Variable Structure," *Automatic and Remote Control*, Vol. 25, No. 1, p. 128, Jan. 1964, p. 128.
[385] Truxal, J., "Adaptive Control—A Survey," *Proceedings of the 2nd IFAC Congress*, Vol. 2, 1963, pp. 286–292.
[386] Whitaker, H. R., "Design Capabilities of Model-Reference Adaptive Systems," *Proceedings of the National Electronics Conference*, Vol. 18, 1962, p. 241.
[387] Hiza, J. G. and Li, C. C., "Analytical Synthesis of a Class of Model-Reference Time-Varying Control Systems," *IEEE Transactions on Applications and Industry*, Vol. 82, Nov. 1963, pp. 356–362.
[388] Sworder, D., *Optimal Adaptive Control Systems*, Academic Press, New York, 1966.
[389] Pringle, R., "On the Stability of a Body with Connected Moving Parts," *AIAA Journal*, Vol. 4, No. 8, Aug. 1966, pp. 1395–1404.
[390] Sandler, S. H., "Dynamic Equations for Connected Rigid Bodies," *Journal of Spacecraft and Rockets*, Vol. 4, No. 5, May 1967, pp. 684–685.
[391] Cloutier, G. J., "Dynamics of Deployment of Extendible Booms from Spinning Space Vehicles," *Journal of Spacecraft and Rockets*, Vol. 5, No. 5, May 1968, pp. 547–552.
[392] Gevarter, W. B., "Attitude Control of a Flexible Spinning Toroidal Manned Space Station," *Journal of Spacecraft and Rockets*, Vol. 4, No. 7, July 1967, pp. 878–884.
[393] Hutchinson, I. N. et al., "Space Station Stabilization and Control Study," Final Engineering Rept. AB-1210-0020, Dec. 1963, Sperry Gyroscope Co., Great Neck, N. Y.; also NASA CR-66019.
[394] Fuller, A. T., "Bibliography of Pontryagin's Maximum Principle," *Journal of Electronics and Control*, Vol. 15, No. 5, Nov. 1963, p. 513.
[395] Miller, R. E., "Use of the Field Method for Numerical Integration of Two-Point Boundary-Value Problems," *AIAA Journal*, Vol. 5, No. 4, April 1967, pp. 811–813.
[396] Plart, J. B., "An Iterative Procedure for the Computation of Fixed-Time Fuel-Optimal Controls," *IEEE Transactions on Automatic Control*, Vol. AC-11, No. 4, Oct. 1966, pp. 652–660.

MARCH-APRIL 1969 J. AIRCRAFT VOL. 6, NO. 2

Concept and Characteristics of the Concorde Exhaust Noise Suppressor

G. RICHTER* AND R. HOCH
Société Nationale d'Etude et de Construction de Moteurs d'Aviation, Paris, France

Performance and design considerations for the Concorde exhaust noise suppressor are discussed. The suppressor makes a radial injection of mixing air in the primary jet stream using ten lobes in the form of triangular prisms hinged to the divergent section of the ejector nozzle. When suppression is no longer necessary, a feedback linkage allows the lobes to retract so as to eliminate all thrust losses in the cruise position. Results of model tests used to develop detailed geometry of the design are also presented. Performance of a retractable suppressor is compared with one of fixed geometry taking into consideration the effects of weight, fuel consumption, and the initial climb trajectory of the aircraft. It is concluded that the Concorde suppressor provides substantial noise attenuation at low weight and without cruise thrust loss.

Introduction

ENGINE noise during takeoff and landing has been a problem ever since turbojet aircraft were first introduced to the airlines. Exhaust noise, a major factor at this time, led to development of turbojet-noise suppressors and also contributed later the introduction of dual flow (turbofan) engines having reduced exhaust noise. Noise reduction efforts were then oriented towards attenuation of acoustical emission from the fan and compressor. The situation has changed since SST studies began and exhaust noise of the required high-thrust, low frontal area engines is again a major factor.

Engines of this type inherently have high exhaust speeds which are sources of acoustic emissions of high intensity (the acoustic energy of a jet being proportional to the eighth power of its relative velocity). At takeoff, exhaust noise of this type engine is much greater than compressor noise; it is only in approach flight with reduced thrust that acoustic emission from vanes and blades of the engine (compressor and turbine) plays an important part in the noise level of an SST. Although the high jet velocity generates noise, it offers in return a high thrust which allows the aircraft to climb rapidly, thereby reducing the zone around the airport exposed to intense noise. Another favorable characteristic is that the divergent portion of the nozzle (necessary for high thrust at supersonic speeds) slightly reduces acoustic emission from the engine primary nozzle at takeoff conditions. Furthermore, the horizontal diffusion of noise from multi-engine aircraft is reduced by engine grouping which causes noise from inboard jets to be masked by outboard jets. In the Concorde, this mask effect may be reinforced by interaction between the jets (closely spaced) of each pair of engines. In spite of these attenuating influences, the noise level of every large supersonic aircraft remains high, and the incorporation of an exhaust noise suppressor is still necessary to cut down, to reasonable levels, the discomfort for people living near the airports.

Performance Considerations

Unfortunately, the presence of a noise suppressor in the exhaust produces thrust losses which, in general, become greater with increased acoustical effectiveness. The thrust loss is not great when the suppressor is designed for an engine with only a convergent primary nozzle. But in the case of an ejector or convergent-divergent nozzle, a considerable thrust loss of 10 to 15% can occur in the sub- and transonic stages of flight because the suppression device can cause the jet to attach to the

Presented as Paper 67-391 at the AIAA Commercial Aircraft Design and Operation Meeting, Los Angeles, Calif., June 12–14, 1967; submitted July 10, 1967; revision received July 8, 1968.
* Chief of Department, Aerodynamics and Acoustics.

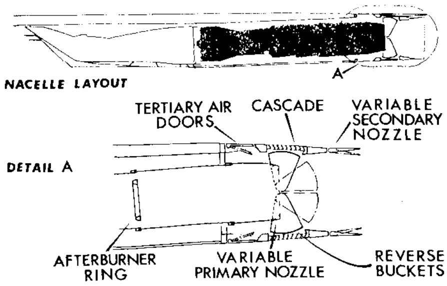


Fig. 1 Olympus 593 exhaust system.

divergent wall and thereby overexpand the flow. Any thrust loss in this stage of flight prolongs the stage so that total fuel consumption increases significantly. Still more important is the cruise thrust loss. For example, a 1% cruise thrust loss for a plane of the Concorde type requires extra fuel equal to the weight of five to ten passengers. For constant payload, the takeoff gross weight must increase by about twice the additional fuel weight. A solution that allows almost complete avoidance of the cruise thrust loss, is a retractable noise suppressor such as the one developed by SNECMA for the Concorde.

Design Considerations

The Concorde nacelle and exhaust system components are illustrated in Fig. 1. It was necessary to develop a noise suppressor that would fit within this system without increasing nacelle drag, and to achieve a noise attenuation of 5 PNdb with the least possible weight and thrust loss.

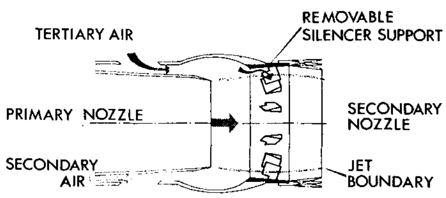


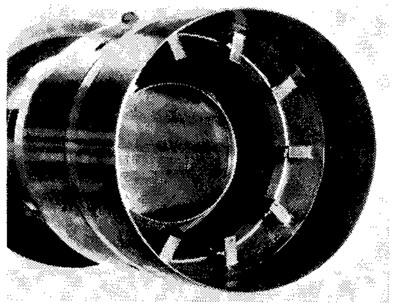
Fig. 2 Typical $\frac{1}{10}$ scale model of the OL. 593 exhaust system with retractable silencer.

The suppressor principle selected is the result of numerous studies made at SNECMA in the field of noise reduction for supercritical jets.[1,2] The concept is to introduce dilution air into the jet boundary by means of radial lobes located downstream of the primary nozzle. The combined effects of this dilution air and the wake of the tubes speed the mixing process and shorten the length of the noise generating zone, thereby reducing the sound energy emitted.

Model Test Results

A systematic experimental study was conducted to determine noise attenuations and thrust losses as a function of lobe design. The characteristic lobe parameters were number, axial depth, jet penetration depth, dihedral angle, incidence of leading edge, inclination of discharge, and method of ventilation. The test model is shown in Figs. 2 and 3.

Fig. 3 Test model of the OL. 593 exhaust system.



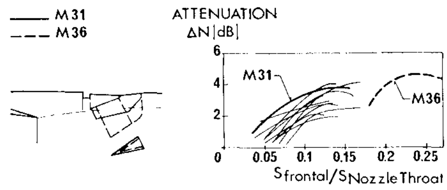


Fig. 4 Attenuations vs immerged frontal area.

Before examining some typical results obtained on the cold jet models, it should be pointed out that all the noise attenuations and thrust losses are measured in relation to the convergent-divergent ejector nozzle configuration. Note that this configuration provides by itself an attenuation of about 1 to 2 db in relation to the convergent type (conical) nozzle. The test data are expressed as ΔN(db) which is the difference between maximum noise measured for the convergent-divergent ejector model without a suppressor, and that measured on the same nozzle with a functioning suppressor. The maximum db levels are the polar levels, measured on the model and scaled approximately 1:11.

The first attempt to compare results of a large number of models, differing either in lobe shape or in number of lobes, is illustrated in Fig. 4 as a function of the immerged frontal area of the lobes. It can be observed that for a frontal area above 15% of the nozzle-throat area, there is little gain in attenuation. The accompanying thrust losses (not shown) would continue to increase. As an example for an expansion ratio of 3, the thrust loss of Model 31 in Fig. 4 is about 2% while it is 5% for Model 36. It seems that after a certain amount of immerged frontal area, the attenuation gain is a result of thrust losses which produce a reduction of the effective jet velocity.

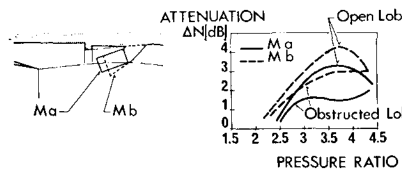


Fig. 5 Effect of normal aeration of lobes.

In this context, it was of interest to determine the effect of normal aeration of the lobes. Figure 5 illustrates two configurations tested with open and obstructed lobes. Open lobes produced more attenuation, and as shown the attenuation is a function of lobe shape and jet-expansion ratio. Flow visualization with open lobes has demonstrated that the aeration flow penetrates the jet beyond the physical end of the lobe. This effect is reduced as jet-expansion ratio is increased and also as lobe depth increases. Because of this, forced aeration of the lobes was investigated. Some results, shown in Fig. 6, reveal that noise attenuation gains were limited with forced aeration. This was due to a "saturation" phenomenon

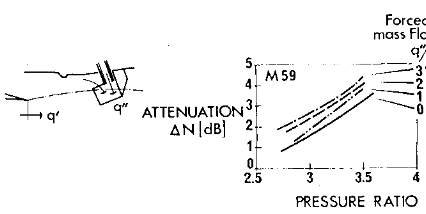


Fig. 6 Effect of forced aeration of lobes.

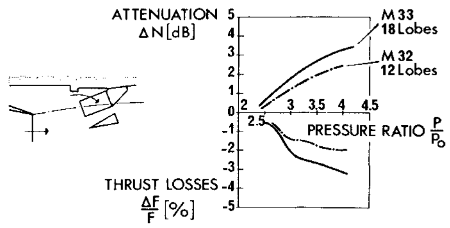


Fig. 7 Effect of lobe number.

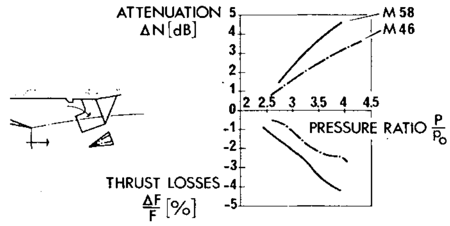


Fig. 8 Effect of the dihedral angle of lobes.

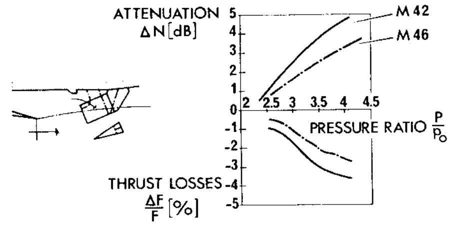


Fig. 9 Effect of the axial depth of lobes.

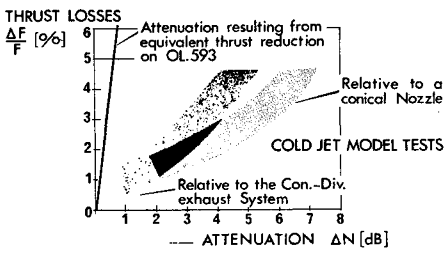


Fig. 10 Summary of performances of retractable silencers.

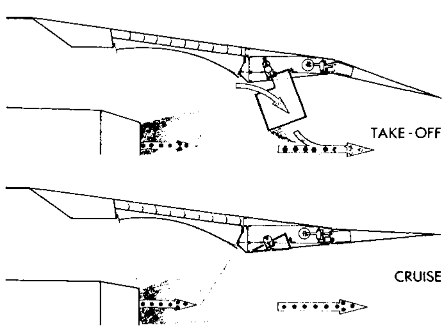


Fig. 11 Operating principle of the retractable silencer.

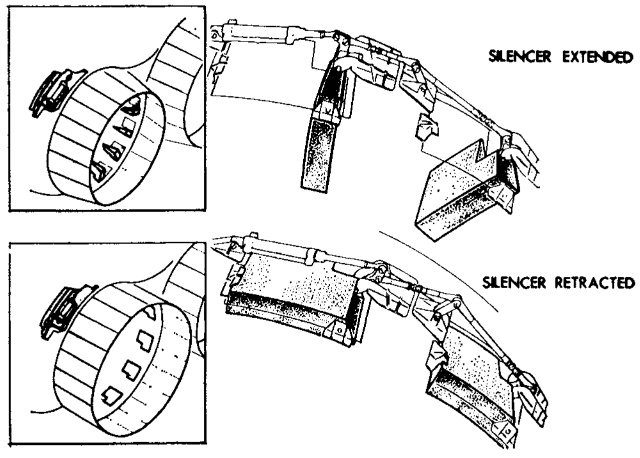


Fig. 12 Retractable silcencer control system.

which has been observed in other tests on principles of aerodynamic suppressors.

The following three figures show the influence of lobe geometry on performance of this type of suppressor with normal aeration. Figure 7 compares 12 and 18 lobes of the same shape. Figure 8 illustrates how changing dihedral angle from 23° (M46) to 29° (M58) increases both attenuation and thrust loss. Figure 9 shows the effect of increasing lobe depth from 14 mm (M46) to 18.8 mm (M42). Results from many models are summarized in Fig. 10. Attenuation and thrust losses are shown relative to both a convergent-divergent ejector and a convergent (conical) nozzle. The previous figures present a view of the tests already made on models. Model and full-scale tests are being continued in an attempt to find ways of increasing attenuation without larger thrust losses. Results so far permit us to count on 5 PNdb noise attenuation with thrust losses not exceeding 3% at takeoff and which are nonexistent during the remainder of the mission.

Suppressor Operation

Retraction of the suppressor lobes presented some difficulty because of limited space available. This was overcome by making a circumferential retraction of the lobes, as illustrated in Fig. 11. This solution limits the number of lobes depending on lobe depth. A 10-lobe design was adopted as the best compromise.

When the suppressor is in the operating position, the lobes are in a radial position with one end inserted into the primary jet stream where the flow is greatly expanded. Dilution air from the tertiary stream is sucked into the upper position of the hollow lobes and injected radially into the primary jet. When the suppressor is no longer needed, a kinematic transmission folds the lobes back into the structure of the ejector nozzle. In this position, one surface of the lobe is flush with the ejector inner wall. This nearly smooth con-

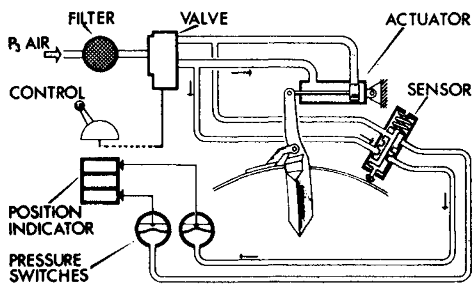


Fig. 13 Detection and control system.

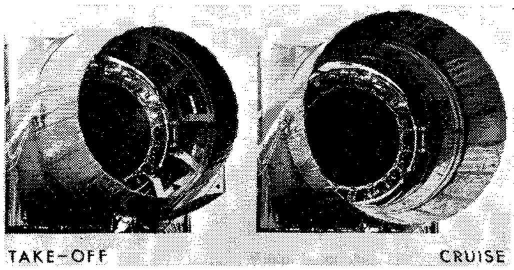


Fig. 14 Olympus 593 exhaust system.

tour then does not change normal ejector operation and no performance loss is present.

A prototype version of the retracting mechanism is shown in Fig. 12 with two lobes linked to one pneumatic actuator. For the semiproduction version each lobe will have an individual actuator. The actuators are fed by high-pressure compressor air through a filter and multiple distributor with electrovalves as illustrated in Fig. 13. Lobe position (active or inactive) is set by double pneumatic sensors connected in series. The sensors also operate two pressure switches which activate a position indicator for the flight engineer. Safety devices are planned at the multiple distributor level so that the suppressor cannot be activated at the wrong time. Also, the design is such that failure of any one lobe is detected and displayed on the indicator.

Total weight of the suppressor parts and the control mechanism is less than 30 kg per engine. This very low weight (compared to fixed position silencers on present aircraft) is a result of light construction made possible by the retractable principle. In fact, when the lobes are retracted (during most of the flight) they are in a "cold zone." When activated, only the lobe tip is in the hot flow, and even this part is cooled by dilution air. Photographs of the suppressor assembled on the engine at the test stand are shown in Fig. 14 at takeoff and cruise positions of the lobes and the ejector nozzle.

Fixed vs Retractable Comparison

Introducing suppressor parts into the supersonic portion of the primary jet limits the possibility of working on the structure and shape of the jet, if excessive thrust losses are to be avoided. In the light of tests made so far, it therefore appears that notable improvements in acoustic effectiveness of this type of suppressor are limited by acceptable thrust losses. Tests on suppressors with axial tubes fixed on the flaps of the primary nozzle have given slightly greater attenuations for comparable thrust losses. However, an examination of the noise level perceived at the ground when the plane flies over shows that the attenuation advantage of the fixed suppressor is only apparent because of the flight path.

In fact, as already pointed out, the presence of a fixed suppressor in the jet during the entire flight leads to a takeoff weight increase if the payload is constant. This results in a longer takeoff run and lower initial climb angle as indicated in the top of Fig. 15 where the SST climb paths are depicted. Since noise becomes louder when it is closer, the attenuation gain of a fixed suppressor is offset to a large extent by the altitude decrease as the aircraft flies over. This effect is plotted in Fig. 15 as the increase in ground noise level as a function of thrust losses in flight. Therefore, a fixed suppressor would have to achieve very large attenuations or very low thrust losses to be as effective as a retractable suppressor without perceptibly decreasing the economy of the aircraft.

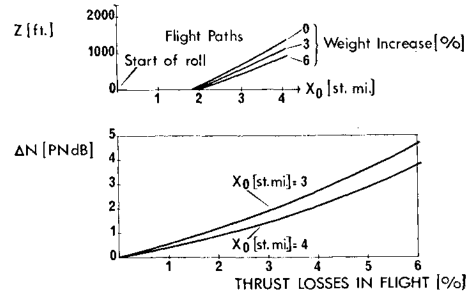


Fig. 15 Fixed silencer: noise increase on ground, due to thrust losses in flight.

Conclusion

The studies and tests at SNECMA have permitted us to arrive at the concept of an exhaust-noise suppressor with a new and retractable principle which to a certain extent realizes a balanced compromise between the different requirements to be satisfied.

Being entirely retractable, this suppressor is particularly advantageous in the area of flight economy because cruise-thrust losses are eliminated. The retractable feature also allows for extremely low-suppressor weight because of its low-temperature environment. The design was accomplished in little space and fits within the ejector geometry.

Concerning attenuation levels produced on the ground when the plane flies over just after takeoff, the retractable suppressor shows unquestionable superiority over a fixed suppressor of equivalent performance. In its present stage of development, and in view of planned improvements, this suppressor should allow the Concorde to be classed favorably in relation to exhaust noise from present commercial aircraft.

References

[1] Richter, G., "SNECMA Studies on Noise Reduction of Jets," *International Conference on Reducing Noise and Disturbance Caused by Civilian Transport Planes*, INC/C1/P17, London, Nov. 1967.

[2] Hoch, R., "Problems Posed by the Flight Silencer for Concorde," *Concorde Symposium*, Versailles, France, Nov. 1966, Société Nationale d'Etude et Construction de Moteurs d'Aviation.