JOURNAL OF AIRCRAFT
Vol. 46, No. 2, March–April 2009

Engineering Notes

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Can Supersonic Transport Be Ultraquiet?

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DOI: 10.2514/1.39185

I. Introduction

THE subject of this Note is the big supersonic transport (SST), not the business jet. The problems are really different. Up until now there has been no official regulation for any supersonic civil aircraft. However, the specialists agree that takeoff and approach noise will have the same limits for supersonic and subsonic aircraft. For the sonic boom, there is some anticipation that a business jet (that means about 50 tons), with a moderate velocity (Mach 1.3) and a well-designed shape, would generate a sonic boom which could be acceptable. No dubious assumption has to be considered for the big aircraft: Whatever its shape, its sonic boom will be so loud that it will not be authorized to fly over populated areas. As a consequence, it will have to be competitive in subsonic cruise with usual subsonic aircraft. Thus, the question "can supersonic transport be ultraquiet?" only concerns takeoff and approach noise.

A 250 passenger aircraft with a 10,000 km (5400 n miles) range is within the scope of this paper. The relevant properties for the discussion are its maximum takeoff weight $M_t = 320$ t (700,000 lbn), its cruise Mach number = 2, and its takeoff speed $V_0 = 100$ m/s. Up until now, none of the SST projects drawn after the Concorde can comply with the future noise limits.

Before discussing an "ultraquiet" airplane in the second part, a "quiet" SST is presented in the first part. The word quiet is explained, the requirements to design such an aircraft are reviewed, a draft design is given, and the drawbacks and limits of that solution are determined. This first step is necessary because it explains the requirements for a new architecture which is, however, limited in terms of noise reduction capabilities. Thus, the further step in noise reduction, so-called ultraquiet, needs additional configuration improvements. The extension to a Mach 3 airplane is discussed in the third section. Then a conclusion is given with some perspectives.

II. Quiet Supersonic Transport

A. What Does Quiet Mean?

The takeoff and approach noise properties can be defined according to the International Civil Aviation Organization (ICAO) rules of certification. The three measurement points are shown in Fig. 1: climb, sideline, and approach. For an SST, it is usually anticipated that the most difficult point to be controlled is the sideline, and the following discussion is limited to that point accordingly. ICAO stage 3 limit for sideline is 102.2 EPN dB (effective perceived noise) for a 320 t aircraft. Stage 4 requires a global reduction of 10 dB for the total of the three points but does not define the reduction for each point. A 3.2 dB reduction for sideline, that is, a 99 EPN dB limit, is the present definition of quiet. It is assumed that other noise sources could be significant to limit jet noise at 96 EPN dB. A 3 dB precaution margin is chosen to aim at a 93 EPN dB jet noise limit.

B. Requirements for Designing a Quiet Supersonic Transport

The required flow rate and engine cross sections have been determined in [1]. Minor adjustments to the data of that reference are included thereafter. According to Fig. 2, the 93 EPN dB jet noise for a takeoff thrust $F_g = 942$ kN is obtained with a jet exhaust velocity $V_j = 370$ m/s. The resulting airflow rate is $Q_g = 3\,489$ kg/s and the total engine cross section is 18.2 m^2 according to a practical engine capability of 192 kg/s $\cdot$ m^{-2} (hub included).

End of climb needs a 320 kN thrust with a specific thrust of 320 m/s that is, a 1000 kg/s airflow rate becoming 1510 kg/s for static ground conditions. The corresponding engine cross section requirement is 7.86 m^2. Thus, the cross section requirement at takeoff is about 2.3 times that for end of climb. This factor of 2.3 for engine cross section cannot be obtained by 1) any variable-cycle engine for which the design is practically limited to a factor lower than 1.5, or 2) any ejector for which the mixing ratio is practically limited to 100%, that is, a factor of 2 in terms of cross sections.

As a consequence, the propulsion system for that supersonic transport must include 1) low-BPR (bypass ratio) turbofans for supersonic climb and cruise, which are operated at a lower power setting or/and with some ejector for noise reduction at takeoff, and 2) high-BPR turbofans for boost at takeoff and subsonic cruise, which are to be stowed inside the fuselage for supersonic operation.

Low- and high-BPR engines share takeoff thrust according to their cross section (same average exhaust velocity). In the event of any engine failure at takeoff, low-BPR thrust can be increased well above that of the noise limitation in an emergency.

The weight optimization of that propulsion system has also been discussed in [1]. The unique acceptable solution avoids any ejector, and the structures to move and store the high-BPR turbofans must be light enough (half the engine weight). Under those conditions, the total weight of the propulsion system (30 tons) is lower than one-tenth of the total takeoff weight (it was more than that on the Concorde).

Thus, the so tightly determined propulsion system is finally constituted of the following:

1) Two fixed low-BPR (1.25) turbofans without ejector are optimized for supersonic cruise and used at a lower power setting (370 m/s jet velocity) for takeoff. Their weight is 7 tons each and their diameter is 2.3 m, because the total engine cross section of 7.86 m^2 has been corrected to 8.27 m^2 to take into account an inlet pressure recovery ratio assumed to be 0.95.

2) Two retractable high-BPR turbofans provide takeoff boost and economic subsonic cruise with a total 10.34 m^2 cross section. They are similar to subsonic aircraft engines, 5.3 tons in weight each and 2.6 m in diameter.

Received 18 June 2008; revision received 6 October 2008; accepted for publication 16 November 2008.

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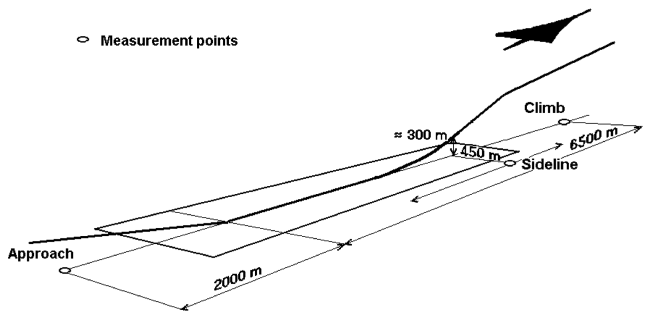

Fig. 1 Definition of the measurement points for noise certification.

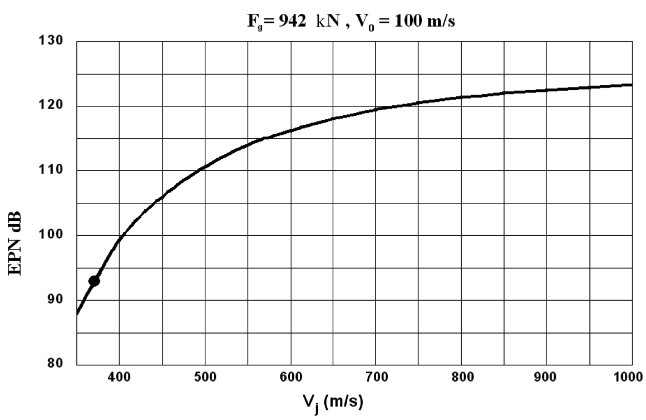

Fig. 2 Effect of jet velocity on sideline noise of a 320 t aircraft.

3) A structure is included to ensure motion and storage of the retractable engines, weighing less than 5.3 tons. To stay within this limit, the rails for engine motion (short horizontal translation) must be existing wing beams. Additionally, the engine storage volume must not increase the structure weight, neither the fuselage cross section nor the fuselage length, which is a challenge.

Fortunately, the choice of the propulsion system resulting from the noise requirements provides the aircraft with an economic solution for subsonic cruise, as needed.

C. Description of a Quiet Supersonic Transport

It could be anticipated that a 250 passenger aircraft would have a fuselage 4.2 m in diameter (6 abreast). Such a diameter cannot accommodate two engines 2.6 m in diameter side by side. Those retractable engines have to be at the same elevation as the fuselage to be moved horizontally, and they must be under the wing for strong reasons of operation and maintenance. Thus, the fuselage and the retractable engines must be under the wing. Then, for permitting engine accommodation, the fuselage must be turned into a twin-cylinder cross section. Keeping constant the initial cross section of the unique 4.2 m cylinder results in two joined cylinders, 3 m in diameter each. Incidentally, the basic twin-cylinder cross section can be smoothed at the top and bottom concavities to approach the area rule easily. A schematic front view of that aircraft is shown in Fig. 3 and an underside view in Fig. 4.

The twin aisle, 8 abreast, cabin arrangement is shown in Fig. 5. There is a nice space for passenger comfort and hand luggage but just a limited bottom volume for fuel. The volume for the baggage hold is to be found elsewhere.

The approximate cabin length for 250 passengers with a 1.5 m row separation is 63 m with 6 abreast (circular fuselage) and 48 m with 8 abreast (twin-cylinder fuselage). Thus, with the same 63 m length, 15 m are available in the flattened fuselage for engine hold (6 m) and baggage hold (9m).

Artist pictures given by the Tupolev Design Bureau are also shown in Fig. 6. A number of four low-BPR turbofans was chosen instead of two in Figs. 3 and 4. The reason is that big engines (2.3 m in

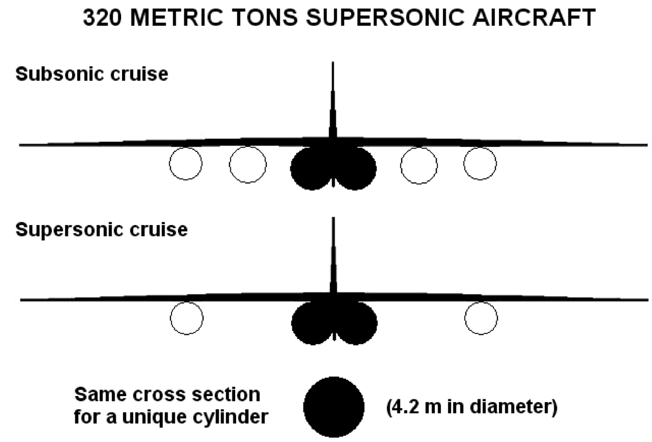

Fig. 3 Schematic front view of a quiet SST.

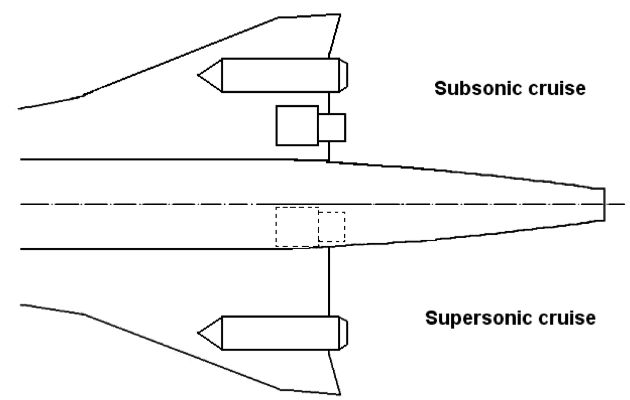

Fig. 4 Schematic underside view of a quiet SST.

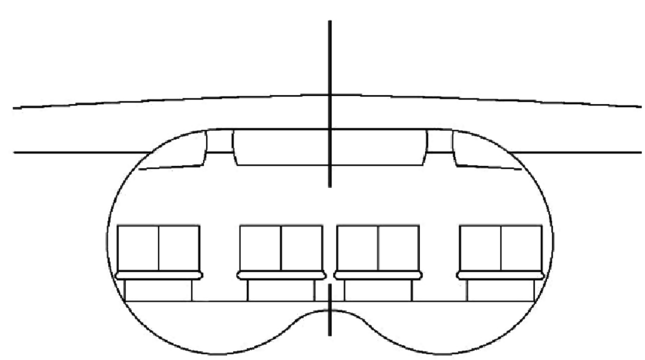

Fig. 5 Cabin section of a quiet SST.

diameter) do not exist yet. The Concorde Olympus was only 1.15 m in diameter. On the other hand, the Russians still use the everyday Tu 160 (so-called Blackjack by NATO), a bomber of 300 t propelled at Mach 2.3 by four engines. The purpose of the picture is to remind the reader that a supersonic transport, as described, can use engines almost from the shelf without any risky development.

D. Drawbacks and Limits of the Suggested Solution

Moving two high-BPR turbofans under the wing is an obvious difficulty. The large weight (2×5 t) is an issue for structural design. The storage bays (6 m in length, 2.6 m in diameter) need large doors and airflow control. A major drawback could even be the number of important connecting or translating parts for fuel, air, electricity, and control wiring.

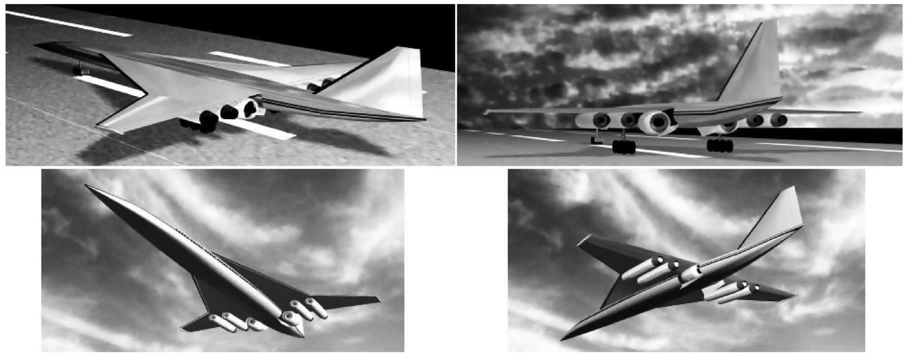

Fig. 6 Artist view of a quiet SST.

In addition, the proposed solution includes some basic limitations. As the engine bays are completely filled up by the big turbofans, the diameter of those engines cannot be increased any more for generating less noise.

III. From Quiet to Ultraquiet Supersonic Transport

A. What Does Ultraquiet Mean?

In Sec. II, a precaution margin of 3 dB was chosen to define the quiet aircraft. This margin is now extended to 20 dB to define an ultraquiet aircraft. Thus, the new jet noise limit is 76 EPN dB. This figure is out of the scope of Fig. 2 indeed, but in a region where the curve is very steep (V_j^8 law). To make sense, other noise sources will have to be reduced accordingly.

B. Requirements for Designing an Ultraquiet Supersonic Transport

As a consequence, V_j is limited to 310 m/s. The difference with respect to the 370 m/s of the quiet aircraft looks small but, in terms of required cross section, the 18.2 m^2 are turned into 23.4 m^2. The total thrust is the same (942 kN) but 5.2 more square meters are needed.

It is suggested to use two more retractable fans (coreless), 1.8 m in diameter, powered by shafts from the two high-BPR turbofans (retractable fans powered by a turbine were also suggested in [2]).

C. Description of an Ultraquiet Supersonic Transport

A schematic front view of such an ultraquiet SST is shown in Fig. 7. Obviously, the difficulty is still increased with the extraction of the new additional coreless fans. But the limitation in engine cross section is overcome. It is overcome so well that the coreless fans can be made bigger to accept some flow rate loss in the high-BPR turbofans. This is an unhopedfor opportunity to make those high-BPR turbofans fixed and buried inside the fuselage. Instead, to move them, there is just to deploy their air intakes and nozzles. The major drawbacks are thus withdrawn. This more realistic solution is shown in Figs. 8 and 9. The airflow loss in the fixed high-BPR turbofans is supposed to be up to 20% and its recovery is obtained in the coreless fans, the diameter of which is increased to 2.2 m.

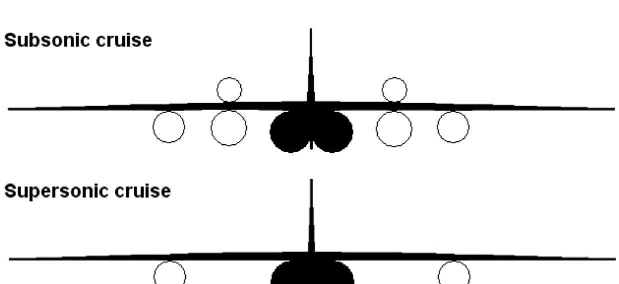

Fig. 7 Schematic front view of an ultraquiet SST.

IV. Why Not Mach 3?

The Mach number was limited to two on the Concorde owing to the temperature capabilities of the aluminum alloys. The materials available today can sustain a higher temperature. And this higher temperature, about 600 K at Mach 3 instead of 390 K at Mach 2, only occurs on points and leading edges. Then, what about propulsion and noise? Mach 3 is the good domain of the turbojet (BPR $= 0$). The same exercise as described for Mach 2 yields a similar positive conclusion. Mach 3 cruise altitude is chosen to be 22,500 m (73,900 ft) to keep the same dynamic head as for Mach 2. The L/D ratio is assumed to be only nine instead of 10.5 at Mach 2. A required 359 kN end of climb thrust and a chosen 394 m/s specific thrust result in a 911 kg/s flow rate at end of climb, corrected for static ground conditions in 826 kg/s. The total area of the low-BPR propulsion means is then 4.30 m^2, corrected in 5.06 m^2 to take into account an assumed 0.85 pressure recovery ratio. Hence, the turbojets are only 1.8 m in diameter. The buried high-BPR turbofans remain sized at 2.6 m in diameter; the retractable coreless fans become 2.6 m in diameter also, what can actually be accommodated in the 3 m twin fuselages.

There is a final favorable comment for Mach 3 which was not discussed earlier. Up until now, the discussion was limited to the

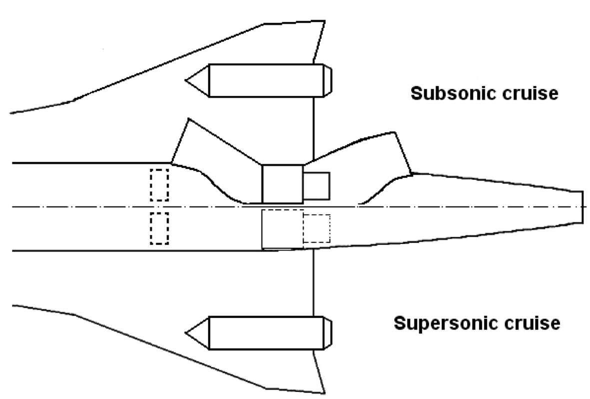

Fig. 8 Schematic underside view of a more realistic ultraquiet SST.

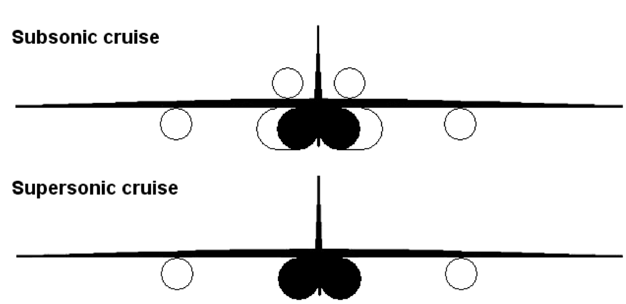

Fig. 9 Schematic front view of a more realistic ultraquiet SST.

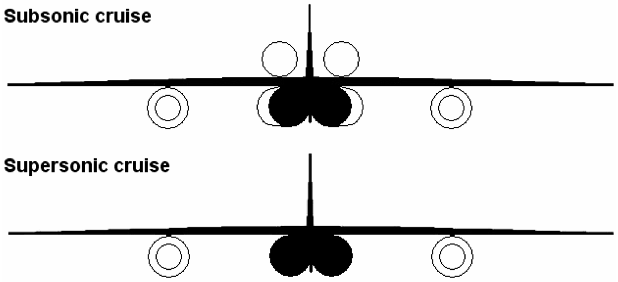

Fig. 10 Schematic front view of a Mach 3 ultraquiet SST.

engine cross sections. For Mach 2, the freestream cross section for the 1000 kg/s flow rate is 10.48 m^2. The nacelle thickness (about 20% area loss) leaves 8.38 m^2 available for the engines, the area of which must be 8.27 m^2 as determined in Sec. II.B. Then, for the Mach 2 cruiser, the requirement coincides with the availability with a small 1% margin. For Mach 3, the freestream cross section for the 911 kg/s flow rate is 14.6 m^2, which leaves 11.7 m^2 available for the engines after nacelle thickness correction. However, the total required engine area is only 5.1 m^2. Thus, in the Mach 3 case, a large margin (6.6 m^2 in the current example) can be used at takeoff to divert some substantial airflow rate from the low-BPR air intake to the high-BPR turbofans, in addition to their own deploying air intakes. As a consequence, the size of the deploying air intakes can be reduced, as shown in Fig. 10, and the air inflow homogeneity can be improved. Incidentally, a cruise Mach number lower than two is a bad idea because the engine diameter is larger than the space available in the nacelle with the same freestream airflow rate, which results in a drag penalty.

V. Conclusions

Yes, either a Mach 2 or Mach 3 supersonic transport can be ultraquiet for takeoff if jet noise is the main noise source. No dubious assumption was used to obtain this conclusion. The fuselage must be under the wing and its cross section made of twin cylinders. The buried high-BPR turbofans are those of subsonic aircraft but a shaft must be added to power the deploying fans. The low-BPR turbofans can really be optimized for supersonic cruise without any addition for takeoff boost. They do not even need to provide reverse, which can be left to the high-BPR engines. Mach 3 cruise is preferred. Such an SST can be developed without important risks because all of the engines are almost available from the shelf. The reduction of the other noise sources cannot be discussed in detail in this short Note but the following should be noted:

1) A large fan cross section means a low tip speed, and fan noise is basically proportional to that velocity to the power of about 6.

2) A fuselage under the wing means a very short landing gear, which is also a significant airframe noise reduction.

Acknowledgments

A large fraction of this paper was presented as an invited talk at the NASA/Confederation of European Aerospace Societies/AIAA Workshop on Revolutionary Aircraft for Quiet Communities, held in Hampton, Virginia, on 24-26 July 2007. The same presentation was also invited at the West East High Speed Flow Fields Conference by the Russian Academy of Sciences in Moscow in December 2007 and at the Association Aeronautique et Astronautique de France Congrès d'Aérodynamique Appliquée in Poitiers, France in March 2008.

References

[1] Fournier, G. F., "Supersonic-Transport Takeoff Silencing," *International Journal of Aeroacoustics*, Vol. 3, No. 3, 2004, pp. 249–258. doi:10.1260/1475472042887498

[2] Huete, J., and Singh, R., "A Novel Concept for the Next Generation Civil Supersonic Transport Propulsion System: The Retractable Fan," *Journal of Aircraft Engineering and Aerospace Technology*, Vol. 69, No. 6, 1997, pp. 512–517.