Geared Fan Engine Systems—Their Advantages and Potential Reliability

T. A. Lyon* and R. D. Hillery†
Detroit Diesel Allison Div. of General Motors, Indianapolis, Ind.

Studies indicate that a reduction in aircraft noise is attainable through the use of high-bypass-ratio, low-fan-tip-speed turbofan propulsors. The weight and installation penalties associated with high-bypass-ratio, direct-drive engines could be reduced significantly by incorporating a small, high-speed turbine to drive the fan through a reduction gear system that is designed to current criteria as represented by the Allison T56 reduction gear planetary system. Operational experience with the T56 reduction gear indicates that the addition of a geared fan drive system will not compromise engine reliability.

Introduction

NOISE pollution is receiving ever-increasing attention from the American public and numerous legislative bodies. Commercial aircraft noise is already subject to federal legislation administered through stringent FAA certification requirements. The requirements of further reductions in aircraft noise, particularly for short takeoff and landing (STOL) aircraft, are practically assured, and maximum noise levels of from 90 to 95 PNdB may very well become a standard for future commercial aircraft. To maintain a healthy and expanding air transportation industry within these projected noise requirements, the aircraft engine designer will have to meet the challenge of developing viable, quiet engines.

Studies have indicated that the use of very high-bypass-ratio, low-fan-tip-speed turbofan propulsion systems can effectively contribute to a considerable reduction of aircraft noise. These engines are characterized by large fans which operate at a relatively low speed—a characteristic which, if imposed on the fan drive turbine, could result in weight- and installation-related penalties.

It is feasible, however, to design a low-weight, high-speed fan turbine and to drive the fan through a geared speed reducer similar to current propeller reduction gear planetary systems. This approach provides the flexibility to optimize the turbine design and could result, depending on by-pass ratio and/or fan tip speed, in a considerable engine weight reduction from that of a direct drive configuration.

In this paper, the low noise potential of very-high-bypass-ratio turbofan engines is reviewed. Moreover, it is shown that geared turbofan engines will provide a decided weight advantage over direct drive configurations with comparable reliability and that the required gear system is within the existing gear design state of the art.

Low Noise Potential

Turbofan engine noise is generated by three primary sources: the fan, the fan jet, and the primary jet. These sources, although acoustically independent, are linked by their dependence on engine cycle parameters—fan pressure ratio, bypass ratio, fan tip speed, etc. Figure 1, i.e., shows the dependence of exhaust jet noise on fan pressure ratio and bypass ratio. As fan pressure ratio decreases, the fan jet and primary exhaust jet velocities decrease. As a result, the jet exhaust noise is reduced considerably. A decrease in fan pressure ratio requires an increase in engine bypass ratio if optimum cycle performance is to be maintained. Jet noise is produced external to the engine due to aerodynamic turbulence, and velocity. This is best accomplished by increasing bypass ratio as previously discussed.

The remaining critical engine noise—fan mechanical noise—is strongly dependent on fan blade relative velocity (Fig. 2). Forward as well as rear arc noise is reduced with a decrease in blade relative velocity. As fan pressure ratio is reduced (by increasing bypass ratio), fan relative tip speed can be reduced to effect a reduction in fan broadband forward and rear arc noise.

Figure 3 is indicative of the noise reduction potential of high-bypass turbofans. Note that a bypass ratio of 10 or more will be required to meet an aircraft noise goal of 95 PNdB.

In view of this noise reduction potential, several direct- and gear-driven high-bypass-ratio turbofan engines were designed and weighed for comparative mission and reliability analyses. The results of these analyses are presented in this paper.

Engine and Reduction Gear Design

The preliminary design study included six engines in the 20–25,000-lb thrust class. Direct-and gear-driven engine configurations at bypass ratios of 8, 10, and 13 were designed and analytically weighed. All engines were configured to incorporate a common gas generator, and all geared fan engines made use of a common fan turbine, indicative of the degree of flexibility available with a geared fan design approach. The direct- and gear-driven fan tur-

Table 1 Reduction gear design criteria

Gear life	Infinite
Gear type	Helical
Helix angle	14°
Gear material	AMS-6265
Maximum pitch line velocity	21,000 ft/min
Maximum crushing stress	160,000 psi
Maximum bending stress	35,000 psi

Presented as Paper 72-1173 at the AIAA/SAE 8th Joint Propulsion Specialist Conference, New Orleans, La., November 29–December 1, 1972; submitted December 21, 1972; revision received March 23, 1973.

Index categories: Aerodynamic and Powerplant Noise (Including Sonic Boom); Aircraft Powerplant Design and Installation; Aircraft Propulsion System Noise.

*Senior Project Engineer.
†Program Reliability Engineer.

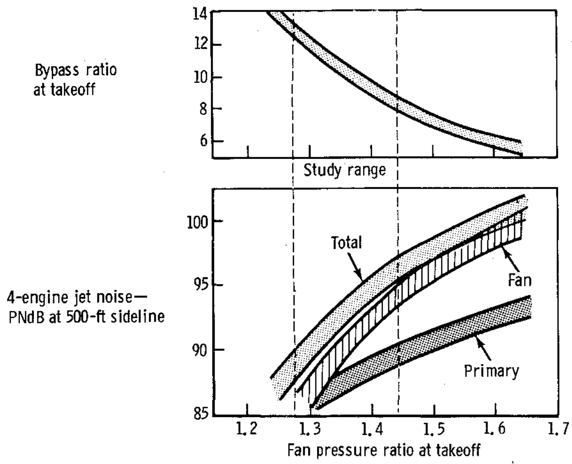

Fig. 1 Jet noise as a function of fan pressure ratio and bypass ratio.

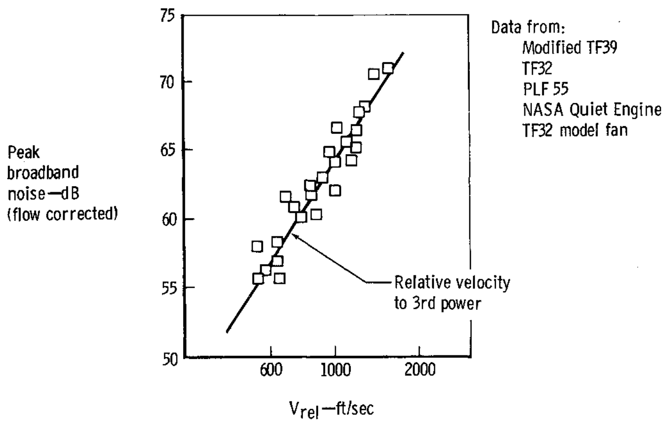

Fig. 2 Normalized broadband fan noise (rear arc)—225 ft radius.

bines were designed to identical criteria. Selected fan and reduction gear design requirements are shown in Fig. 4.

The design of the reduction gear sets embodied certain gear design criteria (Table 1) which were based on operational experience with the reduction gears of the Allison T56 series of turboprop engines. The adequacy of the material and stress criteria is demonstrated in Fig. 5, which indicates that the design stress levels have resulted in gears capable of infinite life.

The 14° helical gearing was used to minimize gear noise and vibration. In all cases, the helix "hand" was selected to assist in balancing the fan and turbine system thrust loads, thereby reducing the load requirements imposed on the rotor thrust bearings. This design approach

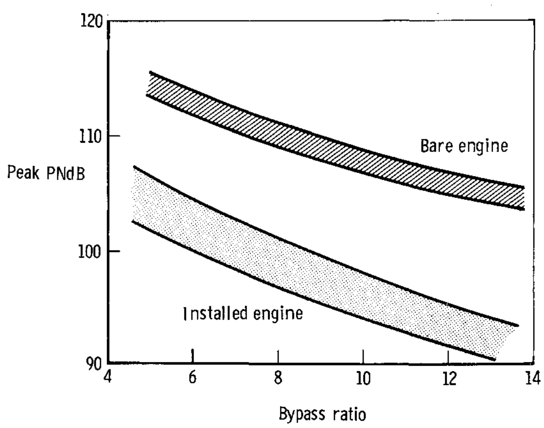

Fig. 3 Four-engine noise levels at 500-ft sideline, 25,000-lb thrust class.

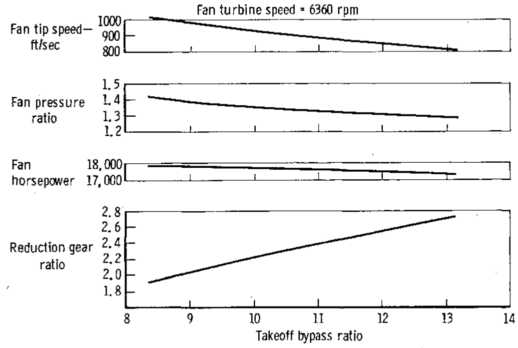

Fig. 4 Engine and reduction gear design requirements.

has been successfully applied in the Model T56-A-18 planetary reduction system. Figure 6 shows the spur and helical planetary gear and bearing systems used in T56 reduction gears.

The reduction gear sizes, stresses, bearing lives, etc, for each study engine and existing T56 planetary reduction systems are compared in Table 2. Note that the gear system for each study engine is within existing state-of-the-art design capability as represented by operational T56 gear systems. This fact lends considerable credibility to the gear system weights used in the mission analysis.

Figure 7 is a comparison of direct- and gear-driven fan configurations at an 8:1 bypass ratio; the difference in fan turbine diameter and length is discernible. An engine weight comparison for the two configurations (Fig. 8) indicates that the direct-drive engine is 11% heavier than the geared-drive engine. A similar comparison was made at 10:1 and 13:1 bypass ratios; Fig. 9 shows the results for the 13:1 bypass ratio engine. The direct-drive engine also outweighed the geared-drive engine by 11%. Engine thrust-to-weight ratios of the direct- and geared-drive configurations are plotted in Fig. 10.

Clearly, the application of state-of-the-art gear design expertise will provide high-bypass geared turbofan engines with a considerable weight advantage over similar direct-drive engines. The following mission analysis results will establish the significance of this weight advantage.

Mission Analysis

Each study engine configuration was "installed" in a given aircraft and analytically "flown" over a typical STOL short-range mission. Aircraft gross weight at constant mission payload was calculated for each engine configuration and used as the figure of merit. The results of the mission study are plotted in Fig. 11.

As stated previously, bypass ratios in excess of 10:1 will be necessary to attain the aircraft maximum noise goal of 95 PNdB. Figure 11 indicates that in the bypass ratio range of interest, the use of a direct-drive engine instead of a geared fan configuration will increase the aircraft gross weight by approximately 3%.

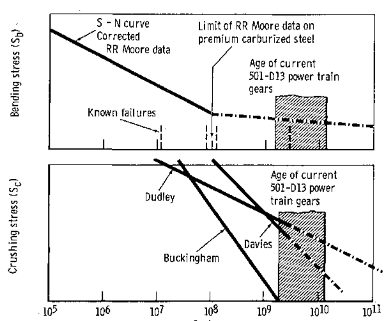

Fig. 5 Allison aircraft gears.

Table 2 Reduction gear comparison

	T56/501-D13	T56-A-18	Engine 1	Engine 2	Engine 3
Bypass ratio	...	...	8.0	10.0	14.3
Type of gear arrangement	Spur epicyclic	Helical epicyclic	Helical star	Helical star	Helical star
Gear ratio	4.33	3.30	1.90	2.34	2.75
Output torque, in.-lb	308,000	340,000	376,000	462,000	555,000
Crushing stress, psi (sun to planet)	160,000	144,000	160,000	160,000	160,000
Bending stress, psi (sun to planet, HPSTC)	23,800	21,000	26,000	31,540	33,600
Planet bearing type	Spherical	Inverted spherical	Inverted spherical	Inverted spherical	Inverted spherical
Planet load, lb	11,420	9,600	8,540	14,000	18,600
Planet bearing life, B_{10} hr	425	430	700	700	700

Table 3 Part failures causing T56 premature reduction gearbox removals from U.S. Navy T56 engines[a]

Part name	−7	−10W	−14	−16	per 1000 hr
1) Planet gear and bearing assembly			2		0.00137
2) Planet rear carrier bearing		2	1		0.00206
3) Sun gear					
4) Planet gear		1			0.00069
5) Ring gear					
Parts not applicable to gear drive for turbofan	8	72	60	26	
Totals	8	75	63	26	0.08378
Engine flight hours	108,772	597,110	544,588	207,512	

[a] Includes all −7, −10W, −14, and −16 failures from Jan. 1, 1969 through Dec. 1970.

Of course, if the incorporation of a reduction gear system were to result in a significant decrease in engine reliability, the weight advantage would be to no avail. Therefore, to determine the effect of the reduction gear system on total engine reliability, an in-depth reliability analysis was undertaken. This analysis and its results are discussed in the following paragraphs.

Reliability Study

The following approach was taken in making the reliability study. A common reliability tool—mean time between removals (MTBR)—was used as the reliability index.

1) Estimate geared-drive element reliability from service history records of similar T56 gearbox elements, adjusting for differences in speed and load.
2) Estimate reliability differences between the large, low-speed turbine and the smaller, high-speed turbine.
3) Utilize reliability history, apportionments, and estimates for the more conventional features, especially for those features common to both concepts.

As the first step, the elements of the T56 gearbox that are similar to the elements of the gear-drive system were identified. Next, the reliability values of those elements were extracted from the over-all gearbox reliability.

The elements of the T56 gearbox which were selected to constitute the baseline for estimating the geared drive reliability are shown as the darkened portion of Fig. 12. The circled numbers identify the functional pieces listed in Table 3, which is a summary of reliability history. The data of Table 3 represent the premature removal events of Navy T56 gearboxes chargeable to gearbox parts. The engine flight hours represented by this list total nearly 1.5 million hr for the 2-yr span.

Fig. 6 T56 planet gears.

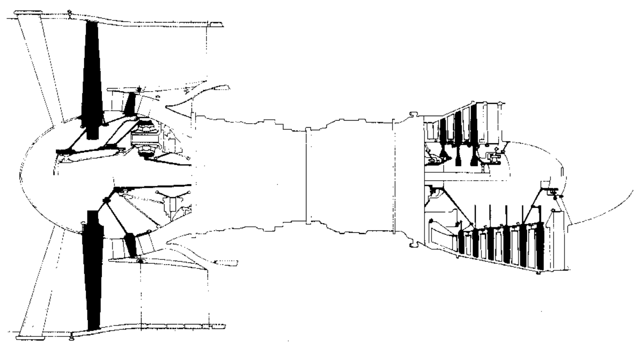

Fig. 7 Composite general arrangement—direct and gear driven fan configurations.

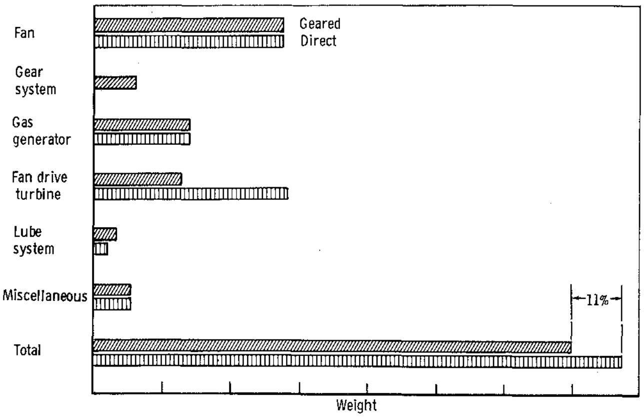

Fig. 8 Component weight comparison—8:1 bypass ratio configuration.

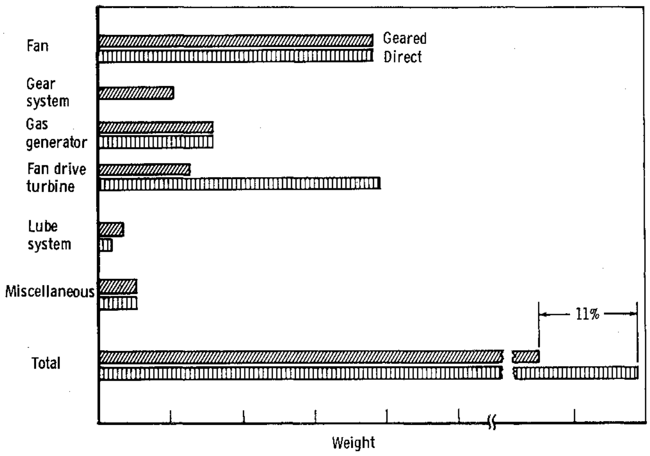

Fig. 9 Component weight comparison—13:1 bypass ratio configuration.

The MTBR of the entire gearbox was 12,000 hr for all confirmed events. This exceptional reliability record was established with time between overhaul (TBO) periods ranging from 4000 to 5000 hr.

Evident from the data of Table 3 is the fact that the common elements have caused very few removals and, therefore, have a very high reliability. These common parts (with the same identifying numbers) are listed in Table 4 with the adjustment factors used to adjust the T56 service history to the geared drive estimates to allow for the possible effects of such elements as speed differences and mounting. The resulting rate for these elements was estimated to be 0.0166 removals per 1000 engine flight hours or an equivalent MTBR of 60,000 hr.

The thrust bearing requirements for the geared-drive concept are more severe because the fan and the turbine call for separate thrust bearings. The arrangement of the direct-drive system permits mutual thrust balancing to reduce total bearing thrust loads. An extra assessment for

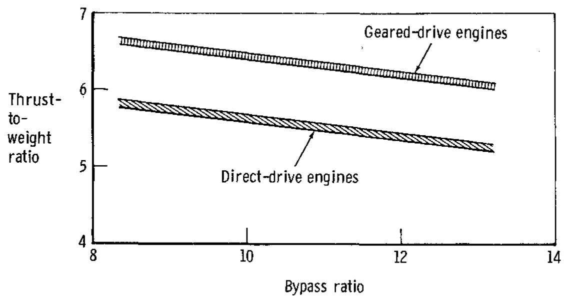

Fig. 10 Thrust-to-weight ratios for direct- and geared-drive engines.

Table 4 Geared fan components

Part name	Historical rate, removals/1000 hr	Speed-load adjustment factors	Resulting estimated rate, removals/1000 hr
1) Planet gear and bearing assembly	0.0019	2.8	0.0053
2) Ring gear carrier bearing	0.0029	2.8	0.0081
3) Sun gear	0.0003	2.04	0.0006
4) Planet gear	0.0010	2.04	0.0020
5) Ring gear	0.0003	2.04	0.0006
Total for these elements	0.0064		0.0166

Table 5 Comparison of failure rates

	Failures/1000 hr					
	Geared fan (total: 0.0202)			Direct drive (total: 0.0208)		
	Wheel	Vanes	Blades	Wheel	Vanes	Blades
1st stage	0.0009	0.0090	0.0050	0.0006	0.0090	0.0035
2nd stage	0.0008	0.0010	0.0010	0.0005	0.0010	0.0007
3rd stage	0.0006	0.0010	0.0009	0.0005	0.0010	0.0006
4th stage	...	...	...	0.0004	0.0004	0.0006
5th stage	...	...	...	0.0003	0.0003	0.0005
6th stage	...	...	...	0.0003	0.0002	0.0004

a fan thrust bearing was therefore made for the geared-drive arrangement. The mounting and lubrication schemes are conventional.

The technical features of the direct-drive and the geared-drive engines differ from those of current turbofan engines in ways other than the high bypass blading. The fan turbine for the direct-drive engine would be much larger in diameter, have twice as many stages, and be heavier. The turbine-to-fan shaft also would be heavier.

Cycle studies have indicated that a three-stage turbine is needed for an 8:1 BPR gear-driven fan. Similar studies have shown the need for a six-stage turbine for an 8:1 BPR direct-driven fan. A comparison of the two turbine

Table 6 Reliability comparison–geared-drive and direct-drive 8:1 bypass-ratio turbofan engines

	Geared drive	Direct drive
Time between overhaul (TBO) period, hr	3000	3000
Design life, hr	12,000	12,000
Premature engine removals/1000 hr		
common sections (compressor, hp turbine, combustion, accessories, and drives)	0.4000	0.4000
fan section		
gears and bearings	0.0166	0
thrust bearing	0.0200	0.0100
common	0.0400	0.0400
LP turbine section		
thrust bearing	0.0003	0
blades, vanes, wheels[a]	0.0202	0.0208
common	0.0292	0.0292
Total removal rate	0.5263 (105%)	0.5000 (100%)
Mean time between removal (MTBR), hr	1900	2000

[a] From Table 5.

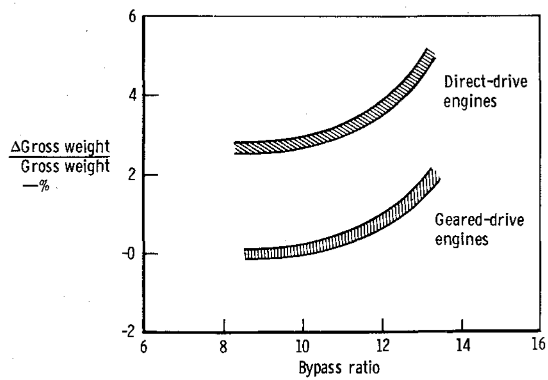

Fig. 11 Mission study results for high-bypass turbofans.

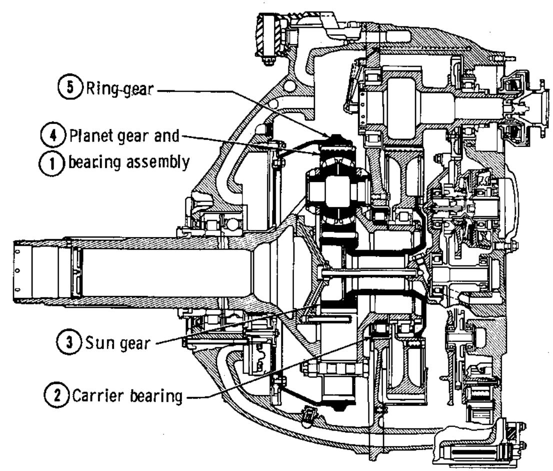

Fig. 12 Location of common elements in T56 reduction gearbox.

concepts for failure rate differences disclosed that the estimated failure rates were practically equal. The higher predicted failure rates for the detail parts of the 3-stage turbine were offset by the lower individual part failure rates of the 6-stage turbine, although the latter has more parts.

The detail results for turbine wheels, vanes, and blades are listed in Table 5. The remaining fan-turbine parts were estimated to account for 0.03 additional removals per 100 hr. The extra thrust bearing for the geared-drive version added an estimate of 0.0003 removals per 1000 hr.

The nominal 0.050 removals per 1000 hr for the fan turbine compares with an estimated 0.100 rate for the common high-pressure turbine. The resultant turbine rate (low pressure + high pressure) is 0.150. In comparison, recent three-year T56 turbine removal rates ranged from 0.095 to 0.177.

The unique features of the two concepts are essentially restricted to the low-pressure rotor system. The core or gas generator system would be the same for both concepts. Therefore, the reliability index for the gas generator would not be a variable dependent on the concept. Military operation, which was the basis of estimates for this study, would bend to produce higher engine removal rates than commercial airline operation. A review of domestic airline experience indicates turbine removal rates of 0.08 to 0.12 for JT8D, Spey 511, CJ 805, and JT3D engines.

Similar correlation exists in the rates estimated for the remaining portions of the engines which would be common between the two concepts.

The estimates for the common and the different portions of the geared-drive and direct-drive, high-bypass, low-noise turbofan engines in military transport application are listed in Table 6.

The results of the reliability study indicate that the geared-drive turbofan engine would have a reliability index almost as high as that of the conventional, straight-drive turbofan engine with the larger, low-speed turbine. The MTBR for the geared-drive engine was estimated to be 1900 hr and that for the direct-drive engine 2000 hr—a 5% difference.