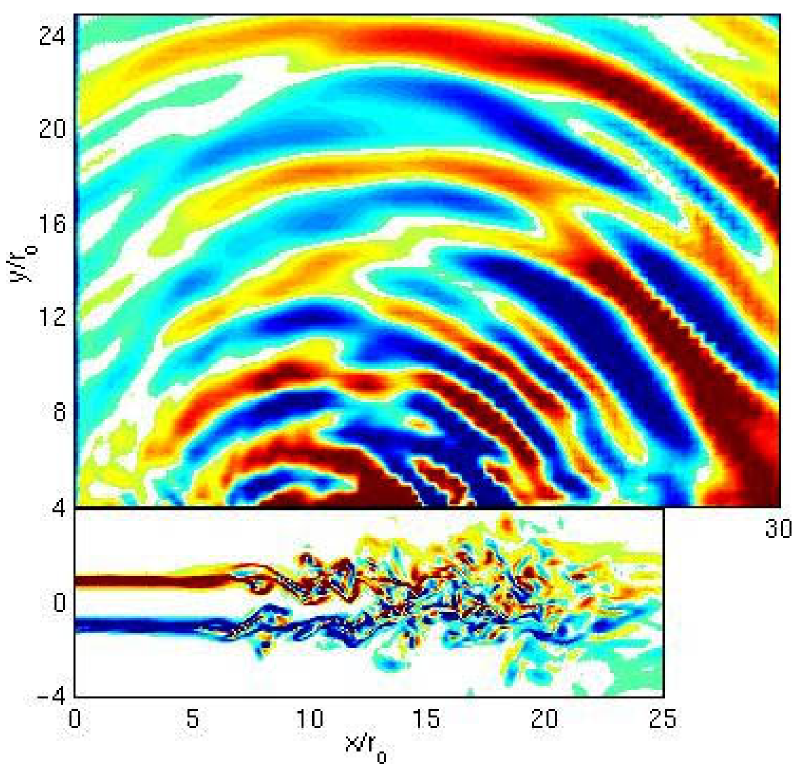

Fig. 4 Large eddy simulation of jet noise radiation. The lower part of the figure shows the instantaneous distribution of vorticity in the jet. The upper part displays wave radiation represented by the spatial distribution of dilatation.

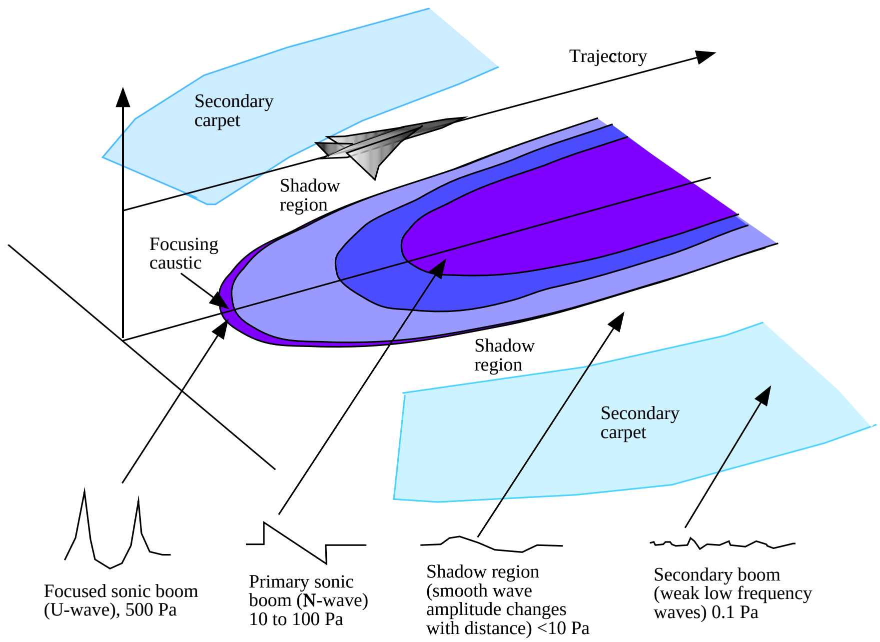

Fig. 5 Sonic boom distributions on the ground and corresponding wave patterns.

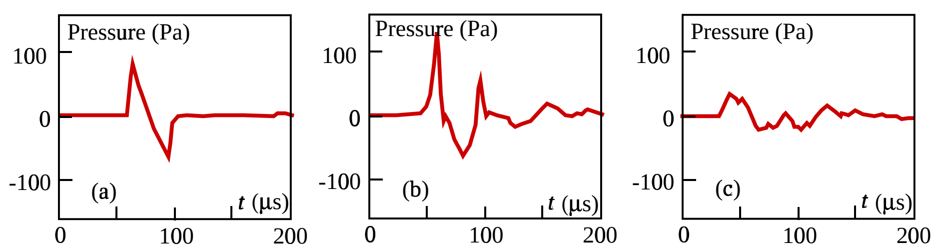

Fig. 6 Influence of turbulence on an N-wave. An initial N-wave propagates in a region of turbulence. (a) Wave shape after propagation in the absence of fluctuations, (b) and (c) Effects of turbulent fluctuations on the wave shape.

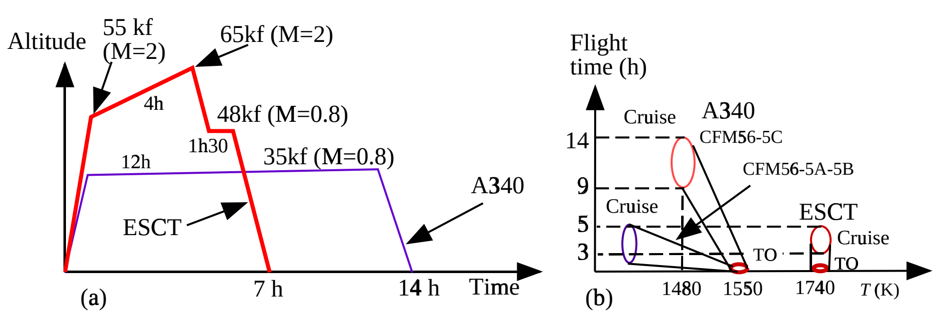

Fig. 7 (a) Flight profiles of subsonic and supersonic aircraft, (b) Maximum temperatures for subsonic and supersonic aircraft engines.

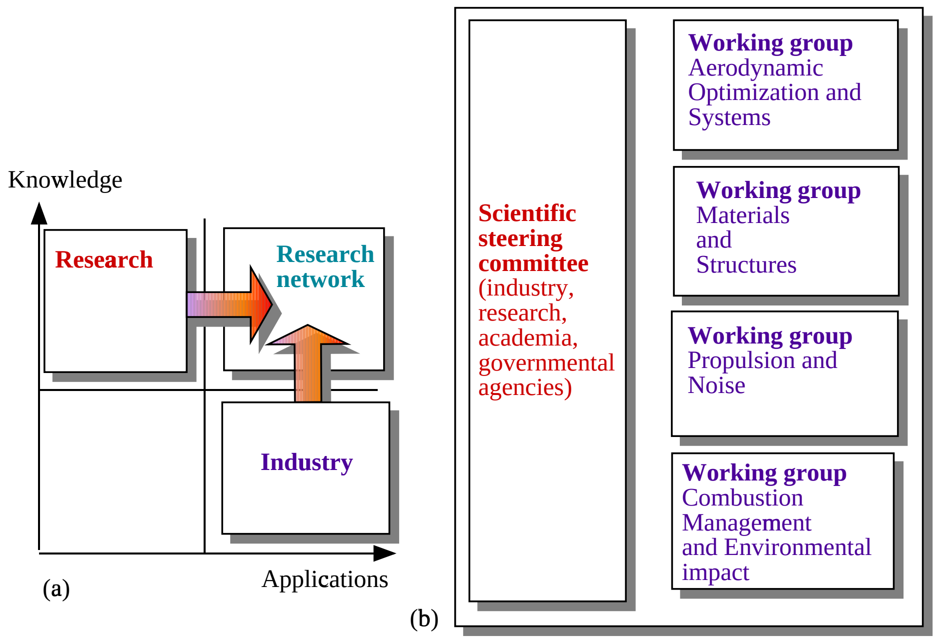

Fig. 8 (a) Position of the network, (b) Organization of the Supersonic Research Network.