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Powerplant Aspects of High-Speed, Inter-City VTOL Aircraft

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This paper reviews the problems associated with installing an advanced self-contained lift fan engine in wing pods for a high-speed, inter-city civil VTOL aircraft. It is shown that community noise levels can be approached which will permit city-center aircraft operation. The advantages of using multiple self-contained lift fans are discussed together with general installation problems such as the design of low noise level air intake systems. Methods of providing aircraft control during transition and engine thrust deflection for acceleration are examined. It is concluded that, with the latest technology, podded installations of low noise level self-contained lift fans can be designed within the same installed volume as an equivalent RB 162 lift jet installation of the type now flying in the Dornier Do 31 military VTOL transport aircraft.

1. Introduction

Civil VTOL Field

THE rapid growth of conventional air transportation and increasing surface traffic congestion is providing a strong incentive to find a solution to the problem of civil VTOL operation. Of existing VTOL aircraft, the high subsonic cruising speed direct jet lift approach, although becoming accepted for military applications, is too noisy for city-center operation. The helicopter, although potentially quiet enough, suffers from severe speed and endurance problems.

A wide range of aircraft types, from compound helicopters through tilt wing and tilt propeller aircraft to fan lift aircraft, is currently being investigated. Except for very short haul duty, the emphasis is upon a reasonably high cruise speed to minimize journey time and to improve productivity. The combination of low noise level and high cruise speed potential, together with the engine-out safety requirements necessary for civil operation, can be met with the self-contained lift-fan concept. One possible evolutionary route from the German Dornier Do 31-1, the world's first military jet lift VTOL transport aircraft, to a high-speed, inter-city VTOL civil aircraft with pods of self-contained lift-fan engines is illustrated in Fig. 1.

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Although it is possible that the ultimate inter-city VTOL civil aircraft using self-contained lift-fan engines will be one in which the powerplant and airframe are closely integrated, the separate lift pod concept remains a perfectly practical "first generation" solution. A conventional airframe can be employed, thus avoiding the combination of a new powerplant principle with a new airframe concept. With this arrangement it is relatively easy to take advantage of future developments in either lift- or propulsion-engine developments. If necessary, aircraft growth need not await lift-engine development, since the pod configuration allows the installation of extra lift engines with minimum airframe modifications.

Lift-Engine Development

The concept of VTOL using multiple single-purpose lift engines was originated by Dr. A. A. Griffith of Rolls-Royce, whose first paper on jet lift VTOL was presented to the Aeronautical Research Council in 1941. The RB 108 specialized lift jet first ran in 1955, to be followed by the RB 162 in 1961.

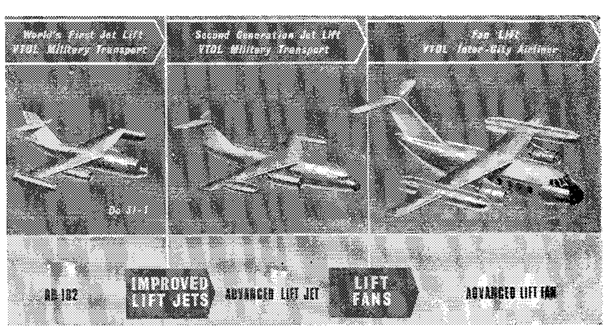

Fig. 1 Development of civil VTOL transport.

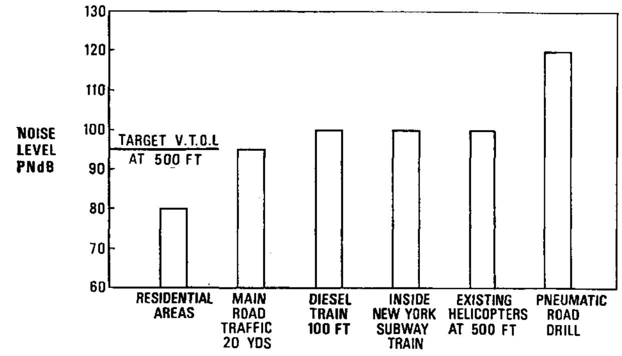

Fig. 2 Existing urban noise levels.

In 1957 Dr. Griffith proposed the RB 144 lift-fan system for civil VTOL. This was followed in 1961 by design studies on a range of integral or self-contained lift-fan engines which used versions of the RB 162 as a coaxial gas generator. This series of engines, designated RB 175, was restricted by the standard of technology then available particularly as regards methods of designing for low noise. The RB 175 has now been superseded by studies of advanced self-contained lift-fan engines aimed specifically at the achievement of noise levels low enough to permit civil city-center operation.

On Table 1 the leading features of one such lift-fan proposal are compared with those of the RB 162 and a typical RB 175 design. This new lift-fan proposal has a by-pass ratio of 12 and will be referred to as the advanced lift fan. It will be seen that, relative to the RB 175, a slightly better value of the near nondimensional installation parameter, the ratio of thrust divided by volume to the two-thirds power is achieved despite the fact that the by-pass ratio has risen from 4.25 to 12.0. The thrust/weight ratio for the advanced lift fan is of the same order as that of the RB 162.

Although the specific volume of a basic advanced lift fan is worse than that of the basic RB 162 lift jet, it is possible to take advantage of the advanced lift fan's high by-pass ratio to minimize the additional volume occupied by installation features such as thrust deflectors. In addition, it is possible to tailor the external profile of the high by-pass ratio engine with further benefit to the installed volume. The marked improvement of the advanced lift fan's specific fuel consumption relative to the RB 162 can be regarded as a valuable bonus which may be utilized either for reducing fuel load or for allowing longer hover and transition times.

2. Noise

Target Noise Levels

High on the list of problems of any civil VTOL aircraft is that of noise. For true city-center operation, the noise heard by the community on the ground must be low enough to allow unrestricted and hence economically viable operation. At this date, no mandatory requirements exist for such operations. It is obvious that those applicable at existing airports for conventional (CTOL) aircraft are not satisfactory for downtown operation.

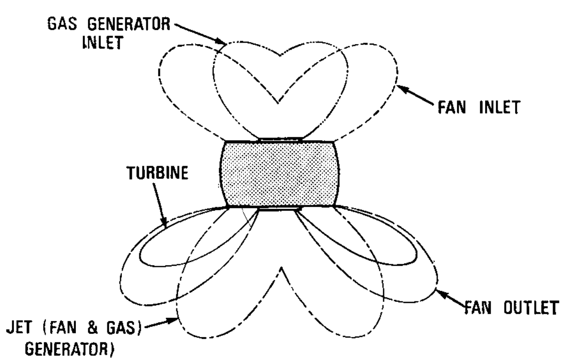

Fig. 3 Lift-fan engine noise sources.

Table 1 Lift-engine development trends

(VOLUME BASED ON ENCLOSING CYLINDER)	RB 162	RB 175	ADVANCED LIFT FAN
By-pass Ratio	0	4·25	12·0
S.F.C.– lb/hr/lb	1·12	0·62	0·41
Thrust/Weight – lb/lb Thrust	16	13	17
Thrust/(Volume)$^{2/3}$	4·8 lb/in²	3·4 lb/in²	3·6lb/in²

Figure 2 shows some of the noise levels to which the occupants of large cities are already subjected throughout the working day. Obviously, to site a VTOL port in a residential area and then to restrict the noise to existing levels is not likely to be possible for many decades. However, there are now in most cities areas such as railway stations, railway sidings, docks, and industrial sites where comparatively high noise levels already exist and residential habitation is at a minimum. Location of a VTOL port in such an area would allow noise targets which are not impossible with the technology now available for the design of future lift-fan engines.

In the United Kingdom, the Ministry of Aviation (now the Ministry of Technology) suggested in 1963 a target for civil VTOL operation of 105 PNdb at 200-ft radius. London has several possible sites which are sufficiently centrally located to accommodate a VTOL port where the nearest communities are at a rather greater distance than 200 ft. The target presently being considered is therefore 95 PNdb at 500-ft radius which represents a noise of approximately equivalent power to the 1963 target.

The pure VTOL aircraft has a noise advantage over CTOL or STOL aircraft since it can climb or descend in a substantially vertical direction, thus minimizing the area on the ground subjected to its noise. Furthermore, subject to air traffic control procedures, the height of this vertical maneuver could be adjusted to avoid any community noise contribution from the propulsion engines. Therefore, it is necessary to consider only the noise generated by the lift fans.

Noise Sources

Figure 3 shows the sources of the noise generated by a typical self-contained lift-fan engine. The noise radiated upwards from the gas generator and fan inlets is not likely to be a problem unless the landing site is surrounded by high buildings. In any case, the noise radiated in this direction is typically less than that radiated downwards, the latter being composed of jet noise (from both fan and gas generator streams) plus downwards-radiated fan noise and turbine noise.

Jet noise is a function of jet velocity, and, by increasing by-pass ratio, the jet velocity can be lowered to a point where this noise no longer predominates. This is illustrated on Fig. 4, which shows the maximum perceived noise heard on the ground 500 ft from the takeoff point during the vertical ascent of an aircraft having lift engines providing a total installed lift of 80,000 lb.

Increase of by-pass ratio also requires, for optimum efficiency, a reducing fan pressure ratio, and, if the by-pass ratio is sufficiently high, this pressure ratio can be achieved with a single stage fan. For conventional designs incorporating inlet guide vanes, even single stage fans generate sufficient noise to maintain a total noise level which does not significantly reduce below that of the basic gas generator. This is shown by the curves at the top of Fig. 4. It is therefore necessary to remove the inlet guide vanes and to choose a by-pass ratio and engine configuration where the required pressure ratio can be achieved with a single stage fan of low tip speed and hence low relative Mach number.

With such designs, no discrete blade passing tones are produced as a result of wakes from the inlet guide vanes impinging on the rotor blades, and the main source of fan noise, the rotor self or vortex noise, generated by the action of the blade to the air passing over its surface, is reduced by the smooth inlet stream at low relative Mach number. There may be discrete tones produced by the wakes from the rotor blade impinging on the outlet guide vanes, but the use of a wide gap between rotor and stator results in these tones being below the level of the rotor vortex noise. Furthermore, the use of a large number of high-aspect-ratio rotor blades insures that the blade-passing tones and the characteristic vortex noise frequency are sufficiently high to be above the critical annoyance band. This, and the greater atmospheric absorption of sound at high frequency, enables the fan noise to be reduced by about 25 PNdb as shown on Fig. 4.

The third noise source, the turbine noise, reduces with increasing by-pass ratio because, for a given thrust, the turbine is smaller and its characteristic frequency can be further raised by the use of high-aspect-ratio blades, so minimizing the subjective effects. Thus, the total noise level for this design of unit is approximately 105 PNdb, remaining substantially constant for by-pass ratios above about 8 (see Fig. 4).

However, further reductions of both fan and turbine noise can be achieved by attenuation devices such as sound absorbent linings and splitters. The volume and weight of such absorbent treatment are dependent upon the frequency of the noise to be attenuated. In insuring a high frequency by the design actions previously mentioned, it is estimated that attenuations of 5 and 10 PNdb on the turbine and fan noise, respectively, can be achieved without significant increase to the volume of the engine.

To insure that the jet noise does not predominate over the attenuated fan and turbine noise levels, it is necessary to use by-pass ratios above 8 (see Fig. 5). It is this factor which has determined the by-pass ratio of 12 selected for the advanced lift fan. Figure 5 shows a final attenuated total noise level of approximately 98 PNdb for an aircraft powered by by-pass ratio 12 advanced lift fans.

The preceding calculations have all been made for lift-fan engines operating continuously at their maximum rating. The aircraft's total installed lift will be determined by the worst design conditions likely to be encountered, such as a hot and high takeoff. In addition, some thrust/weight margin will probably be allocated for aircraft control and the engine failure case. Therefore, the vast majority of takeoffs will actually be accomplished at less than maximum lift-engine rating, and the noise will be further reduced. During vertical descent for landing even less thrust will be required due to the decelerative nature of the maneuver and the reduced aircraft weight, which again will be beneficial from the noise point of view.

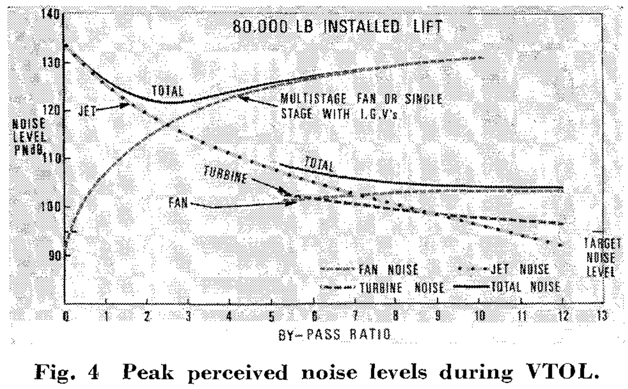

Fig. 4 Peak perceived noise levels during VTOL.

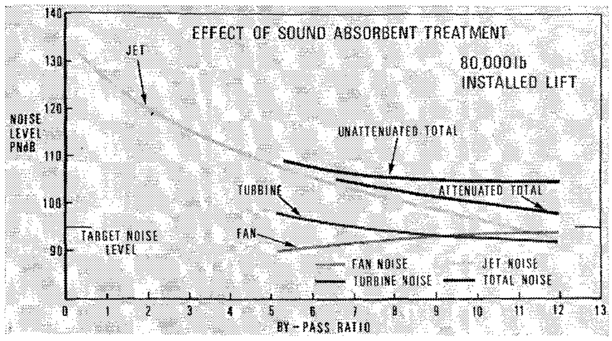

Fig. 5 Effect of sound absorbent treatment.

Considerable research work is currently being expended on the subject of engine internal noise and sound absorbent materials, construction and configuration. The target noise level of 95 PNdb previously mentioned is therefore considered an achievable target for operation by lift-fan engines in the mid 1970's.

3. Use of Multiple Lift Engines

Integral lift-fan engines capable of being produced in relatively small thrust sizes offer the airframe designer a means of providing engine-out safety without mechanical interconnection. Prototype aircraft flight development has already indicated solutions to the problems usually associated with multiple lift-engine installations such as multiple engine control, powerplant servicing, and starting reliability.

Lift-Engine Control

The feasibility of controlling banks of lift engines from one or two cockpit levers has now been well proven over a range of VTOL hovering rigs and aircraft. These include the Short SC1, the Marcel Dassault Balzac and Mirage, the EWR-Süd VJ 101 C, and the Dornier Do 31-1.

A single-banked cockpit instrumentation display showing comparative engine thrust has also been developed. This single comparator instrument enables a rapid check to be made for loss of thrust or failure to start on any individual engine. The only other form of cockpit instrumentation normally proposed is an "engine dangerous" warning light which signals the excessive overspeeding, overtemperaturing, or vibration of any individual lift engine.

Powerplant Servicing and Starting

The former problem is being tackled by evolving special servicing techniques such as the Do 31-1's "lift engines functioning correctly" panel which is provided for ground crew inspection between flights and the use of a common oil replenishment point per bank of engines. The development of life recorders which will present a digital display of remaining lift-engine life to the ground crew after each flight is under way in order to insure the safe utilization of all the lift engine's potential running time between overhauls.

Starting reliability is being achieved by a tightening of design standards relative to propulsion engines, and successful 3000 start development test runs have already been completed. Lift engines are not normally required to start or operate at altitudes above 10,000 ft, and this absence of a high-altitude operational requirement considerably simplifies the basic concept of the combustion chamber and fuel system, thereby facilitating the design of a really rugged and reliable system.

A point to be emphasized when discussing servicing or starting is the potential simplicity of the specialized lift engine

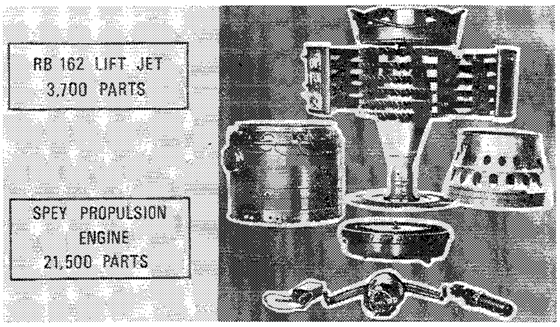

Fig. 6 Simplicity of RB 162 lift jet.

(see Fig. 6). For example, the RB 162 has only 3700 parts compared with the 21,500 parts of its contemporary propulsion engine, the Spey.

Advantages of Multiple Self-Contained Lift Fans

Besides allowing the direct optimization of the forward propulsion engine design to its cruise duty, the advantages in lifting a transport aircraft by means of several relatively small thrust size self-contained lift-fan engines may be listed as follows.

1) The airframe designer is allowed a much greater flexibility in his choice of powerplant configuration. More total lift can be produced by filling a given aircraft space (plan area × depth) with small, as opposed to large, lift fans. The reduction in engine length produced by scaling down lift fans would clearly be particularly helpful for buried wing installations.

2) An improved installed specific weight should be possible. This will be derived not only from the basic engine but also from the installation. For a given thrust level, it should be possible to reduce the volume and consequently weight of surrounding aircraft structure for increasing numbers of engines.

3) For a given thrust level, the noise produced by small engines has a higher frequency with consequent benefits to the over-all noise level. Perhaps of even greater importance is the better response of this higher-frequency noise to sound absorbent linings and splitters which can be fitted inside the engine.

4) The installed excess thrust marg into provide engine-out safety can be reduced with increasing number of engines.

5) Small engines have small rotating masses with consequent benefits to their thrust response characteristics, thus easing the problems of aircraft control by thrust modulation. In addition, the absence of large engine or rotor rotating masses during transition will provide a higher standard of passenger comfort.

These, then, are the advantages for large numbers of small thrust-size, self-contained lift-fan engines, against which the aircraft designer must set their principle disadvantage of increased powerplant cost for a given aircraft production quantity.

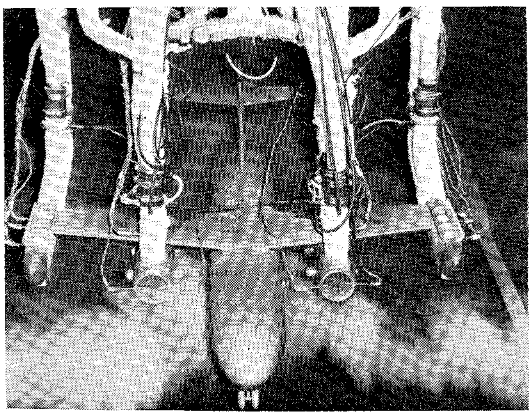

Fig. 7 Do 31-1 hot gas recirculation model.

Table 2 Comparison of lift-engine exhaust conditions

	RB 162	RB 175	ADVANCED LIFT FAN
By-Pass Ratio	0	4·25	12·0
Hot Nozzle Velocity	2,000 ft/sec	1,040 ft/sec	860 ft/sec
Cold Nozzle Velocity	———	660 ft/sec	590 ft/sec
Mean Exhaust Temp.	1,470°F	340°F	210°F

4. Lift-Fan Installation Features

Under this heading it is proposed to discuss briefly air intakes, hot gas recirculation, ground erosion, and aircraft transitional control.

Air Intakes

For civil VTOL aircraft of the type under consideration, it may be assumed that air bleed from the propulsion engines will always be available for in-flight lift-engine restarting by means of turbine air impingement. Provided the thrust deflection arrangement can produce an in-flight negative engine exhaust pressure, then suitably profiled entry bellmouths matched to the open intake doors will probably be sufficient to provide a satisfactory intake arrangement for an in-line lift pod installation of advanced lift fans. At worst, a single vane or blown lip may be required to help turn the air into the first fan bellmouth. If a vane were fitted, it would only be required to assist in-flight restarting. Once the lift fans had satisfactorily restarted, this vane would retract back into the bellmouth profile, thus avoiding any increase of fan noise level which might otherwise result from discrete tones produced by interaction of intake vane wakes with the fan rotor

Hot Gas Recirculation and Ground Erosion

A comparison of lift-engine exhaust characteristics is given in Table 2. This tabulation indicates the low exhaust temperature and velocity characteristics of the advanced lift fan which, properly utilized in conjunction with prepared city-center operating sites, will reduce recirculation and erosion to problems of little or no significance. Figure 7 shows a model of the Do 31-1 under test to determine the optimum aircraft operating technique from hot gas recirculation considerations. This model technique, which was originally developed in

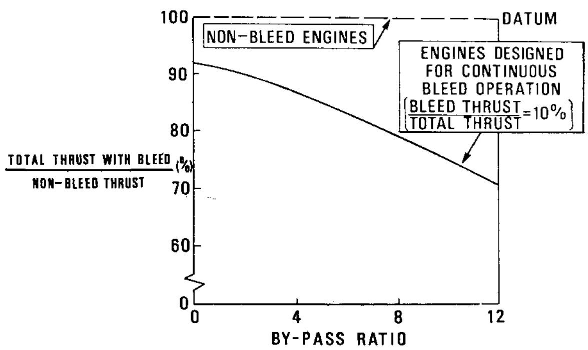

Fig. 8 Lift-engine bleed for aircraft control.

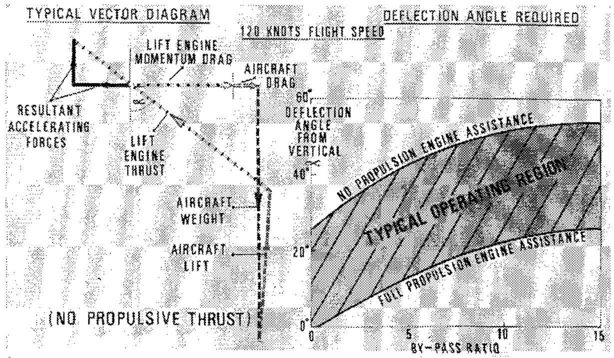

Fig. 9 Lift-engine thrust vectoring for acceleration.

connection with thrust reverser installations, is becoming well established through correlation against full-scale prototype VTOL aircraft testing.

Aircraft Control during Transition

Rolls-Royce lift jets have always been designed with the capability of taking compressor delivery air for generating control thrust in nozzles located at the aircraft extremities. However, with lift fans, the gas generator size is reduced for a given total lift as by-pass ratio is increased and it therefore becomes increasingly difficult to design the lift fan to supply sufficient gas generator compressor delivery air for this purpose. Figure 8 shows that the total thrust penalty paid for producing a constant proportion of control thrust in this manner becomes increasingly unattractive with increasing by-pass ratio.

Fortunately, it is probable that the type of aircraft discussed in this paper will have its advanced lift fans displaced some distance from its center of gravity. It then becomes possible to provide roll and pitch control by differential thrust modulation of the appropriate lift engines together with lift engine differential vectoring for yaw control. If lift fans of a relatively small thrust size are preferred, this should ease the engineering problems involved in producing the required engine thrust response characteristics.

Control of the EWR-Süd VJ 101C aircraft is achieved in the manner proposed previously. Similarly, roll and yaw control of the considerably larger Dornier Do 31-1 aircraft are accomplished (respectively) by differential throttling and differential vectoring of the RB 162 lift engines.

5. Lift-Fan Thrust Deflection

Figure 9 illustrates the point that the increased intake momentum drag of a high-by-pass-ratio lift fan relative to a lift jet produces a more stringent thrust deflection vector requirement if transition times are to remain similar. However, the greatly improved specific fuel consumption of the lift fan allows some relaxation in transition times at the expense of thrust vectoring capability. Nevertheless, the engineering of an efficient, light, and compact thrust deflection system is one of the most difficult installation problems to be solved for the high-by-pass-ratio lift fan. The deflection system to be adopted clearly depends upon the cruise and transition speeds, the location chosen within the aircraft for the lift fans, plus the provision of any differential thrust vectors which may be required for aircraft stabilization.

Further discussions on thrust deflection will be restricted to methods of obtaining a typically required range of thrust vectors, say between $-15°$ and $+45°$ from vertical, with reference to a lift pod installation.

Swivelling Engines

In principle, the simplest method of providing thrust deflection is by means of swivelling the whole engine, and the Rolls-Royce advanced lift fan can be given a substantially spherical profile to suit such an installation. Figure 10 illustrates the inter-engine pitching required for differing degrees of thrust deflection. In addition to lengthening the pod, large vector requirements also present inter-engine pod structural problems, since pod structure can only be positioned in regions where it does not interfere with either intake or exhaust airflows.

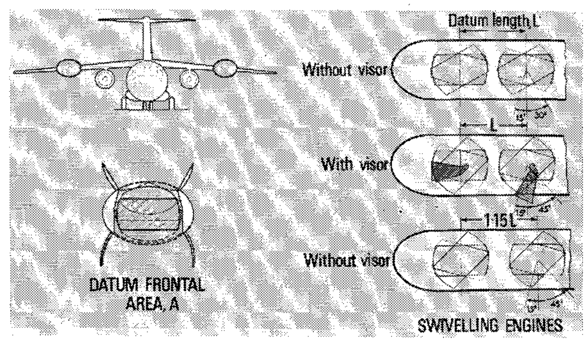

Fig. 10 Swivelling lift-fan installations.

As illustrated in Fig. 10, increased propulsive thrust vectors can be obtained by combining an additional thrust deflection visor with the swivelling engine concept. For a given standard of vectoring, it is then necessary to tradeoff the increased weight, thrust loss, and mechanical complexity of the visor against the additional pod length necessary to accommodate the equivalent simple swivelling engine. Lift pod frontal area is largely dependent on whether intake and exhaust doors should be shaped as shown to permit closure over a fully jammed swivelling engine.

An alternative "dispersed engine" approach is to install eight lift fans per aircraft in four pairs. Each pair could be located at a "corner" of the aircraft (rather in the manner pioneered by the Bell X-22) and the two fans arranged to swivel about a common transverse axis. Stowing of some or all fans within the fuselage during cruise flight could be investigated. This "dispersed engine" approach is suggested as a method for avoiding the excessive lengthening of a pod to accommodate a row of swivelling engines.

Exhaust Deflector Doors

Another approach, illustrated in Fig. 11, is to fix the lift fans within the pod and to design lower doors which, in addition to closing off the exhaust outlets during cruise, also provide the required thrust deflection. The lift fans can now be installed in near square cross-section compartments or modules with closely cowled upper and lower doors. This approach has important volume-saving implications since, by "squaring-off" the engine's by-pass duct, the dimensions of the module square can now be less than the diameter of the previous circular by-pass duct. This square cross-section by-pass duct does not involve any significant weight penalty

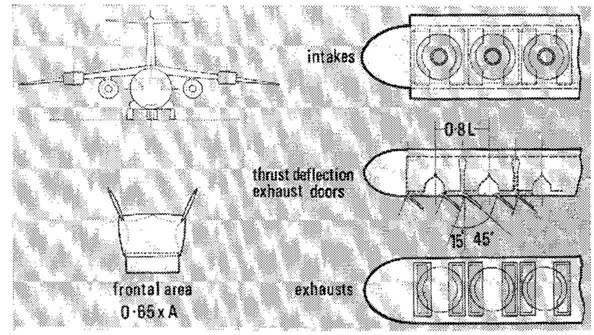

Fig. 11 Lift-fan thrust deflector doors.

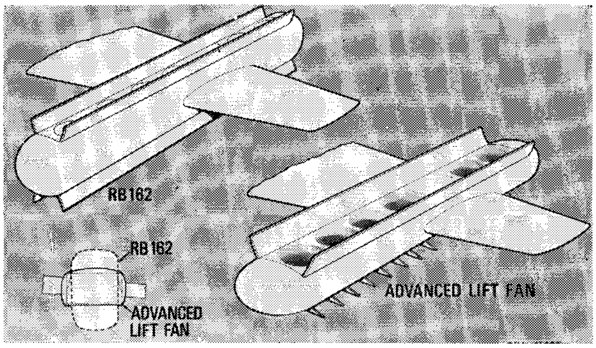

Fig. 12 Lift-fan pod installation.

since the internal pressures are very low with high-by-pass-ratio lift fans.

As shown on Fig. 11, the lift-fan spacing is now largely determined by the need to provide satisfactory inter-engine bellmouth shapes. In addition, pod sidewall and inter-engine structure could be combined with each engine's by-pass duct.

Since air is compressed in the engine, the outflow or exhaust area from each module is less than the inlet. Figure 11 illustrates one method of taking advantage of this area compression in combination with the available square outlet shape. The resulting two exhaust slots per engine produce an outlet flow which is very suitable for deflection by means of exhaust doors similar to the ones already successfully developed for the eight RB 108 engines in the Marcel Dassault Balzac VTOL aircraft. It is anticipated that weight savings relative to the Balzac deflector doors can be incorporated into a future fan lift-engine installation due to the considerably reduced exhaust velocities and temperatures involved. Another advantage of having two exhaust slots per engine is the ventilation to atmospheric pressure of the final nozzle's central base area.

Assuming the concept of fixed lift fans installed in near cubic modules, another approach is to use variable angle exit louvres for thrust deflection. This principle has been pioneered by General Electric for the Ryan XV-5A aircraft. The louvres would close completely during cruising flight so presenting a relatively smooth lift pod undersurface.

Table 3 Lift-pod comparison

	6 × RB 162-84 lift jets per pod	6 × advanced lift fans per pod
Aircraft nominal lifting thrust	75,000 lb	80,000 lb
Engine by-pass ratio	zero	12
Lift-engine noise at 500 ft	135 PNdb	98 PNdb
Liftpod length	34.7 ft	38.8 ft
Liftpod height	6.2 ft	3.2 ft
Liftpod width	3.6 ft	5.6 ft
Gross frontal area	20.5 ft^2	16.0 ft^2
Gross wetted area	550 ft^2	585 ft^2
Isolated drag (0.8 min. 20,000 ft)	735 lb	690 lb

The concept of installing lift fans in near cubic modules produces a considerable reduction in pod volume and frontal area relative to a swivelling lift fan installation (refer to Fig. 11). The resulting installed pod volume and frontal area now becomes directly comparable with that of an equivalent RB 162 pod, as illustrated on Fig. 12.

6. Conclusions

Within the limits imposed by security, an indication has been given of the characteristics of a self-contained advanced lift-fan engine. This engine proposal has the low noise potential necessary to provide an attractive composite powerplant system for the high-speed, inter-city VTOL aircraft of the mid-1970's.

The composite powerplant VTOL aircraft could benefit directly from the installation experience being built up by the multi-engine VTOL aircraft prototypes now flying in Europe. Additional installation problems associated with the high by-pass ratio of the advanced lift fan will not be greater than those already solved for the lift jet. By adopting a compact installation arrangement for the advanced lift fan, the lift pod comparison shown in Table 3 is obtained. It is therefore concluded that it is now possible to design a low-noise lift-fan installation within the same volume as an equivalent thrust RB 162 lift-jet installation.

Editor's Note: AIAA/RAes/CASI 10th Anglo-American Aeronautical Conference Papers

A proceedings of the 10th Anglo-American Aeronautical Conference, which was held in Los Angeles, California, October 18–20, 1967, will not be published. Instead, most of the papers will be published in one of the following Journals: *Journal of Aircraft, Canadian Aeronautics and Space Journal,* and *The Aeronautical Journal* of the Royal Aeronautical Society. There will be no duplicate publication of the papers in any of the Journals.

The papers by Pickerell and Cresswell and by Schaub (Papers 67-745 and 67-746 on pp. 467–472 and 473–478, respectively, in this issue) are the first to be published in the *Journal of Aircraft.*

The following papers have been published in the *Canadian Aeronautics and Space Journal*:

Macdonald, I. S., "The SST–Economic Tightrope of the Airlines" (Paper 67-749), Vol. 14, No. 1, Jan. 1968, pp. 13–15.

Beauregard, J. P., "Progress Report on a Small Turbine for STOL Aircraft and High Speed Surface Vehicles" (Paper 67-744), Vol. 14, No. 1, Jan. 1968, pp. 17–23.

Whittley, D. C., "The Augmentor-Wing Research Program: Past, Present and Future (Paper 67-741), Vol. 14, No. 2, Feb. 1968, pp. 45–56.

The following papers have been published in *The Aeronautical Journal* of the Royal Aeronautical Society:

Black, H. C., "The Airworthiness of Supersonic Aircraft" (Paper 67-751), Vol. 72, No. 686, Feb. 1968, pp. 115–122.

Lederer, J., "The Jumbo Jet and Public Safety" (Paper 67-762), Vol. 72, No. 688, April 1968, pp. 291–298.

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