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DESIGN STUDIES OF LIFT FAN ENGINES SUITABLE FOR USE IN CIVILIAN VTOL AIRCRAFT

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ABSTRACT

Low pressure ratio fan engines are receiving increasing attention as a means to provide low speed lift for civilian VTOL transports. Two general types of fan lift engines that are being studied are integral fans and remote powered fans. Preliminary engine design studies of both types of lift fan systems have been made. The paper summarizes a portion of the results of the engine design studies, including the crucial engine requirements, and some of the characteristics of the emerging engine designs of each type.

INTRODUCTION

Large VTOL airliners are being considered for future civil air transportation systems. One of the problems that must be solved before such aircraft can be designed is to find a suitable vertical lift engine system. Many different types of lift engine systems have been proposed including rotors, propellers (tilt wings), jets and ducted fans. Rotor and tilt wing aircraft have been considered for civilian transport use but these aircraft have lower cruise speeds (ref. 1), and may have poorer ride qualities than jet powered aircraft. In addition, the public may not accept rotor or propeller driven aircraft after becoming accustomed to jet powered airliners. The use of lightweight, compact turbojets for vertical lift has been demonstrated (the Dornier DO31) but the high noise level of turbojet engines makes them unacceptable for civilian use. Therefore, the favored civilian VTOL configuration evolves as one utilizing low pressure ratio (high bypass ratio) fans for low speed flight (ref. 2). A number of lift fan engines have been studied and designed to various depths (refs. 3 and 4), but as the aircraft and engine requirements are further defined there is a need to reexamine and update the engine studies. Also since there are different types of lift fan systems the engine studies may provide, for a given set of design requirements, a part of the information needed to make a comparison. In line with this objective NASA-Lewis currently has underway a program to study civilian lift fan engines and provide a technology base for these engines.

This paper summarizes a portion of two NASA sponsored contracts with the General Electric Company to make design studies of lift fan engines. The crucial engine requirements, as presently viewed, are discussed and the chief characteristics of the emerging engine designs are described.

LIFT FAN SYSTEM TYPES

Lift fan engine systems can be generally categorized by type drive arrangement as either integral or remote. The integral engine has a co-axially located lift fan and core engine in a single self-contained unit such as that shown in figure 1(a). It is fundamentally similar to a high bypass ratio turbofan engine with special emphasis placed on achieving a short engine length. Some of the design features used to shorten the engine are a low cycle pressure ratio, and hence a minimum number of compressor stages, minimum number of turbine stages, and a reverse flow combustor.

In the remote fan system the gas generator and lift fan are separate units connected by gas ducting. In the presently preferred fan arrangement the lift fan is driven by a single stage turbine attached to the fan blade tip shroud. Two types of gas generators are being considered, a turbojet and a turbofan (fig. 1(b)). For the turbojet, hot exhaust gases are ducted from it to the lift fan turbine. In the turbofan system a large amount of relatively cool air is bled from the low pressure spool and delivered to the lift fan turbine. Before entering the scroll the temperature level of the air is increased in an auxiliary combustor. The primary difference between the turbojet and turbofan systems is the ducting of a smaller volume flow of cool air for the turbofan system, but with the addition of a more complicated gas generator. Typical aircraft configurations employing integral and remote fans are described in the following paragraphs.

Two basic propulsion concepts most often considered for VTOL aircraft having integral lift engines are shown in figure 2. One concept (fig. 2(a)), utilizes the integral engine only for VTOL, and a different engine for cruise. The cruise engine, with appropriate thrust vectoring devices, could also be used to augment the lift of the integral engines and/or be used for low speed control of the aircraft. Designing the aircraft with different lift and cruise engines permits each engine type to be optimized for a particular function but requires two kinds of engines per aircraft. The second concept (fig. 2(b)), utilizes the same engine type for both VTOL and cruise. The lift/cruise engines are used during VTOL by deflecting the thrust downward with variable angle hoods. The hoods then retract into the engine nacelle after transition.

Of the many versions of packaging the remote lift fans in VTOL aircraft those configurations that utilize all or part of the lift system for cruise appear most promising. Two aircraft concepts that illustrate the multi-functions of the propulsion components are shown in figure 3. The arrangement shown in figure 3(a) utilizes the fans for all three propulsion functions, lift, control, and cruise. Four of the lift fans have their axis vertical and are used for lift and low speed control. The two aft fuselage fans are used during cruise as well as VTOL. These lift/cruise fans have thrust vectoring hoods on them which retract into the nacelle for cruise. Near each fan is a turbojet gas generator which feeds hot gases to the fan drive turbine. The ducting between gas generators is used for fan control changes and gas sharing if an unscheduled turbojet shutdown occurs. This particular aircraft arrangement has been extensively studied by McDonald-Douglas Aircraft and is described further in reference 5.

The aircraft illustrated in figure 3(b) has four main lift fans, eight control fans, and four turbofans. The main lift fans are used only for lift. The control fans have a total thrust equal to the lift fans but are made smaller to provide system redundancy and faster control response. Each turbofan gas generator provides a quantity of pressurized air sufficient to drive one main and two control lift fans. A complicated system of ducting is used to share the pressurized air among a number of fans to minimize the effects of a premature turbofan shutdown. After the aircraft is wing borne the flow from the turbofans is diverted rearward for cruise thrust. Additional details of this aircraft concept are reported in reference 6.

ENGINE DESIGN REQUIREMENTS

Before promising lift fan engines can be identified a list of engine requirements must be established. This is not easily done for lift engines since the VTOL aircraft mission, aircraft propulsion needs, and applicable government regulations are in a state of flux. Also, after the initial engine requirements are established, results of engine and aircraft studies may indicate needed changes to the requirements. Defining the engine design requirements then is an iterative procedure and the requirements will probably change as more information is assembled. The requirements given in the following paragraphs then, represent the current thinking concerning lift fan engines for commercial use in the 1980's. They are not meant to be all inclusive but to represent the primary considerations identified as of the writing date of this paper.

<u>Noise</u> Noise is currently the most dominant consideration affecting the selection of the lift engine design variables. The task to design the engine for low noise is complicated by (1) an incomplete understanding of the engine noise generating mechanism and (2) no officially pronounced noise limitation for VTOL aircraft. However to proceed with the lift engine study a target noise level was set. The total aircraft noise goal used for these studies was 95 PNdB at 500 ft with the engines at takeoff power and developing a total of 120 000 lb thrust.

If the fans are used for aircraft attitude control some units will momentarily operate at higher fan pressure ratios while simultaneously other units will operate at lower pressure ratios. The nominal thrust condition is defined as the "noise rating point" and is lower than the engine design thrust.

The total engine noise consists of exhaust jet noise and the turbomachinery noise associated with the turbulence produced by the rotating blades within the engine. Figure 4 shows the perceived exhaust jet noise level at 500 ft as a function of fan pressure ratio. Assuming that a balanced acoustic design is most desirable (i.e., the suppressed rotating machinery noise equals the jet noise and thus both are about 3 PNdB less than the total noise) the jet noise cannot exceed 92 PNdB. As can be seen from figure 4 for this noise level the fan pressure ratio is in the range 1.22 to 1.25 with the engines at nominal takeoff thrust.

<u>Engine thrust</u>. The total thrust of the lift engine systems is made up of different constituents depending on the type of fan system. In the integral fan system both the fan flow and core flow contributes to the total thrust. In the remote fan-turbojet system the total thrust consists of the fan flow and tip turbine flow thrusts. In addition to the thrust contribution of the fan and tip turbine flows, an additional vertical thrust may be obtained from the core flow of the remote fan-turbofan system. In the engine design studies the total thrust of the different engine types was specified the same for all and is referred to in the following paragraphs as engine thrust.

The different levels of engine thrust specified for the studies are explained with the help of figure 5. The left side of the figure represents the operation of a lift engine during a normal vertical takeoff. A nominal engine thrust of 10 000 lb at sea level static (SLS) for a 90° F day was used in the study. This thrust value is the noise rating point as mentioned earlier. About this nominal thrust are shown control excursions. It was estimated that thrust excursions as high as 12 500 lb or as low as 7500 lb (±25 percent) could be required. Since the engines may have to produce the maximum control thrust (12 500 lb) during takeoff, that condition was chosen as the engine design point.

On the right hand side of the figure is shown the change in thrust levels should one engine or fan have an unscheduled shutdown and a second engine shutdown to balance aircraft moments. Then it was estimated the remaining engines must produce a nominal emergency thrust of 11 600 lb and have a control margin of ±12.5 percent or a maximum thrust of 13 000 lb. Some or all of these thrust demands may change depending on the aircraft configuration, the type of lift engines used and the aircraft low speed control design.

For all of the above thrust values the engines were flat rated to 90°. That is they produced the same thrust levels on cooler days but at reduced turbine inlet temperatures. On hotter days the turbine inlet temperatures remain fixed at the maximum operating levels and the thrust decreases.

<u>Fuel consumption</u>. It is desirable to minimize the fuel consumption of the lift engines because a significant percentage of the total on board fuel may be used during takeoff and landing procedures (ref. 6). Low fuel consumption is also important should the plane have to hover for extended periods of time, for example, during low visibility landings. However because of the large number of lift fans that will be needed on the aircraft low fuel consumption considerations must be balanced against other engine considerations such as weight, compactness, and low cost. Accordingly cycle pressure ratios of the integral engines and remote gas generators were kept at or below 14:1 and modest decrements in component

efficiencies of all engines were accepted to achieve a balanced engine design.

Engine service life. It is intended that the lift engines have the same service life as the airframe. With an assumed aircraft life of 30 000 hr, and an average flight time of 45 minutes the lift engines must undergo 80 000 start-stop cycles. The 80 000 cycles were converted to operational times and are listed in Table I. As can be seen from the table the total engine life is 5000 hours.

In addition to normal engine operation the lift engine must also be able to operate at an over thrust condition in case another engine fails. This it must do during the life of the aircraft without a necessity for engine removal after such an occurrence.

Other considerations. Two other design requirements that will be mentioned briefly are thrust vectoring and low pollutant emissions. A thrust vectoring range of -15° to +45°, measured from vertical, was specified for the engines. The means of obtaining this amount of vectoring may be different for different engine types. At present the integral engine would swivel whereas the remote fan would have thrust deflecting louvers.

A recent addition to the requirements of the lift engines is that they be environmentally acceptable. To partially satisfy this requirement the engines must minimize engine pollutants. Table II lists the maximum combustion pollutant emissions established as an objective for the lift engines. This is not to say that the engines so far studied meet these limits but it forces an in-depth study of the combustion process from another point of view.

INTEGRAL ENGINE STUDY RESULTS

Preliminary design layouts of two basic integral engines were made based on results of an initial parametric analysis. The two engines differed in thermodynamic cycles and levels of technology. Only one of the two engines will be described in this paper, the other engine being very similar in concept.

General description. A general description of the engine is given in Table III and a cutaway drawing is presented in figure 6. The cycle numbers given in the table are design point conditions (12 500 lb thrust) and correspond to the maximum control excursion (fig. 5), for normal engine operation. The single engine perceived noise of 87.2 PNdB is estimated for the noise rating thrust of 10 000 lb.

Some of the salient design features of the engine are composite fan blades in the bypass duct, separate airflow inlets for the bypass and core flows, a radial offset between the compressor and turbines, and a somewhat unconventional reverse-flow combustor. Some of the acoustic design features of the engine are a serrated fan leading edge, a large spacing between the fan rotor and fan stators, and generous use of noise suppression material. The engine is supported by the fan stators and a small number of rear stabilizing struts mounted to trunnions. Controls and accessories are kept to a minimum. The engine has an air impingement starter and a small bleed air turbine that drives the fuel and oil pumps.

Fan spool. One of the problems peculiar to the integral engine is the high aerodynamic loading of the fan drive turbine. This is due to the high engine bypass ratio and the moderate fan blade speed, which together results in a high turbine work factor, (the ratio of specific work to blade speed squared). Two approaches were considered to improve the turbine aerodynamics, (1) gearing between the fan and fan turbine and, (2) adding a large number of turbine stages. The use of gears was abandoned because of the added engine complexity and no apparent advantage in engine weight. Figure 7 shows the effect on the work factor of adding turbine stages. The single curve shows the reduction in average stage work factor as stages are added. The shaded area represents the probable turbine efficiency. To achieve efficiencies in the 90 and above range requires six to eight stages. This was considered an excessive number of stages for a lift engine. Three stages appeared appropriate considering the trade between performance and turbine simplicity.

Engine noise. Since a total aircraft noise limit was specified in the engine requirements the noise calculations of the study were made and are given below for twelve engines. The total engine noise is made up of jet exhaust noise and rotating machinery noise. The levels of exhaust jet noise were set with the selection of the engine thermodynamics and size. The fan jet noise was calculated to be 85 PNdB and the core jet, 85.8 PNdB, for a total jet noise of 88.7 PNdB; all at a 500 ft distance. This jet noise as well as other engine noise constituents are shown by the bar graph in figure 8.

On the left hand side of the figure are shown the unsuppressed and suppressed noise levels of the fan and turbine. Two columns are shown for the fan, the aft radiated noise and the inlet radiated noise heard in the aft quadrant. As shown a 5 PNdB reduction in source noise is assumed to account for advances in engine acoustic technology between the time of this study and the 1975-80 time period when a lift engine may be demonstrated. The 19.5 PNdB noise suppression in the exhaust duct is achieved by three acoustic splitters and duct inner and outer wall treatment. It is estimated that the inlet radiated noise will be reduced 4 PNdB by the fan blade serrations and another 5.7 PNdB must be absorbed by inlet treatment such as rings. The inclusion of inlet treatment may however increase the engine depth and would require anti-icing provisions. The turbine noise is reduced from 96.4 PNdB to 83.8 PNdB by the two acoustic splitters and wall treatment.

The total noise of twelve engines is shown on the right hand side of the figure with the level depending on the amount of inlet noise treatment. If the fan inlet is treated to reduce that noise by 5.7 PNdB the total noise for twelve engines is calculated to be 96.1 PNdB. Without inlet treatment the noise is 98 PNdB. These noise levels for the integral engine and those to be discussed later for the remote fans are subject to the uncertainties of fan inlet flow conditions and cross-flow effects during transition.

REMOTE ENGINE STUDY RESULTS

The remote lift fan study included the preliminary design of a turbojet and turbofan gas generator and two fans. Both kinds of remote fan systems were designed for the same total thrust of 12 500 lb. The delivered air from either gas generator was at the same pressure level but different duct temperature. The temperature within the tip turbine scroll, however, was the same for either remote fan system. The primary difference between the two fans is their design pressure ratios, one was 1.2 and the other was 1.25. In the following paragraphs some specific details of the higher pressure ratio fan and both gas generators are given.

Lift fan. The lift fan is described in Table IV and a cutaway is shown in figure 9. The fan has a single stage nickel base alloy rotor mounted in two grease packed bearings. The rotor is supported by three equally spaced struts at the inlet. The remote fan also has rotor leading edge serrations and increased spacing between the rotor and downstream stators to minimize rotating machinery noise. The downstream fan stators support four acoustic splitters in the exhaust duct as well as the centerbody fairing. The contour of the exhaust duct provides added flow area to compensate for the splitter blockage and to control the aerodynamic loading on the fan stator.

Mounted at the tips of the fan blade is a full admission turbine. The turbine scroll is divided into two 180° sections, each fed by its own inlet pipe. The temperature of the gas in the scroll is 1508° F. The turbine inlet temperature and pressure ratio are the same with either the turbojet or turbofan supplying the pressurized gas. Downstream of the turbine blades is a diffuser where the exhaust gases are decelerated to the same velocity level as the fan flow to lower the jet noise.

The breakdown of the fan noise constituents is shown in figure 10. For these calculations it was assumed that the gas generator inlet noise is sufficiently suppressed so that it would not add to the fan noise. As in the case of the integral engine the numbers shown in the figure are for twelve fans operating at a nominal takeoff thrust of 10 000 lb. A 2.5 PNdB source reduction is assumed to account for technology advances. This assumed reduction is 2.5 PNdB less than that used in the integral engine design. This difference is due to the circumferentially leaned fan stators included in the integral engine design, that are expected to reduce the engine noise, which the remote fans do not have. The incorporation of leaned stators in the remote fans was not possible for aerodynamic and mechanical reasons. Further reduction in the aft radiated noise is accomplished by acoustically treated exit louvers, 3 PNdB, and the four acoustic splitters, 12.3 PNdB. For the inlet radiated noise in the aft quadrant fan blade leading edge serrations are planned to reduce the noise 4 PNdB and inlet treatment, if used, another 5 PNdB. On the right of the figure are shown the jet noise and total fan noise with and without fan inlet treatment.

Turbojet gas generator. The turbojet gas generator (fig. 11) is a single spool engine sized to deliver hot pressurized gases to two lift fan units. The compressor pressure ratio of 14:1 is developed in seven stages, three of which have variable stators. The compressor is driven by a single stage cooled turbine having a tip speed of 1700 ft/sec and an inlet temperature of 2140° F. A double annular combustor is used to shorten the overall engine length. Composite materials are planned for use in the variable inlet guide vane and the first three compressor stages. Additional engine information is listed in Table V.

Turbofan gas generator. The turbofan was designed as an alternate to the turbojet and offers several important system changes. While the turbojet delivers large volumes of hot gases to the lift fan turbine the turbofan delivers smaller volumes of cool gas. In addition the core flow of the turbofan may possibly be used for low speed aircraft attitude control, assisting or relieving the lift fans of this function. Also the bleed flow may be diverted after transition and used to provide cruise thrust. These apparent advantages of the turbofan, however, must be weighed against the increased complexity of the unit. A layout of the turbofan is shown in figure 12 and it is described in Table V.

The turbofan is a two spool machine incorporating technology similar to that in the turbojet. The pressure ratio in the low pressure spool is 3.64 and in the high pressure spool 3.33. The five bearings in the engine are supported by front, mid, and rear frames. Extensive use of composite materials is made in the low pressure spool blading and in the first two compressor stages of the high pressure spool.

CONCLUDING REMARKS

On the basis of the current lift engine studies a number of quantitative results may be noted. Comparison of the information contained in Tables III to V shows that dimensionally, the integral engine has a longer axial length than the remote lift fan but has a smaller overall diameter. These dimensions may have an impact depending on the installation of the lift engines in a particular aircraft configuration.

The specific fuel consumption of the turbojet-remote fan system (0.38 lbf/(hr)(lbt) and the integral fan engine (0.36 lbf/(hr)(lbt) are very similar. The turbofan-remote fan system, however, has a somewhat higher specific fuel consumption (0.48 lbf/(hr)(lbt).

The noise levels of the different lift fans are about the same and neither type has yet reached the goal of 95 PNdB at a 500 foot sideline. Additional studies must be made of inlet noise suppression of the lift fans, if they are to be used for cruise (i.e., horizontal fan axis), and the gas generators. Also the affect on the noise levels of the fans and gas generators in crossflow and with inlet distortion must be examined.

The weights of the two types of lift fans show that the integral engine is lighter. A more comprehensive comparison of weights cannot be made however, until both types of lift fans are installed in optimized aircraft configurations and the total propulsion weights determined.

The above quantitative results must now be weighed with other engine and aircraft considerations if a preferred lift engine type is to be identified. Such considerations include total installed weight of each engine type, transition performance of the engines, in-flight starting considerations, and engine control functions.

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TABLE I. - LIFT ENGINE OPERATIONAL TIMES

Engine operational segments:	
Startup, checkout, and taxi, min/flight	2
Takeoff and transition, min/flight	1
Maneuver and landing, min/flight	3
Taxi in, min/flight	1-1/2
Total time during engine life (40 000 flights)	
Startup, checkout, and taxi, hr	1333
Takeoff and transition, hr	667
Maneuver and landing, hr	2000
Taxi in, hr	1000
Total	5000

TABLE II. - ENGINE POLLUTANT LIMITS

Pollutant	Critical condition	Maximum limit
Smoke	Takeoff	Smoke No. 15 (SAE ARP 1179)
Carbon monoxide	Idle	40 lb/1000 lb fuel
Total unburned hydrocarbons	Idle	8 lb/1000 lb fuel
Nitric oxide	Takeoff	3 lb/1000 lb fuel

TABLE III. - INTEGRAL ENGINE DESCRIPTION

Fan pressure ratio	1.25
Fan hub pressure ratio	1.05
Cycle pressure ratio	10
Bypass ratio	12.6
Turbine inlet temperature, 90° day, °F	2500
Core jet velocity/fan jet velocity	1.3
Specific fuel consumption, lbf/(hr)(lbt)	0.36
Corrected fan flow, lb/sec	604
Corrected core flow, lb/sec	47
Design thrust, 90° day, sea level static, lb	12 500
Total engine noise, PNdB at 500 ft (at 10 000 lb noise rating thrust)	87.2
Noise of 12 engines (without inlet treatment)	98
Fan tip diameter, in.	57.1
Maximum engine diameter, in.	69.8
Overall length, in.	43.5
Weight, lb	1048
Thrust/weight	11.9

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TABLE IV. - REMOTE FAN DESCRIPTION

Fan pressure ratio	1.25
Bypass ratio	10
Turbine inlet temperature, °F	1508
Turbine jet velocity/fan jet velocity	1.0
Corrected fan flow, lb/sec	674
Turbine flow, lb/sec	65
Design thrust, sea level static, 90° day, lb	12 500
Total fan noise, PNdB at 500 ft (at 10 000 lb noise rating thrust)	88.2
Noise of 12 fans (without inlet treatment)	99
Fan tip diameter, in.	62.1
Maximum fan diameter, in.	87
Overall depth, in.	29.5
Overall weight, lb	805
Thrust/weight of fan	15.5

Note: The above dimensions and weight are representative of a turbojet gas generator system and will decrease slightly if the fan is coupled to a turbofan gas generator.

TABLE V. - GAS GENERATOR DESCRIPTION

	Turbojet	Turbofan
Fan pressure ratio	----	3.64
Cycle pressure ratio	14	12
Bypass ratio	----	1.9
Turbine inlet temperature, °F	2140	2350
Specific fuel consumption, lbf/(hr)(lbt)	0.38	0.47
Transfer duct gas temperature, °F	1508	350
Corrected inlet flow, lb/sec	133	190
Core flow, lb/sec	129	64.2
Maximum engine diameter, in.	38	39
Overall length, in.	71	117.8
Weight, lb	1015	1255
Auxiliary combustor weight, lb	----	185
Weight of two fans plus gas generator, lb	2625	[a]3137
Thrust/weight (no ducting)	9.5	8.0

[a]Also includes weight of auxiliary conbustors for two lift fans.

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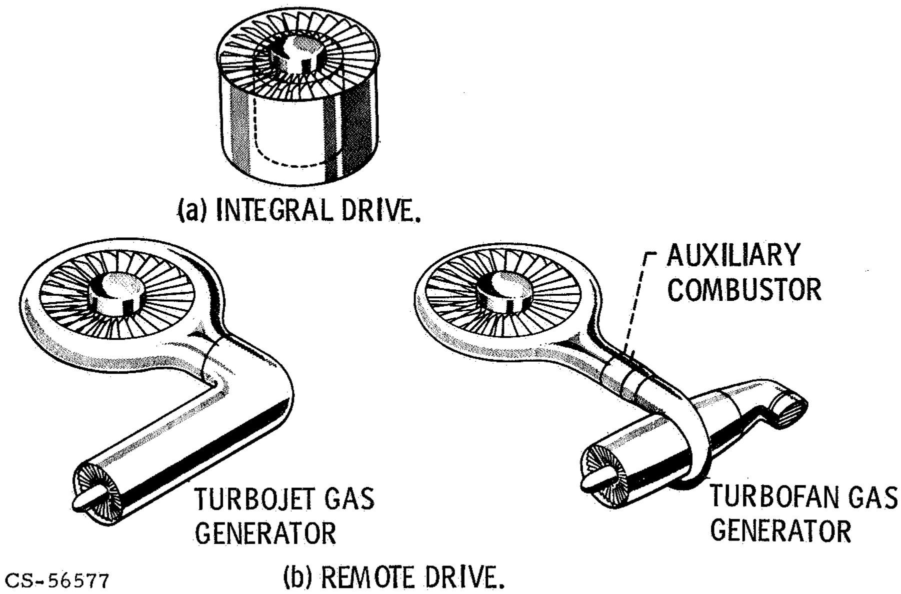

Figure 1. - Lift fan engine types.

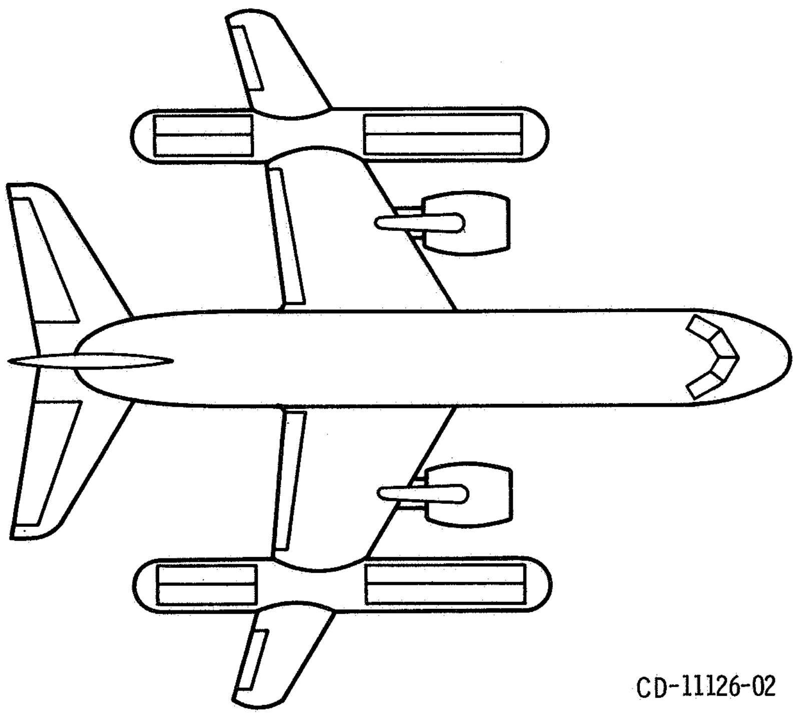

Figure 2(a). - VTOL Airliner concept utilizing integral engines for lift and separate engines for cruise.

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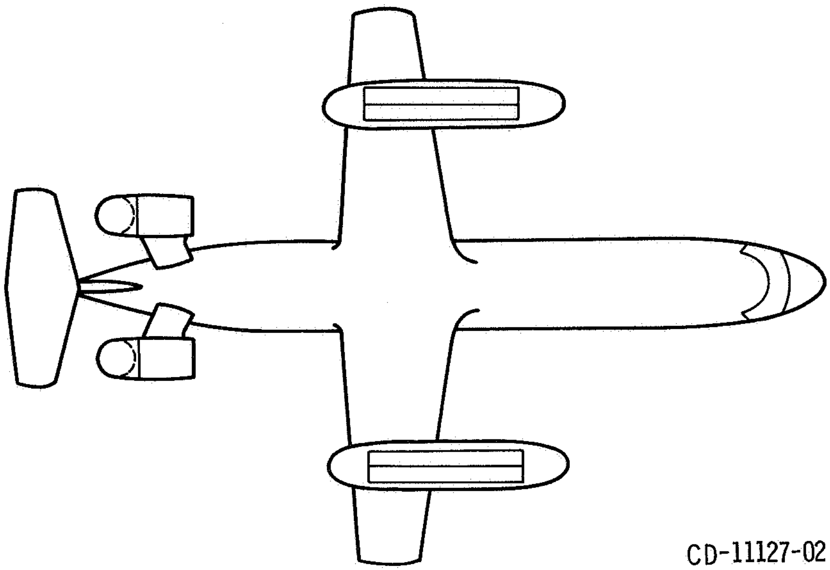

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Figure 2(b). - VTOL Airliner utilizing integral engines for lift and cruise.

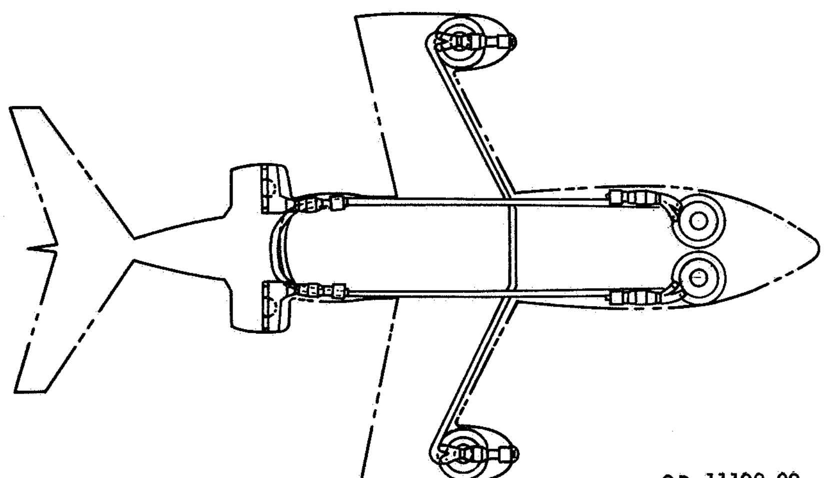

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Figure 3(a). - Airliner concept with remote fans used for lift and cruise.

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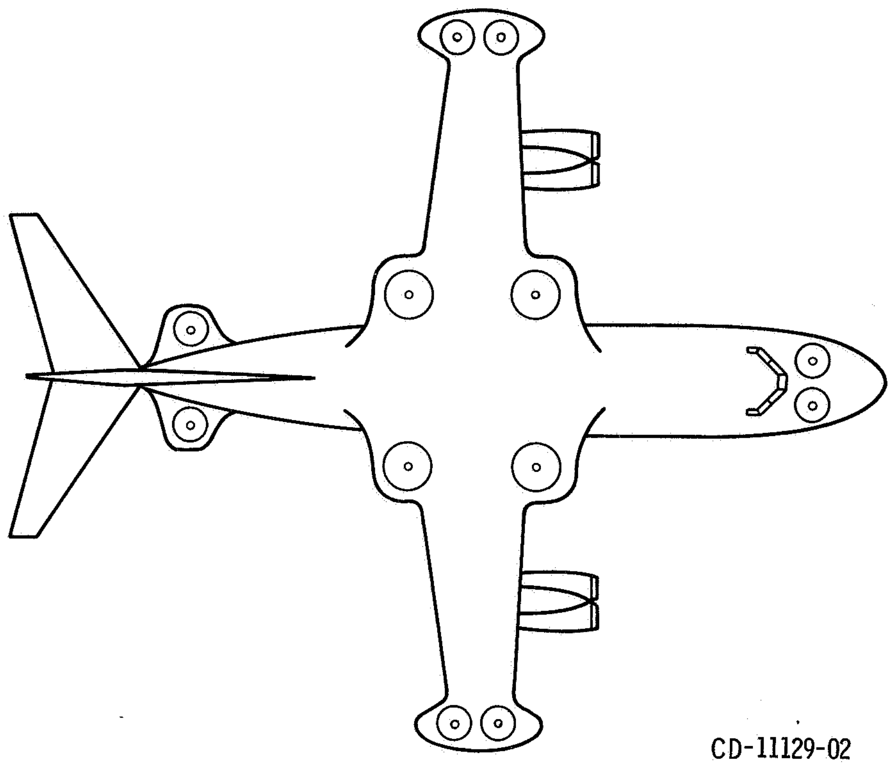

Figure 3(b). - Airliner concept with remote fans used for lift and gas generators used for cruise.

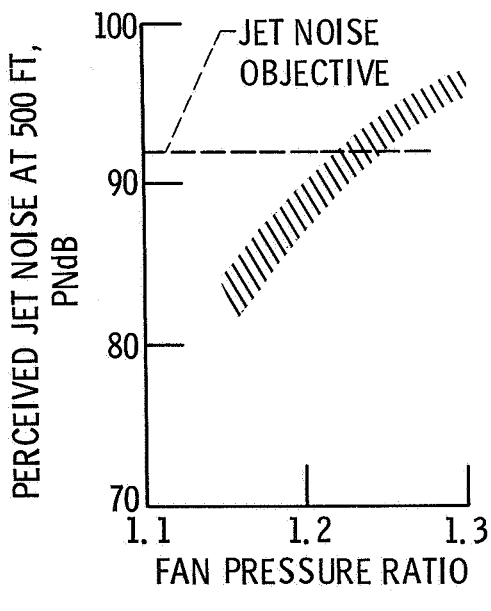

Figure 4. - Exhaust jet noise variation with fan pressure ratio, 120 000 lb total thrust.

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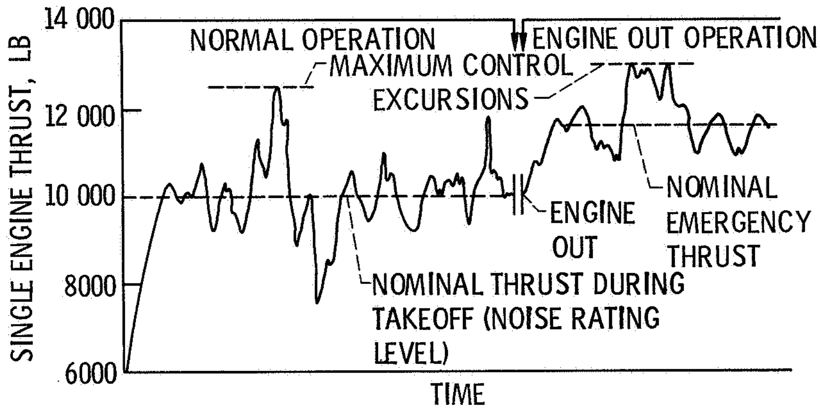

Figure 5. - Lift engine thrust variations.

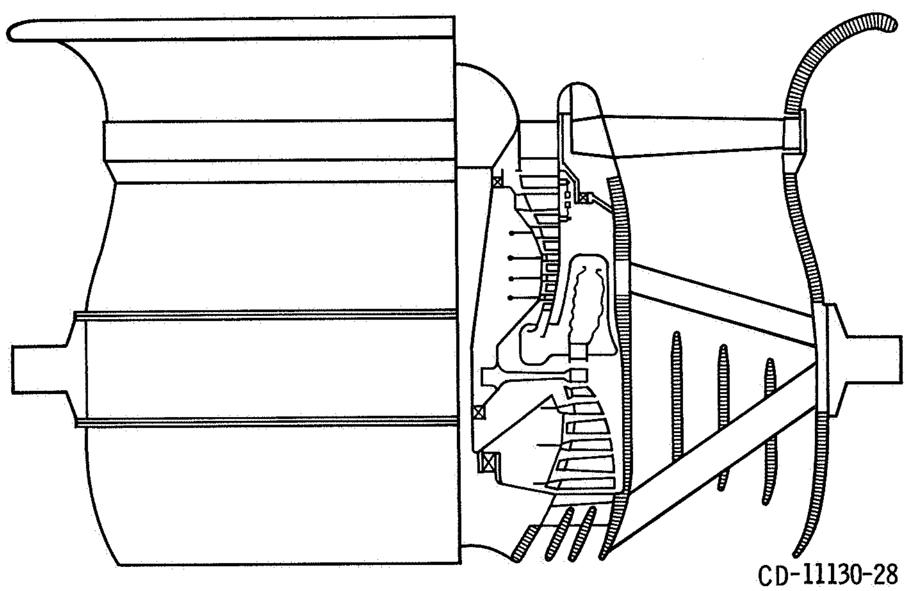

Figure 6. - Integral lift engine.

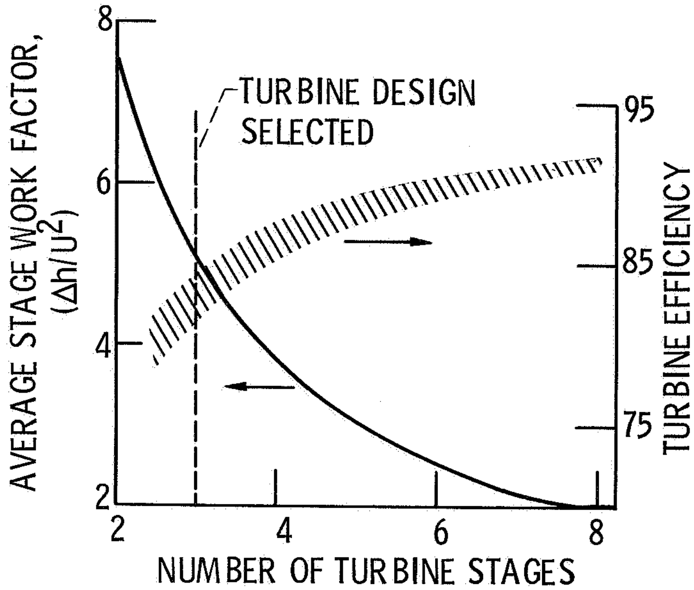

Figure 7. - Fan turbine loading and efficiency characteristics.

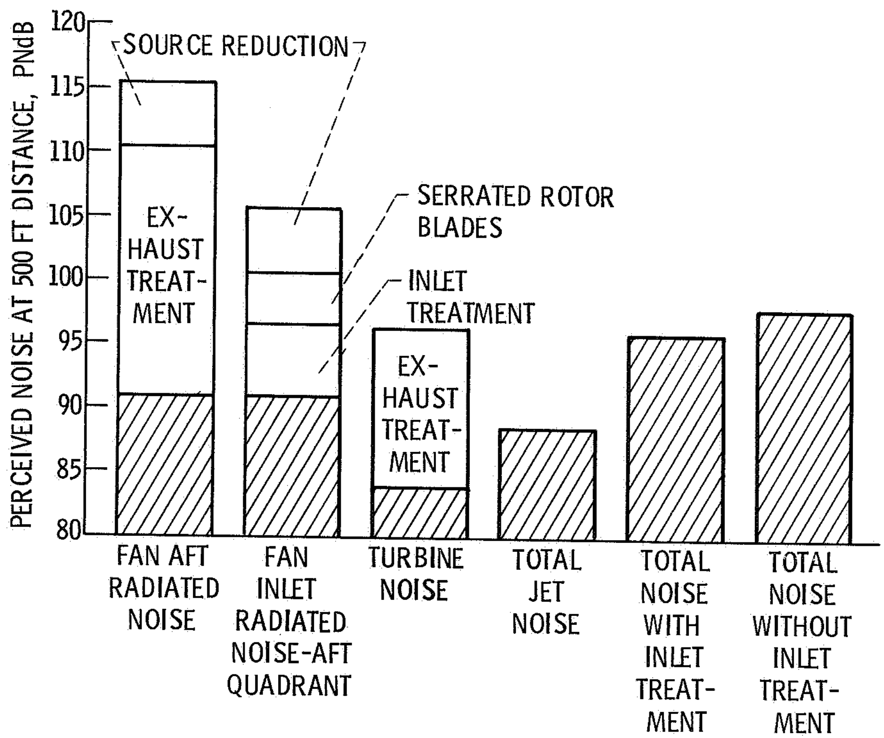

Figure 8. - Integral engine noise constituents, 12 engines, 10 000 lb thrust each.

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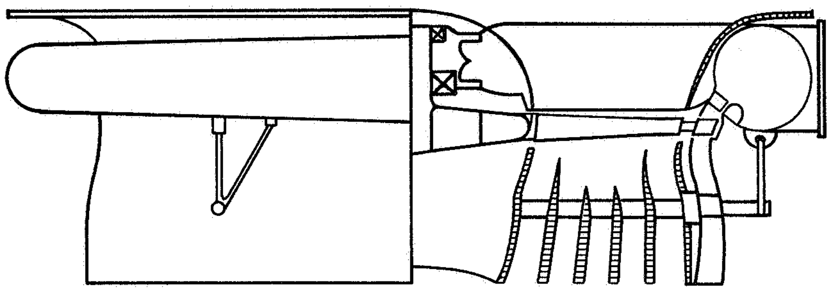

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Figure 9. - Remote lift fan.

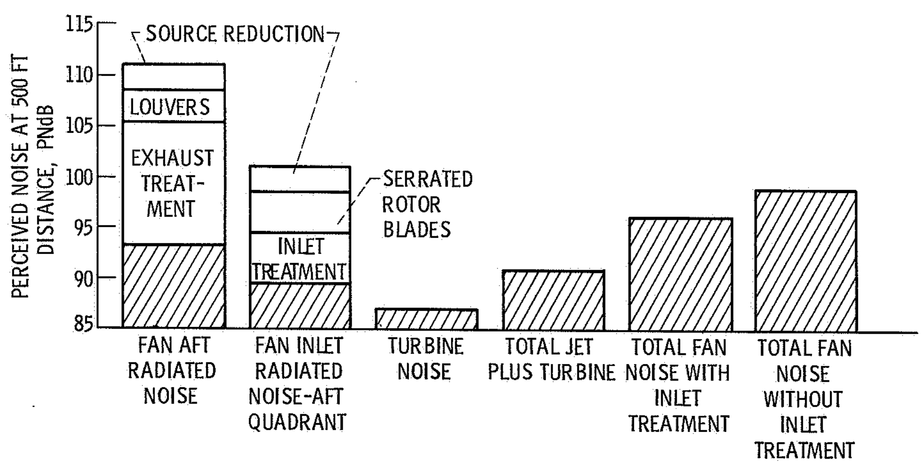

Figure 10. - Remote fan noise constituents, 12 fans, 10 000 lb thrust each.

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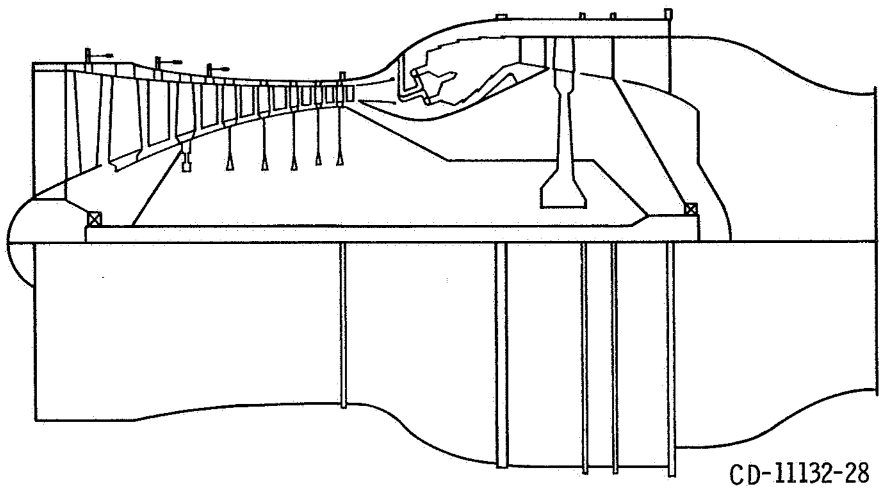

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Figure 11. - Turbojet gas generator.

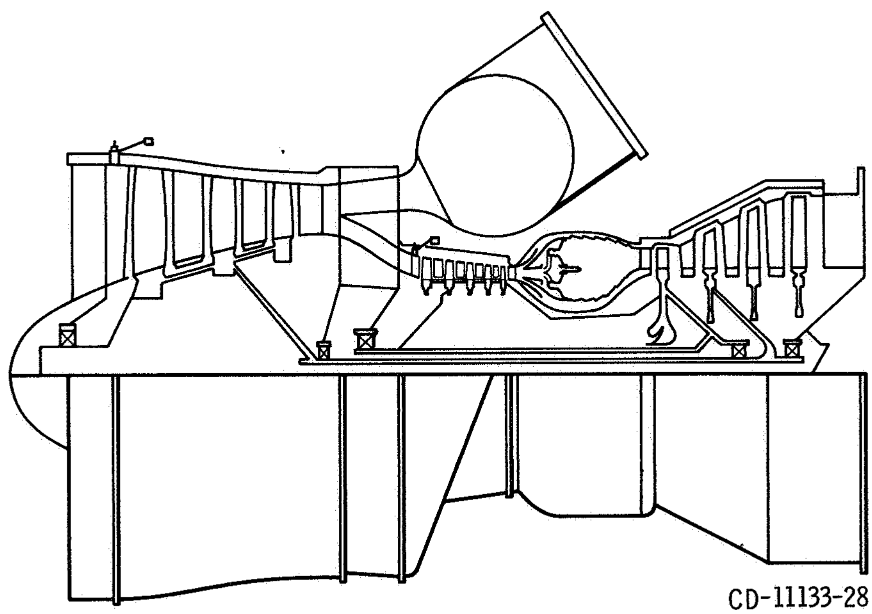

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Figure 12. - Turbofan gas generator.