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Noise Research Effort for Advanced Supersonic Transport Engine: An European Perspective

J. Julliard

Snecma – Moteurs – 77550 – Moissy – Cramayel

The future supersonic civil aircraft should be economically viable and environmentally acceptable. It will be operated from existing international Airports and therefore will have to satisfy, by the time of its operational service the more recent noise regulation required for the subsonic civil transport. For the engine design, the very high jet velocities required for cruise operation are rather incompatible with low noise around airports. Consequently, in order to accommodate both performance in cruise and low noise at take off a substantial noise research effort has been dedicated since the 90s in Europe as well as in US and Japan aimed at the propulsion system and more particularly the exhaust system associated, jet noise being a major problem in the design of quiet engines.

In order to cover the wide range of aircraft projects going from $M = 1$ up to $M = 2.4$ and to take into account the environmental issue in term of community noise, several concepts of engines have been investigated, acoustic studies being mostly based on the exhaust system. First studies concerned aircrafts with a cruise mach number of 1.8 up to 2.4. Quit a few concepts were proposed and studied, the more relevant ones being on one hand the so-called Mid Tandem Fan (MTF) a variable cycle engine with a relatively low jet velocity and on the other hand the mixer-ejector engine with a high jet velocity, even though the objective was to obtain an averaged exhaust velocity close to 400 m/s to meet the noise requirements of chapter 3. Since, the noise objectives are more stringent and lower exhaust velocities are considered. More recent studies concern aircraft projects flying at lower mach number $(M = 1.6)$. In this case, solutions based on conventional engines architectures are considered, which begin to be competitive at those lower Mach, with a lower complexity requirement.

To cover these requirements and to acquire an aeroacoustic data base, experiments on models were undertaken. From aeroacoustic considerations, exhaust and fan models were designed and manufactured and a description of different test models and configurations is given. Most of experimental investigations were based on MTF concepts but also on axisymmetric and 2D mechanical suppressor/ejector systems. Acoustic and aerodynamic tests were conducted in static and in a low speed anechoic wind tunnel. Acoustic results including parametric studies are presented and discussed in detail for both exhaust concepts. For instance, the effects of cycle, of reverse system with buckets and of treated mixer-ejector have been considered and assessed. An other concern is the fan noise associated with the MTF concept involving an additional air intake close to the fan which can be required during the take-off operation. A fan model was therefore designed and manufactured. A specific noise test was also performed to evaluate this contributor.

Supersonic Aircraft: Balancing Fast, Affordable, and Green

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In relatively recent history, humans have realized remarkable increases in the speeds of transporting goods and people. At the turn of the 19th century horse powered carts could travel at about 10 kilometers per hour. By the beginning of the 20th century trains could transport passengers and cargo at 100 kilometers per hour. And at the beginning of the 21st century subsonic airliners travel at 1000 kilometers per hour while the worlds only passenger supersonic airliners the Concorde, could travel at speeds exceeding 2000 kilometers per hour, more than twice the speed of sound. Technologists and adventurers dream of a similar ten fold leap in air transportation in the 21st century, possibly hypersonic (above $\sim$ five times the speed of sound) airbreathing airliners capable of traveling at $\sim$10,000 kilometers per hour. Yet, as we celebrate the 100th anniversary of powered flight continued increases in the speed of public transportation are not a “given”. Attempts at developing hypersonic airbreathing vehicles, such as the U.S.s National Aerospace Program I (1960s) and II (1980s) have achieved little success beyond technology demonstrations to date. In fact, the trend of increasing speed appears to be reversing. British Airways and Air France discontinued Concorde service this year. And other attempts at creating supersonic airliners have failed on both sides of the Atlantic – arguably the casualty of economic and environmental barriers.

Will we enter the 22nd century with only military and space missions exceeding the sonic barrier? The premise of this lecture is that the answer to this question depends on a complex multidisciplinary feat to balance the desire for speed with the need for affordable and environmentally acceptable passenger airliners.

The lecture begins by reviewing technological progress since the Concorde. Continued advances in propulsion, materials and structures, aerodynamics, controls, and multidisciplinary design practices can contribute to the success of future supersonic airliners. Advances in jet engine designs have led to a ten fold improvement in reliability.[1] Materials and structures advances have resulted in a

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[1] Roundhill, J. and Radloff, P., “The Future of Commercial Aviation – Building on Our Legacy,” AIAA 2003–2883, AIAA-ICAS International Air and Space Symposium and Exhibit: The Next 100 Years, 14–17 July 2003, Dayton, OH.

35 % decrease in operational empty weights.[2] The Boeing 777 is 300 times more fuel efficient than the early Convair, Douglas, and Boeing jets.[3] Continued research will no doubt lead to more improvements.[4] And overcoming sonic boom remains amongst the foremost technological challenges. Recent results from the U.S. Defense Advanced Research Projects Agency (DARPA) and National Aeronautics and Space Agency (NASA) sponsored Quiet Supersonic Platform (QSP) program showed the feasibility of tailoring sonic booms to reduce overall impact.

The recent QSP results have generated much excitement in the technical community. Yet we must proceed cautiously and remember that technological advances are a necessary but not a sufficient condition for a successful supersonic airliner. After examining technology, the lecture focuses on economics. Manufacturers appear to have learned the economic lessons of the Concorde. While they still try to sell the value of time and make the case that doubling speed brings remarkable transportation value by redefining the “business day” worldwide, todays focus is on a much smaller vehicle – the supersonic business jet.[5] However, the business case for a business jet requires widespread market access, largely dependent on supersonic flight overland. And such planes must not require separate, costly infrastructure.

The lecture then shifts to its main focus, possibly the greatest barrier to successful supersonic airliners – environmental acceptability. In 1995, the U.S. National Science Technology Council stated “environmental issues are likely to impose the fundamental limitation on air transportation growth in the 21st century.”[6] Although the environmental footprint associated with a smaller supersonic jet will be less, challenges remain. Suppressing sonic boom is arguably the leading challenge – and one which the industry must overcome to make overland supersonic flight (crucial for an effective business case) acceptable to the public. Supersonic airliners must also achieve community noise not exceeding those of subsonic aircraft – a formidable challenge given the advances achieved and predicted in the future.[7]

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[2] Ibid

[3] Colpin, J. and Altman, R., “Dependable Power Reinvented,” AIAA 2003–2882, AIAA-ICAS International Air and Space Symposium and Exhibit: The Next 100 Years, 14–17 July 2003, Dayton, OH.

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[6] NSTC, “Goals for a National Partnership in Aeronautics Research and Technology,” Washington, D.C., 1995. Whitehouse Office of Science and Technology Policy, `http://www.ostp.gov/html/aero/cv-ind.html`

[7] Burleson, Carl and Maurice, Lourdes, “Aviation and the Environment: Challenges and Opportuni-

Over the last several decades, the aviation community has made great strides reducing the number of persons exposed to 65 decibels Day-Night Average Sound Level (DNL), defined as "significant." Yet, community noise issues continue to delay construction of new runways, airports are imposing operational constrains, and expenditures in mitigating measures such as insulation or land buys are increasing. The lecture outlines recent steps and future requirements to assess the environmental compatibility and acceptability supersonic airliners. We must acknowledge that public expectations are not favorable to supersonic airliners. We must base any future rulemaking on supersonic flight over land on a careful assessment of the applicability of existing noise metrics to sonic boom and determination of the annoyance caused by low boom waveforms. And we must assess the impact of supersonic airliners on community noise. Moreover, we must remember that ultimate success requires endorsement by the United Nations International Civil Aviation Organization (ICAO) to encourage harmony in rulemaking by all member states.

We must also keep in mind that noise is not the only environmental challenge associated with supersonic airliners. In the long range, dealing with emissions issues could prove equally difficult. A Mach 2 aircraft has about twice the drag of todays subsonic airliners and burns more fuel. Moreover, if these aircraft cruise in the stratosphere – the impact of emissions could be greater.[8,9] And the continued uncertainty in understanding climate change and aviations contribution makes addressing the issue extremely difficult. Also, taking a holistic approach to aviation environmental impact, which takes into account interdependencies between noise and emissions and amongst emissions is a critical element of dealing with the environmental challenges presented by supersonic airliners – we cannot afford to put off dealing with emissions issues until after we have "conquered" noise.

The lecture closes by asking "Is there hope for a way forward?" The answer is "it depends." Undoubtedly aviation is a critical element of economic growth – and supersonic airliners could significantly contribute to worldwide prosperity. However, we must acknowledge the quality of life issues relative to sonic boom and aircraft community noise. And we must understand and deal with the concerns raised by emissions. A successful supersonic airliner "depends" on our ability to successfully deal with these issues. We must move forward in partnership with all stakeholders – regulatory bodies, airlines, communities, manufacturers, local governments, airports, and the public. And we must do this as a global community.

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Aeroacoustics of Supersonic Jet Issued from Corrugated Nozzle: New Approach and Prospects

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According to modern concepts, one of the main sources of acoustic radiation in supersonic jets are the packets of instability waves developing downstream. Such concept permitted explaining and predicting the principal characteristics of sound radiation by circular supersonic jets. The object of this work is a search for the ways of generalization of such an approach to jets of corrugated shape (s-lobed deformation of circular cross-section shape). Presence of additional parameter connected with the corrugation lobe number can lead to appearing a resonance association of different instability waves. These effects can be a cause of intensification and, on the contrary, of suppression of aerodynamic noise. Smallness of corrugation amplitude in comparison with the jet circular cross-section radius permits performing an analytical investigation of the problem with the use of disturbance theory methods.

The experiment presented in this paper is focused on the question about the relative ratio of different azimuthal harmonics in supersonic jet noise. First of all it is important from the point of view of Tam approach, because the theory usually gives the directivity of separate modes but in the experiment we measure the sum of all the radiated modes. The other goal is to elaborate the background for realization of new ideas of jet noise control based on coupling of radiating modes. The control of small dimension mode system (having small degrees of freedom, presented by the first radiating modes) is the problem much more obvious than control of the system inherently stochastic in nature, involving a prohibitively large dimension.

In experiment we consider supersonic cold jet with Mach number $M = 2$. For noise measuring the new technique, recently elaborated by Kopiev et al. (1999) for subsonic jets, is used. This technique gives a possibility of measuring the noise of each azimuthal mode separately. It appears that only the first numbers of azimuthal modes give a real input in the total jet noise. The relative ratio of azimuthal harmonics is measured.

The effect of jet temperature and of co-flow on the realization of resonance interaction of azimuthal harmonics is considered. A possibility of strong interaction of modes is shown not only for supersonic jet, but also for subsonic one at different parameters of mean flow in the jet and co-flow (heated jet in cold gas).

Jet Noise Reduction by Plasma Formation

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Jet noise reduction is a difficult problem in designing of advanced engine for future supersonic civil aircraft. New approaches have to be used in solution of this problem. Plasma technology is one of them. Plasma technology is used for jet noise reduction in present work [1].

Plasma-acoustics (PA) is the background of present work. Remember that PA is a new field of modern physics [2, 3, 4]. Propagation and dispersion of acoustic wave in weakly ionized non-equilibrium plasma (WINP) are studied in PA [3, 4].

Plasma formations created by different electrical discharges (glow discharge, pulse repetitive discharge, HF discharge and other types) are used in our experiments to decrease jet noise. Mach number of jet flow is about $M = 0.9$–1.1. Initial diameter of jet near nozzle is 14 mm.

It was revealed that plasma formations could decrease jet noise considerably. For example, measured jet noise decrease by plasma formation is 4–6 dB (for the acoustic harmonics with the frequencies in $F_\mathrm{s} = 4$–$100\,\mathrm{kHz}$). Note that electric power input in plasma formation is about $N_\mathrm{p} = 100$–$500\,\mathrm{W}$ in this experiment only. This value N_p is 16–80 times less than total mechanical jet power ($N_\mathrm{j} \sim 8\,\mathrm{kW}$). So, plasma formations could be used as effective plasma-acoustic absorbers.

Plasma absorbers used in our experiment are compact, light and cheapest ones. Physics of plasmaacoustic absorbers is not clear today. So, it is need to study this question in detail in future plasma-jet experiment.

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Community Noise Reduction of Supersonic Business Jet

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The integrated so-called “low noise” aircraft-propulsion system control is proposed for community noise reduction during takeoff and initial climb of supersonic business jet (SSBJ).

That control must be taking into account all airworthiness standards restrictions and provide market demand requirements to SSBJ(range, comfort of the passengers, runway length etc).

The considered low noise integrated aircraft-propulsion system control contains special low noise propulsion system control to obtain minimum of cumulative noise level and low noise aircraft control to obtain low noise initial flight path.

The efficiency comparison of conventional aircraft-engine control using for subsonic passenger jet and proposed low noise aircraft-propulsion system control was considered from the minimum community noise point of view.

The proposed approach was applied to the SSBJ project with 6–10 of passengers.

The conducted researches have shown technical feasibility of satisfaction of new stringent market demands on a community noise level of SSBJ.

Robust Optimization of Integrated Aircraft-Propulsion System Control To Meet Takeoff Noise Requirements of Supersonic Business Jet

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The integrated aircraft-propulsion system control are considered from point of view of probability of meeting stringent market takeoff noise requirements to supersonic business jet (SSBJ).

The probability of meeting requirements to SSBJ cumulative noise level was considered taking into account of accuracy of SSBJ noise prediction models.

The robust optimization of integrated aircraft-propulsion system control was used to achieve of maximum of probability of meeting SSBJ takeoff requirements.

The integrated control optimization was conducted with IOSO technology(new generation multidimensional nonlinear optimization technology).

The comparison of conventional deterministic and modern stochastic approach to noise reduction from point of view of maximum probability of meeting of market noise requirements was presented.

The proposed stochastic approach to noise reduction allows to considerable decrease of risk level in meeting future stringent noise requirements.

Supersonic-Transport Take off Silencing

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All the projects of supersonic transport have been canceled because they cannot cope with the noise regulations. The purpose of this paper is to synthetically review the acoustical properties and power performances of engines and ejectors in order to set up a simple empirical model for aiming at a reallistic design solution.

The requirements are only based on jet noise (Fig. 1) with margins taken for including other noise sources (especially fan noise). Fixed and stowable engines have to be considered.

Figure 2 shows an example of arrangements for 1.25 BPR fixed turbofans. Jet velocity is limited to 370 m/s. The first combination is oversized turbofans operated at a lower setting. Their weight is rather low but they are oversized for supersonic cruise too. Both cases including ejectors are much heavier. The last solution with stowable turbofans and without ejectors is still heavy. In that estimation, a factor of two is added to auxiliary engine weight to take into account their motion systems. This factor of two would have to be reduced to 1.5 to get an acceptable total weight of 30 metric tons.

A parametric analysis for Mach = 2 aircraft shows that :

- The fixed engines should have a bypass ratio (BPR) as high as permitted by supersonic cruise (> 1).
- Ejectors are always too havy to participate in an economical solution.
- Boost (stowable) engines with large BPR can only provide a satisfactory solution if their auxiliary systems and structures weight less than 50 % of their own weight.

The sensitivity of those statements to the model estimates is dicussed. Engine selection resulting from noise requirements has consequences on aircraft structure and fuel consumption which are also sketched.

The conclusions are that a supersonic transport is feasible at no technological risk since the required engines (no variable cycle) already exist or are close to available technology.

The discussion shows what are the points to be improved to define an economical supersonic transport.

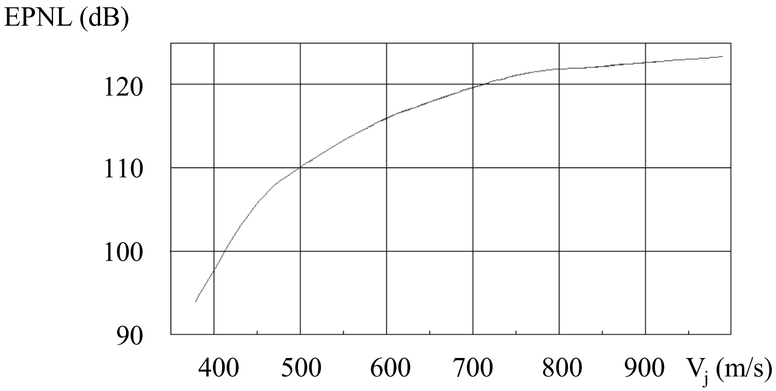

Figure 1: Sideline noise of 340 t aircraft, Mach=0.3, Total thrust = 942 kN

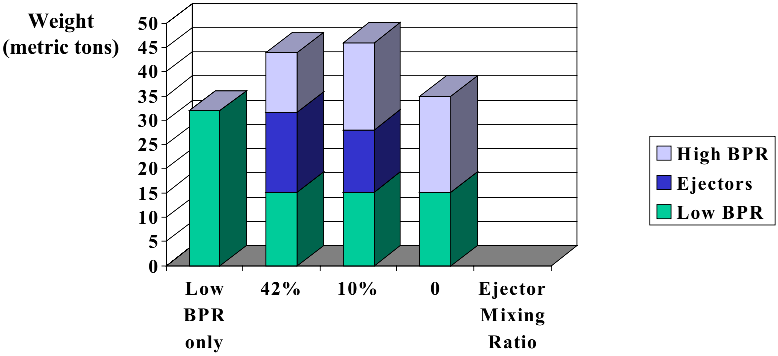

Figure 2: Engine and Ejector Weight 320 t aircraft – BPR = 1.25

New Technologies for Required Vibroacoustical Characteristics in Pressurized Cabin of Supersonic Aircraft and Execution of Norms of Noise on Land (at take-off)

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Power plant during take-off mode is basic source of extra and inter noise. Extra noise is jet noise. In guarantee of comfort conditions in pressurized cabin the decreasing of structural noise is significant problem.

Integration of power plant in airframe structure requires attending the character of dynamical influence on airframe from power plant.

The structural noise excited by vibrational influence of engines will be define not only by rotor components of engine and aggregates but and non-stationary processes in gas flow duct of power plant. And this noise will be pass to the airframe both via mounting attachments of engines and via mounting attachments of air intake device, which are too long.

The present paper shows the way of obtaining the expression for evaluation of the level of engine dynamic effect on airframe structure based on the “engine-mounting-airframe” multi-connecting model using generalized dynamic characteristics (like dynamic compliance) at coupling points (engine mounting points).

Using the set of real dynamic compliances of engines and airframes, defined by method of test effect in the frequency range 10 Hz to 1000 Hz, the limits of coupled vibrations of the “engine-mounting-airframe” system and possibility of presentation of the system in the form of independent one-dimensional vectors as well were investigated.

The solution of structural noise problem for new generation of aircraft requires a specification of calculation models of system “engines-mounting-airframe”.

Generalization of obtained researches of dynamical characteristics of engine bodies and airframe construction of trunk-route aircraft allow significantly specify calculation models of modern aviation construction in frequency range of the engines rotors rotational speed.

The databank of dynamical characteristics of engine bodies and airframes of trunk-route aircraft allow to predict an expected structural noise in a cabin and aircraft compartments on design stage of new aircraft generation and to make a substantiated choice of vibration protection system.

To decrease dynamic effect significantly a new attachment is proposed which includes built-in elastic elements having non-linear characteristics with quasi-zero stiffness zone at proof load.

By-pass ratio of engines of power installation of supersonic aircraft will be not more than 1.0. Consequently low-speed flow will be insufficiently for screening of gas-generator jet.

Recent works in several firms allow choosing a complex of effective actions. There are chevron nozzles and installation of external “vortex-creator”. Both of these devices allow to create an additional vortex and to decrease the turbulence scale in jet. In simple case at take-off regime the chevron cogs must to create an angle with nozzle axis. At the flight these cogs must be collinear to nozzle axis. Because of these circumstances it is expedient to use an intellectual materials or materials with shape memory. These materials can change a shape undergo external signal (electrical or thermal). And using these materials the adaptive construction of sound-absorbing system can be created. Some control schemes of such elements have been developed.

On Airflow Fluctuation in Supersonic Air Intake of TU-144 Prototype Aircraft

E.V.Sergeev

Use of flat outer compression air intake with boundary layer suction slit within duct minimal section of Tu-144 prototype aircraft resulted in intensive almost harmonic fluctuation of total pressure along entire duct during steady flight at $M = 1.7$ - 2.1.

Simultaneously movable ramps vibration was recorded which define intake supersonic airflow deceleration duct and are cinematically connected to each other. Within hydraulic cylinder rod which maintained said ramps in prescribed position harmonic oscillations of forces were measured with amplitudes up to 15 % of maximally possible force for the chosen cylinder. At inlet of the engine total pressure oscillation amplitude made $\sim$ 10 %. The oscillations frequency was lose to own frequency of the 1st tone system oscillation:

movable ramps+hydraulic power cylinder ($f = 15$ - 18 Hz)

The oscillations caused shaking of the aircraft. In this case engine operated steadily. The oscillations appeared in the vicinity of optimal harmonization point of the engine flow rate curve on intake orifice flow curve.

During model tests at supersonic speeds in flat supersonic air intake of “Concorde” a/c approximately in the same point of orifice curve small oscillations of total pressure were obtained within minimal section of the air intake which did not build up into large amplitude oscillations on “Concorde” a/c [1].

Experimental and design investigations were performed to reveal possible reasons for such oscillations occurred in air intake of prototype TU-144 a/c and measures for such type oscillations elimination were found.

2. In TU-144 air intake at $M = 1.2$ control of ram supersonic air flow deceleration started by way of extension of movable ramps. In this case under these ramps some space is defined by movable ramps and duct walls which receives boundary layer which was built up on the front ramp. A classic whistle configuration is formed. Within said space at high engine rating there appear substantially harmonic oscillations of large amplitude which can cause damage of under ramp space elements. Frequency of these oscillations corresponds to own frequency of under ramp space $f = 200$ Hz. It is known that oscillations of such type were recorded in air intake of “Concorde” a/c as well.

In the course of experimental investigations effective methods were revealed for suppression of pressure oscillations under ramp space of TU-144 prototype a/c air intake.

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Propulsion System Concepts and Technology Requirements for Quiet Supersonic Transports

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Any future generation commercial Supersonic Transport (SST) will be required to meet challenging targets on performance, operating economics and development cost, and environmental acceptability. In many ways the requirements of a viable SST place conflicting requirements on the design and configuration of the propulsion system. In particular, optimisation of propulsion systems for supersonic cruise performance is compromised by the requirement to meet stringent targets on takeoff noise.

Pollutant emissions during cruise are fundamentally high in supersonic applications due to high fuelburn and since, to achieve high thermal efficiency, engines are required to operate at high compressor delivery and turbine entry temperatures. Reduction of engine emissions, in particular cruise NOx, is essentially a problem for combustion technology.

The problem of achieving low takeoff noise is, however, more fundamental to the propulsion system configuration. To address the challenge of achieving good supersonic cruise performance whilst meeting takeoff noise targets, Rolls-Royce has studied numerous propulsion system concepts including Variable Cycle Conventional Turbofan (CTF), Mixed Nozzle Ejector (MNE) and Mid-Tandem Fan (MTF) configurations. The engine concepts have been studied for a variety of aircraft applications ranging from large, 300+ seat, commercial SSTs to 8 passenger supersonic business jets (SSBJs), with cruise speeds ranging from Mach 1.6 to 2.4. The optimum propulsion system configuration has been found to be dependent on cruise Mach number.

The market potential of an SST would be significantly enhanced if it can achieve clearance for supersonic operation over land. The propulsion system configuration must be further optimised to minimise the overall aircraft sonic boom signature by matching its external profile to the aerodynamic profile of the airframe.

In addition to the definition of the propulsion system concept, the design of major propulsion system components, in particular the intake and the exhaust nozzle, is also likely to be compromised by requirements of achieving acceptable operability, integrity and acoustic characteristics.

Engine configurations consistent with achieving low takeoff noise will require intake systems which deliver low flow distortion to facilitate good engine performance and aero-mechanical and acoustic compatibility. It will be a considerable challenge to produce an intake design which achieves good internal performance and low external drag at supersonic cruise whilst delivering low distortion, and without being excessively complex or heavy.

The exhaust nozzle of an SST propulsion system will be required to operate with considerable variation in pressure ratio and convergent-divergent area ratio. Performance of the propulsion system will be highly sensitive to nozzle velocity coefficient (Cv). In cruise configuration the nozzle will require a significant divergence ratio to maximise Cv. However, operating with lower pressure ratio at takeoff, an under-expanded nozzle could potentially exhibit undesirable acoustic characteristics. Rolls-Royce is currently studying numerous nozzle concepts aimed at achieving good aerodynamic performance across the range of mission operating conditions and good acoustic characteristics for takeoff.

The different propulsion system concepts which have been studied by Rolls-Royce and the effect of aircraft cruise speed on the optimum configuration will be described and summarised. Optimisation of propulsion systems for low sonic boom signature and implications of preferred engine configurations on the required operating and aeroacoustic characteristics of intake and exhaust nozzle systems will be discussed. Recommendations will be made for interesting and useful subjects for further research and study.

Tupolev-444 Supersonic Business Jet

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Reduction of Business trip travel time represents a major challenge. Development of Concord and TU-144 supersonic aircraft was answer to it. The purpose of the international group of 8 on SPT-2 in 1990–1999 was to continue a development effort to design an economically cost effective and ecologically acceptable second generation supersonic passenger transport. The results of modern studies and polls indicate high demand for supersonic business jet.

Tu-444 project is based on a 40-year experience of Tupolev design bureau in the development of supersonic aircraft : Tu-22, Tu-128, Tu-22M3, “Yastreb” (Hawk), Tu-160, Tu-144, Tu-144FL “Moscow”. The concept of Tu-444 supersonic business jet:

- Reliable, safe, highly comfortable and effective transfer of the government officials and VIP-passengers to any industrial and financial center of the world
- Maximum distance for non-stop flight is 7500 km
- Flight range at subsonic and supersonic speed is the same
- Capability to accomplish work in a place located several thousand miles away and be back home on the same day is released
- Provision of appropriate conditions for work and rest during the flight
- Trips to locations with inadequate scheduled flights service
- The runway near 1800 m is equal to subsonic VIP jets.
- The cost of aircraft and operational expenses per flight exceeds the same parameters of the similar type subsonic VIP jets not more than 20 %.
- Compliance to modern noise ecological requirements in airport area, sonic boom levels and exhausts emissions of the engines.

“Tupolev” has scientific and technical capabilities and experience in the development, certification and operation of the similar design.

Tupolev cooperation of many years with such scientific research centers:

- as TsAGI, TsIAM, LII and etc. for design and testing,

- as SNTK after N.D. Kuznetsov and “Saturn” after A.M. Liulka for joint development of power plants with such companies,
- as Kasan aviation plant after S.P.Gorbunov for implementation on programs of Tu-22M3 and Tu-160 supersonic bombers,
- as NASA, Boeing and etc for accomplishment the Tu-144FL program is guarantee for successful realization of the Tu-444 business jet program.

Suppressing the Downward Shockwave in Supersonic Flight

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An important nuisance of supersonic flight over populated areas is the shockwave sweeping the earths surface. In this paper possibilities to suppress the formation of the downward shockwave of an aircraft flying at supersonic speed are discussed. The idea is: not to exploit the lifting capabilities of the underside of the aircraft. The aircraft than is suspended on the low pressure at its upper surface only. The lift of the lower surface is annihilated, its drag remains. The downward shockwave, being formed at the leading edge, is reflected in and absorbed by a shock-swallowing device below and behind the lifting wing. The external cross-section of the device is constant over its full length, so it does not create any external disturbance (we do not consider boundary layers). In this device the compressed flow is treated in such a way that at the exhaust it leaves the device as a parallel flow at ambient static pressure. The available processes are: 1) cooling the air behind the reflected shock, 2) compressing the air behind the reflected shock and 3) expanding it to parallel flow at ambient pressure. A large variety of combinations of these processes could be tailored to yield the required static pressure condition at the exhaust. The device will generate drag or thrust, the magnitude of which depends on the exhaust velocity. In the discussion below we consider that process where the thrust balances the drag of the upper- and the lower surface of the airfoil. This would be the condition for steady supersonic flight without downward shockwave.

As liquid hydrogen is a potential candidate to become an aircraft fuel the idea of using the required cooling for the evaporation of the liquid hydrogen is obvious. The idea will not work as it yields only a small fraction of the required cooling power.

The conclusion must be that thermodynamic suppression of the downward shock in supersonic flight is a feasible option but unrealistic from the economic point of view.

Description of the shock-swallowing device in a two-dimensional configuration

A downward shockwave is generated at the leading edge of the lifting flat-plate airfoil.c It is prevented from reaching the earth by a shielding plate (shock deflector) parallel to the main flow. This shielding plate and its downstream extension form the lower wall of the swallowing device This device has externally two parallel walls not hindering the external flow. The upper wall extends from the trailing edge downstream.

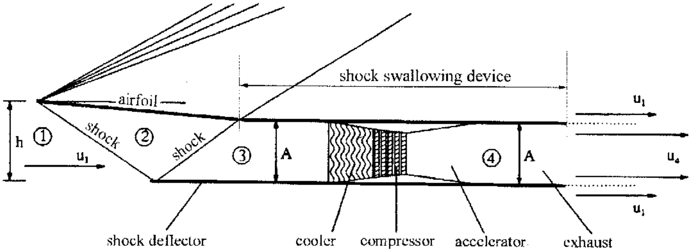

Figure 1: A lifting airfoil without a downward shockwave

The distance A between the walls is chosen such that the reflected shock hits the trailing edge of the airfoil.The reflected shock bounds a region of high pressure flow, labeled 3, entering the swallowing device. The problem of swallowing the shock then is reduced to matching this high-pressure flow to the low-pressure external flow. Letting the flow expand from p_3, without any further treatment, to ambient pressure $p_4 = p_1$ at the end of the channel A would require an increase of the cross-section, thereby generating new shocks in the atmosphere. A matching process must be performed in such a way that at the exit the flow leaves as a parallel flow at ambient pressure. There is a variety of ways to perform the matching. The elementary processes involve cooling , compressing and expanding (accelerating) the air. The effects of the elementary processes can be described as follows.

Cooling increases the density, thereby creating the possibility for an expansion to atmospheric pressure, with a higher than atmospheric density, allowing the passage through the original cross-sectional area A. For simplicity we consider the cooling to be performed at constant pressure and velocity. In the cooling process energy is taken out, resulting in extra drag of the device.

Compressing the air yields an increase in density and pressure that generates the possibility to accelerate the flow, in the expansion to ambient pressure, to so high a velocity and so low a density that the massflow can pass through the original cross-sectional area A. For simplicity we consider the compression to be performed adiabatically at constant velocity. The expansions take place at constant total enthalpy $c_\mathrm{p}T_0$. The work performed on the flow in the compression is associated with the generation of thrust.

As an example a process involving cooling and compression, yielding zero drag D, is sketched in fig. 2. It is a representation in the p–V–T-diagram of a calorically ideal gas (V is the specific volume $1/\rho$). The index ",0" used in this figure refers to the specific process yielding $D = 0$. Other indices: ",W" refers to only compression; ",q" refers to only cooling. The thick line is at the level of total temperature T_0. The thinner line is the static temperature, in the surface $T = pV/R$. The external flow, characterized by p_1, V_1, T_1, T_{01}, yields, after passing through the primary shock and the reflected shock, a parallel flow with pressure p_3 and static temperature T_3. The total temperature has the value of the ambient atmosphere $T_{01} = T_1 + u_{12}/2c_\mathrm{p} = T_3 + u_{32}/2c_\mathrm{p}$. Cooling at constant pressure and velocity reduces T_{01} to $T_{03,0}$. The static temperature is reduced by an equal amount to $T_{3,0}$. The adiabatic compression at constant velocity u_3 is associated with a rise in static- and in total temperature to $T_{b,0}$ and $T_{0b,0} = T_{b,0} + u_{32}/2c_\mathrm{p}$. ($T_b$ refers to the static temperature at the begin of the expansion). In the adiabatic expansion from $p_{b,0}$ to p_4 (=p_1) the total temperature conserves its value $T_{0b,0}$, the velocity increases from u_3 to $u_{4,0}$ at the cost of static temperature which lowers to $T_{4,0}$.

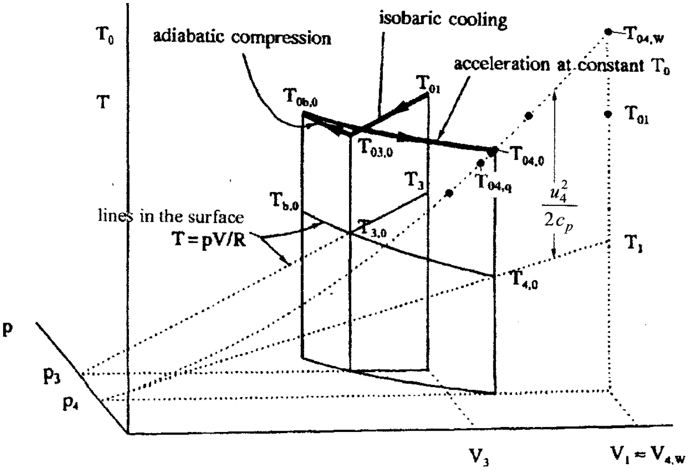

Figure 2: The path in the p–T–V-diagram of the process leading to zero drag

Discussion and conclusion

Considering supersonic flight at a Mach number Ma=2 at an altitude of 20 km, the power required to overcome the drag, in our two-dimensional computation, is 51.6 Watt per Newton lift. For supersonic flight without a downward shockwave, extra power is involved in the cooling, -813.7 Watt/Newton, and in the compression, 171 Watt/Newton. The cooling power is negative, it yields heat, but this heat can not be used as such. A positive power of at least 25 % of the involved heat must be invested, i.e. 204 Watt/Newton. This would lead to a required power of 375 Watt/Newton lift for flying supersonic with the downward shock absorbed in the shock-swallower. This is about 7.5 times the power required to fly with the downward shock.

For the moment the conclusion must be that complete suppression or swallowing of the downward shockwave is not a realistic option for application in supersonic flight. A remaining positive thought about the presented method is that eventually it can be partially applied to decrease the intensity of the downward shockwave.

On the Effects of Viscosity on Sound Generation and Propagation

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Consider the effect of viscosity on the sound generated by moving surfaces, such as wings and rotors. It may be noted that the effects of viscosity on sound is two-fold. The first effect is on sound generation, as the viscosity affects the aerodynamic flow (i.e., the presence of boundary layer wake and their effect on the outer flow, via the Lighthill displacement-thickness or transpiration-velocity correction).The second effect is on sound propagation through the medium, as it causes attenuation and dispersion; this second effect is important only for distant points (in particular for sonic boom analysis).

The formulations typically used to study sound propagation (i.e., Ffowcs Williams and Hawkings equation and Kirchhoff method) the effects of viscosity are included only through the Lighthill tensor (i.e., quadrupole term). This is a computationally inefficient way to capture the effects of viscosity on sound propagation. In Ref. 1, the authors proposed a formulation based on a decomposition of the velocity field into a potential portion and a rotational portion,

$$v = \operatorname{grad}\varphi + w$$

with the rotational portion w that vanishes in the irrotational region of the flow. In Ref. 2 (based a keynote lecture by the first author at the 2002 AIAA/CEAS Aeroacoustics Conference), the formulation is extended and presents an equation for φ which includes certain linear terms due to the viscosity (specifically, one adds a term proportional to the time derivative of $\nu\Delta\varphi$, where Δ denotes the Laplacian). An approximate closed-form fundamental solution for such an equation is also included in Ref. 2. If the viscosity tends to zero, this solution reduces to the classical fundamental solution for the wave equation; if the viscosity differs from zero the fundamental solution includes attenuation and dispersion. This provides one with the possibility of studying the effects of the viscosity on the sound propagation for distant points (indeed, attenuation and dispersion).

The paper will include the complete formulation and numerical applications to sonic boom. In particular it will include a comparison of the following three numerical solutions:

1. an inviscid-flow solution
2. a viscous-flow solution that includes only the first effect (effect boundary layer and wake on the outer flow, as used for non-distant points), without the second one (attenuation and dispersion, for distant points)
3. a solution for viscous flows that includes both effects

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SOnic Boom European Research program (SOBER): numerical and laboratory-scale experimental simulation

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The communication presents an overview of the main results of the European research programme on sonic boom (“SOBER”, 2001–2003) coordinated by Airbus France SAS (Toulouse) and Universit Pierre et Marie Curie (Paris).

Physical modeling and experimental validation

One innovative aspect of the programme is the validation of theoretical and numerical modeling by laboratory-scale experimental simulation. Indeed, real size test flights offer many valuable informations, but are difficult to exploit for a *quantitative* validation of theoretical models due to the huge amount of information required from a flight test (aircraft shape, trajectory, wind and temperature vertical distribution, atmospheric turbulence, ground impedance…). Especially, atmospheric turbulence is known as a source of great variability at the ground level. Therefore this program has been orientated towards the simulation at the laboratory-scale, with the best possible similitude, of some key aspects of sonic boom propagation, in order to validate the physical models by controlled experiments.

Sonic boom propagation from the aircraft down to the ground is classically modelled by geometrical acoustics, modified to take into account nonlinear effects know to be essential to explain the pressure wave distorsion until its ultimate “N” wave shape. However, the geometrical approximation is unsufficient in several cases: to estimate the rise time resulting from mocular relaxation or turbulence, in case of focusing (acceleration or turn), at the carpet edge and inside shadow zone, for secondary boom. All these cases are known to be of special importance. Finite rise time is an important parameter in sonic boom annoyance. Focused boom (superboom), with an amplification factor of about 3 compared to ground track cruise boom, may induce some unacceptable consequences for overflown people (such as window breaking). Sonic boom in the shadow zone may prevent oversea flight corridors too close from the coasts. Secondary boom is known from Concorde exploitation to provoke complaints that implied trajectory changes. Finally, propagation inside the turbulent atmospheric boundary layer near the ground induces a large variability that modifies randomly the boom annoyance. In the mean it has a favorable effect (amplitude decrease and rise time increase), but in a significant number of cases, focusing happens, with an enhancement of the sound level.

Influence of sound absorption (nitrogen and oxygen molecular relaxation) is modeled by an asymptotic local model chosen to be computation time saving. The influence of molecular relaxation will be shown to be significant under some meteorological situations, where a downward refracting atmosphere induces a large widening of the primary carpet.

Focusing induced by maneuvers (attention has been devoted mostly to acceleration) was a key challenge of the SOBER project. Based on the theoretical model developed in the 60s (Tricomi nonlinear equation) to model locally the amplified field, a specific numerical algorithm has been updated. Several validation tests have been performed to demonstrate the code reliability. An innovative laboratory-scale simulation of sonic boom focusing has been realized in a water tank, at the scale 1:100000, relying on the perfect analogy between nonlinear sound propagation in air or in water. Similitude includes all identified physical parameters : nonlinearities, diffraction and absorption. The supersonic aircraft is replaced by an array of piezoelectric transducers controlled electronically to reach the proper curvature of the caustic (the focusing surface). Comparisons with the outputs of the numerical code show an almost perfect agreement. Examples of numerical evaluation of sonic boom focusing will be presented and potential superboom mitigation will be briefly discussed.

Sonic boom diffraction near the carpet edge and inside the shadow zone has also been modeled. It shows how the two sharp shocks of the “N” wave inside the geometrical carpet progressively spread out into a rumbling signal inside the shadow zone. The transition at the geometrical cut-off outlines the influence of ground absorption there, resulting into large rise times. The modeling of sea surface roughness has been carried out in order to examine its influence on overseas sonic boom.

Shock wave propagation in a turbulent medium has been reproduced experimentally, using a spark source generating an acoustical shock wave in an anechoic room. Turbulence is produced either by a heated grid or an air jet. A series of measurements outlines the variability of the signal after propagation through the random medium. Theory confirms that beyond some characteristic distance, focusing effects are more likely to occur, with changes in the shape of the received boom and enhancement of the maximum overpressure. Comparisons between the measured mean rise time and a model based on an approximate dispersion relation show good agreement, which paves the way towards an integration of turbulence effects into numerical simulation of sonic boom. The same experimental set-up has been used to simulate shock wave diffraction at the carpet edge and penetration into the shadow zone, relying on the well-known analogy between diffraction by an upward refracting atmosphere and by a smooth, curved obstacle.

To investigate secondary boom, in addition to the geometrical approximation, two main directions have been explored: sound absorption in the upper atmosphere to estimate the secondary boom sound level, and multiple ray arrivals due to 3D heterogeneities of the upper atmosphere to estimate the duration of received long signals with several bursts.

Numerical simulation of sonic boom

The physical modeling has resulted into the software BANGV simulating primary boom for a maneuvering aircraft, including off design points such as focusing and off-track boom (carpet cut-off and shadow zone). Influences of wind and temperature stratification, air humidity and ground impedance are taken into account. Input data on the aircraft shape can be introduced under the form of either CFD simulations or Whitham functions. Examples of the convergence of simulations (for cruise or accelerating flight) using CFD data at different distances below the Eurosup mock-up will be shown.

The software BANGV has been used to estimate the variability of the primary boom for the Airbus AS709 mock-up of a supersonic transport. The pressure distribution across the sonic boom carpet in cruise conditions along the route Paris to New York and return at Mach 2 over Western Europe (Saint George channel) has been calculated, using the ERA meteorological database (one meteo profile every 6 hours over 10 years), resulting into more than 29000 carpet simulations. Results of the statistical analysis will illustrate the meteorological variability of sonic boom in a realistic configuration.

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