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A HYDRODYNAMIC TURBO-FAN/SHAFT CONVERTIBLE ENGINE

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ABSTRACT

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Advanced powered lift aircraft will require greater translational flight speed to render themselves economically competitive with other future modes of transportation. Initial and operational costs of such aircraft may be reduced significantly by effective consolidation of the various propulsion schemes into a minimum number of prime movers. Such is the motivation behind the concept of the "convertible" engine.

The most common current perception of the convertible engine is a standard configuration turbofan which incorporates aerodynamic devices to redirect the engine's low-pressure-spool shaft-power to an appropriate power takeoff on the engine structure. The available mechanical shaft-power is directed to the VTOL aircraft lift system during the lift-off or landing operations.

The use of a hydrodynamic drive on the low-pressure-spool may present certain engine design, installation, and operational advantages for future vertical lift aircraft. By this system, a compact transformation of a standard configuration turbofan engine can be designed wherein the fan component is operated by a variable geometry hydrodynamic drive unit. This device is directly driven by the two-spool turbofan engine low pressure gas turbine. Actuation of the variable geometry can provide a wide variety of operating modes by controlling the fan speed. As the fan speed is reduced, the gas turbine power is made available on an appropriate mechanical power takeoff for vertical powered lift operation. Power deviation is variable from all thrust-no mechanical power, to all mechanical power-no thrust, and all points in between. A resultant advantage of this system over others is that no residual power consumption need be endured in either of the extreme power deviation modes.

Nomenclature

RSRA	Rotor Systems Research Aicraft
QSRA	Quiet Short-haul Research Aircraft
ABLE*	Advanced Blown Lift Enhancement (*Trademark-General Dynamics Corporation)
PTO	Power Takeoff
HDU	Hydrodynamic Unit
SLS	Sea Level, Standard Day
QCGAT	Quiet Clean General Aviation Turbofan
SR	Converter Speed Ratio
TR	Converter Torque Ratio
KR	Converter Relative Capacity Ratio

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I. INTRODUCTION

As thoughts were directed to rotary wing aircraft achieving high translational flight speeds, it was evident that much more power, installed on the proper thrust axis, would be necessary to achieve the high speeds. This was accomplished by mounting additional engines as feasibility permitted. A prime example of this approach is the NASA RSRA, the X-wing prototype, which has 4 engines installed; two turboshaft engines for the rotor and two turbofan engines for horizontal thrust. However, rationality was always evident for such high speed machines and the idea of a "convertible" engine was immediate. With power installed by a minimum number of power generators sufficient to perform both the vertical and horizontal phases of a flight mission, the addition of mechanical features to transform the installed power to its appropriate mode would be greatly more economical in terms of overall aircraft complexity, operating cost, and weight. Over the course of time, different configurations of convertible engines have been proposed (1)*.

Besides the rotary wing aircraft types proposed for high speed flight (i.e., ABC, X-wing, folding tilt rotor, (Fig. 1), powered lift concepts such as the NASA "QSRA" (2) and General Dynamics "ABLE" (Fig. 2) (3) can effectively use convertible engine capabilities to augment their flight envelopes. Both QSRA (an operational flight demonstrator) and ABLE (advanced concept) use high bypass ratio turbofan engines for both VSTOL capability and high speed forward flight. At flight speeds below which conventional aerodynamic surfaces lose control power, convertible engines, for instance, could perform roll control functions for such aircraft by creating non-homogeneous lift distribution on the aircraft wing surface.

By present convention, a convertible engine is an essentially standard configuration high bypass ratio turbofan type thrust producing engine which has provisions for a mechanical power takeoff to operate a mechanical system; namely a helicopter type rotor. All proposed convertible engines make use of mechanical schemes and arrangements to unload or underpower the fan and thereby make shaft power available. Some of these systems require extensive modification to the engine hot section (4); others require specially designed fan components (5). The engine proposed in this paper would not require specifically designed aerodynamic engine components; only adaptive machinery is necessary.

*Numbers in parentheses indicate references listed at the end of the paper.

II. CONCEPT

Certain underlying objectives must always be considered in approaching any new concept. For this study the objective was to create the most effective overall design to perform the convertible engine functions with a minimal of change to the basic turbofan configuration. The design was to exhibit low cost-increase potential, have high flexibility in terms of performance, and have a convenient architecture relative to power takeoff (PTO) location, c.g., engine mounting to airframe, inlet/exhaust, etc. In this case a number of features have been blended into a particular configuration resulting in a compact, effective design.

The prime criterion in establishing this proposal was to integrate proven component configurations into a "clean", feasible, and demonstrable product. As will be shown, this was accomplished by starting from the proven concept of the geared turbofan engine; some examples of which are the Textron Lycoming ALF502 (Fig. 3), Garrett TFE731, and Textron Lycoming ALF101 (experimental) (6). Besides their important basic advantages of compactness and light weight so important to vertical lift aircraft, the geared fan engine offers a key feature of facilitating the mounting of the key element, the hydrodynamic unit (HDU), within the fan hub spinner and provides a convenient torque converter stator grounding means through the reduction gear planet carrier. For various marketing and size convenience reasons, the class of interest for this study was for a convertible engine having nominal performance of 1600 lbs./3585 dN thrust (SLS static) and as a turboshaft of 1200 SHP/895kW (SLS Static).

The individual components are now briefly reviewed with particular emphasis on "convertible" features (Fig. 4). The convertible engine is made up of two basic modules, the core engine and the fan module.

1. Core Engine

The basic prime mover for this engine is representative of the latest technology available in the class of interest selected, such as the U.S. Army/Textron Lycoming-Pratt & Whitney T800-APW-800 turboshaft (Fig. 5). Some nominal specifications of this engine are (7):

Power	895kW	1200 SHP
Specific Fuel Consumption	283 g/kWh	.465 lbs./HP-hr
Weight	135 kg	298 lbs.
Mass Flow Rate	4 kg/s	8.8 lbs./sec
Pressure Ratio	15:1	

The core engine, which by this definition includes the low pressure or power turbine, is mounted directly to the fan module. The low pressure turbine shaft passes through the gas generator into the main transmission, which is housed within the fan frame.

2. Fan Module

Besides an essential accessory gearbox, which is not a part of this discussion, the entire "rest-of-engine", beyond the core, is constituted by the fan module (Fig. 4). This module consists of:

a. Fan Frame
b. Fan Rotor
c. Fan Rotor Brake
d. Main Transmission
e. Power Takeoff/Cross Shaft Provision
f. Power Takeoff Clutch
g. Hydrodynamic Unit
h. Fan Hub Spinner

a. Fan Frame

The fan frame is the major structural element of the engine from which the entire rest-of-engine is supported and through which the engine mounts to the airframe. The fan frame contains co-axial annular passages for fan exhaust air and core supply air. The main transmission is housed at the center of the fan frame.

b. Fan Rotor

The fan rotor absorbs power from the low pressure turbine converting such to horizontal thrust. About 10% of fan flow is directed to supply air to the core engine. The fan would be of a moderate pressure ratio and can provide high thrust at low vehicle speeds and furnishes highly efficient medium Mach cruise performance. Experience of the Textron Lycoming ALF101 turbofan, the NASA QCGAT demonstrator (6), is applicable to this design.

It is emphasized that the fan is a conventional design with no variable geometry blades, stators, nor any inlet guide vanes. Thrust is modulated by varying the speed of the fan. Thus, the quietness features of the engine are fully retained with this design and are not compromised by parasitic churning losses (5).

c. Fan Rotor Brake

Means are provided for this device to prevent fan rotation as may be desired for certain in flight operations.

d. Main Transmission

The main transmission is essentially a power divider which takes the single power input of the low pressure turbine and directs it toward both the propulsion fan and the mechanical power takeoff (PTO) on the outside of the fan frame.

The fan reduction gear is a planetary type with input by a sun gear on the turbine shaft and output by the ring gear. The planet carrier is locked to the fan frame. A central grounding shaft, essential to the operation of the torque converter, is mounted to the fixed carrier and extends to the center of the HDU.

e. Power Takeoff/Cross Shaft Provision

On the outside of the fan frame the shaft power takeoff (PTO) is available by means of a simple bevel gear set on the turbine shaft. A second bevel gear leading to an output on the opposite side of the fan frame is available for cross shafting to multiple wing-mounted engines on VSTOL powered-lift aircraft.

f. Power Takeoff Clutch

Depending on the aircraft type and its utilization, this clutch will be necessary for autorotation, locked rotor operation (X-Wing), or stowed rotor (folding tilt rotor) flight.

g. Hydrodynamic Unit

The primary element of the system, and one one which makes this convertible engine concept possible, is the hydrodynamic torque converter. Already widely used in automotive traction applications, the torque converter, by its inherent design, effectively performs the function of an infinitely variable speed ratio hydraulic transmission. By controlling fan speed with the torque converter while the low pressure turbine speed remains essentially constant, the turbine power is effectively transferred from the fan to the shaft power takeoff.

The hydrodynamic unit (HDU) in itself is an example of a particular technology and product evolution. For the purpose of this study, limitations were imposed to evaluate what has become the conventional, rotating housing, three element, single stage torque converter. In a practical sense this is also the most rational, since its efficiency is highest (Fig. 6) in the performance zone where the highest power is transmitted. SAE 830575 (8) studies performance matching of the torque converter to the gas turbine engine.

Sizing the Hydrodynamic Unit

A particular significance to this engine is the size of the HDU, because this is the major concern to the feasibility of the entire concept. The HDU had to fit within the fan spinner and simultaneously be able to transmit the required fan power. A converter match typical of C-51 (8) was selected from a study of series of different converter blade geometries. The result of this study is that the converter application is feasible. A 10¼ in./26 cm diameter torque converter will fit in the fan spinner and drive the fan to the nominally selected 95% fan speed (Fig. 7). For cruise flight conditions the direct drive clutch engagement brings the fan to 100% speed.

Performance Range

For the automotive traction application, the torque converter is inherently load sensitive and will automatically change speed ratio in response to load change. For this case, where the load (fan) is a fluid dynamic machine similar to the converter itself and where we are attempting speed control of the load independent of energy input (i.e., gas generator power), it is necessary to alter the power absorption capacity of the converter; which then naturally results in a power output change and consequently a fan speed and resultant thrust change. This power absorption variability is performed by varying the converter internal geometry; most easily done with the proven variable pitch stator (Fig. 8).

Figure 7 shows the variable availability of power to the fan rotor with changing stator position. The steady-state stator reset operating schedule follows the locus of the fan required power curve. Abrupt stator opening toward the high position makes power available for fan rotor acceleration by the vertical difference between the output power available curve and the fan required power. Closing the stator effectively throttles the converter circuit, instantaneously reducing fan input power and consequently fan thrust. Naturally, since the power output of the power turbine is constant for any gas generator condition, the shaft PTO load would have to be varied (i.e., collective pitch) to obtain the expected change in fan thrust.

Figure 9 shows the enormous accelerating torque potentially available to accelerate the fan from stopped or idle conditions; thus assuring rapid response to the pilot's desire for conversion.

h. Fan Hub Spinner

The forward location of the HDU is a salient feature of this design in that, unlike some proposed configurations, direct air cooling of the unit is quite feasible. Consequently, the fan hub spinner is integral to the design for the purpose of transfer of rejected heat to the flow path.

III. ENGINE DESCRIPTION

This design of convertible engine evolved from basic ideas of what the configuration most preferably should be and then was verified by studies ascertaining its feasibility. The engine is first and foremost a turbofan engine that has shaft PTO capability. It can operate as a turbofan with no compromises. Also, importantly, in 100% shaft power mode there is no residual power loss, as in some other designs. Therefore, all power generated by the low pressure (LP) turbine is available on the PTO. The LP turbine is the only work extraction device in the system, fully operating in both thrust and shaft power modes.

The description of this engine (Fig. 10) is quite simple in that it directly follows the convention of standard high bypass ratio turbofans. The propulsion fan is front mounted on a fan frame/housing which constitutes the primary structural element of the engine. The engine core cantilevers from the fan frame and represents the latest core technology (i.e. T800). The high speed low pressure turbine is at the extreme aft of the engine and by means of power extraction shaft, co-axial with the gas generator, drives into a gear transmission system mounted in the hub area of the fan frame. The transmission accepts the single input of the low pressure turbine and distributes it co-axially and forward to the fan section at the appropriate speed reduction as well as radially to the outside of the fan frame and disconnect clutch housing to the eventual rotor head, cross-shafting, etc.

At the forward extreme of the engine and within the fan spinner is the HDU (Figs. 8 & 10). The converter is positioned on a central shaft extending from the fan reduction gear planet carrier, itself fixed to the fan frame. This shaft also necessarily serves to ground the torque converter stator and to position the other converter elements. The torque converter impeller element is directly connected to the gearbox output ring gear by a shaft concentric with the central shaft. The converter turbine, immediately forward of the impeller and stator components, directly drives the fan through the attached rotating converter housing. Within the housing is the converter direct drive clutch, which bypasses the converter by connecting the reduction gear output directly to the fan. Also, within the housing is the variable geometry stator mechanism and the converter fluid control valve. Hydraulic signal lines are provided to activate the stator, direct drive clutch, and fluid control valve. Similarly, converter fluid circulation circuit connections are provided.

It can be seen that even with the addition of all this necessary convertible machinery, this engine is still a very clean turbofan that gives no external hint of its very great operational flexibility except for the provision for the PTO on the fan frame. This is due to all convertible features being concentrated on the centerline of the engine and is a tribute to the hydrodynamic alternative for the convertible engine.

IV. OPERATION

The operation of this or any convertible engine can be defined by three specific modes of operation; all propulsive thrust, all shaft power, and the so-called dual power mode; that is any split between the two extremes. With both the propulsion fan and PTO powered by the same turbine, power splitting between the two must be accomplished by load control over both the fan and the PTO output. The PTO output is aircraft controlled; such as by collective pitch. For the design proposed in this paper, propulsive thrust is controlled by varying the fan speed of a fixed pitch fan by means of an infinitely variable speed ratio hydrodynamic transmission.

Figure 11 indicates the characteristic of power exchange when converting between thrust and shaft horsepower for this engine. Conditions are for constant gas generator speed and static operation. This curve concerns only the power required to operate the fan and does not include core supercharging effects nor core residual thrust. It is intended to exemplify the effectiveness of the torque converter as a thrust to shaft-power translation device. The difference between the theoretical conversion curve and the estimated actual curve represents losses in the system. Note that the curves converge at both extremes indicating 100% efficiency at these points. Some technical challenges would be to improve the actual conversion characteristic forcing it closer to the theoretical and also to adequately design the heat transfer systems which will permit stabilized operation at acceptable temperatures.

Descriptions follow for a rotary wing aircraft example which takes off purely under rotor power and transitions to a horizontal flight condition requiring no rotor power. Also described will be a roll maneuver for a fixed wing augmented lift VSTOL aircraft operating at a flight speed below which aileron control is ineffective.

Rotary Wing

Initially this engine will be used to supply full shaft power to the rotor system for lift off. During this mode of operation the direct drive clutch will be disengaged and the converter chamber is evacuated of fluid and/or the stator vanes completely closed to unload the fan from the turbine shaft. All power from turbine shaft will then be supplied to the rotor system. As the aircraft becomes airborne and forward propulsion is required, the converter is filled with fluid and the variable geometry stator is actuated to gradually increase power to the fan to a selected combination of fan thrust and output shaft power. This must be accompanied by an appropriate reduction in output shaft load to provide power for the fan. In rotary wing aircraft, this can be accomplished through the collective pitch mechanism. After full thrust is reached by the fan, the load on the power output shaft may be disengaged by the PTO clutch, if elected, and the rotor allowed to autogyrate. The direct drive clutch of the HDU may be engaged to lock the fan shaft to converter input shaft for solid rotation at 100% LP spool speed.

During forward flight with full thrust, the HDU is mechanically bypassed. The fan is directly driven by the turbine shaft and there is no load on the power output shaft. The engine purely operates as a two-spool turbofan engine. When it becomes necessary for the aircraft to set down, the output shaft clutch is engaged when the rotor has been brought to synchronous speed with the rotor pitch adjusted for minimum load. The converter will then be activated by disengaging the direct drive clutch. The variable geometry stator will be actuated to decrease fan speed while the aircraft rotor system is regulated to absorb the available power as it is off-loaded from the fan. When the fan speed is reduced to negligible thrust, the converter may be evacuated to entirely release the fan from the turbine shaft if necessary. The optional brake may be used to lock the fan rotor as may be operationally advantageous.

It can be observed that a wide variety of combined modes of operation can be achieved through this system by varying shaft output load, engine fuel flow, power turbine speed, and employment of the various torque converter operating features. The converter therefore, in combination with the direct drive clutch, variable converter stators, and engine and flight controls allows for an effective means of achieving the various modes and providing a smooth transition between them.

Fixed Wing

For this example the assumed aircraft type is a 4 engine VSTOL aircraft, such as the General Dynamics ABLE, with 2x2 wing mounted engines. The aircraft would be in a landing mode at very low flight speed in a maximum augmented lift condition. All four convertible engines are fully cross-shafted for flight safety as well as flight control flexibility.

An initial condition is that the maximum homogeneous horizontal thrust is limited to a specific value, say 90% thrust. To execute a roll maneuver, the variable stators are activated on the low wing causing a decrement in low wing fan speed and thrust and consequently lift. On the high wing the stators are adjusted to allow more power absorption thus increasing fan speed, thrust, and consequently lift. This excess power from the low wing LP turbines is cross-shafted through the PTOs to the high wing fan modules. The excess power accelerates the high wing fans (that is the entire mechanical system composed of the 4 LP turbines, cross shafts, and high wing torque converter turbines and propulsion fans) thus increasing high wing thrust and therefore lift. The non-symmetrical lift distribution rolls the aircraft (Fig. 12). Again, the high accelerating torques from the converter output enhances the response of the system by providing rapid fan rotor reaction.

V. CONCLUSION

The reasoning behind the convertible engine is easy to understand and various ideas for such have been proposed over the course of time; some have been demonstrated. The discussion of this paper has shown an alternative concept which would bring important benefits to an eventual product in terms of construction economics and of operational performance flexibility and cost.

By the judicious application of a hydrodynamic drive unit to current configuration turbofan engines, a simple, effective, and potentially low cost convertible turbo-fan/shaft engine may be created. This, furthermore, may be accomplished without recourse to specifically designed aerodynamic components such as special fan rotors, unloading guide vanes, variable exit stators, actuators, auxiliary inlets, nor special hot section developments such as parallel turbines, variable turbine nozzles, etc. Rather, standard turbofan components may be used.

The central element of the design, the hydrodynamic unit, is a conventional type benefiting from extensive automotive engineering technology evolution. Its sufficiently small dimensions allow its installation within the confines of a projection of the fan hub in a forward installation permitting its direct air cooling.

Additionally, unlike aerodynamic types which suffer from parasitic losses or design compromises at the operating extremes of 100% thrust or 100% shaft power, this design would have no theoretical end-point losses.

By this configuration engines which have been sized for VTOL operation become significantly augmented in turbofan mode, thus producing much greater than proportionate thrust as is necessary for high speed translational flight.

The engine concept and configuration presented in this paper represents a proposal for further development. The technologies employed are available but substantial integration analyses congruent to the standards and exigencies of man-rated certificated aircraft as well as adequate proof and durability testing remain. Indications are that this concept is totally feasible and that further investigation is merited.

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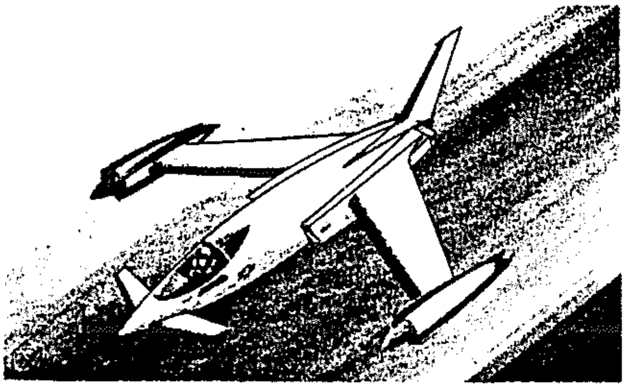
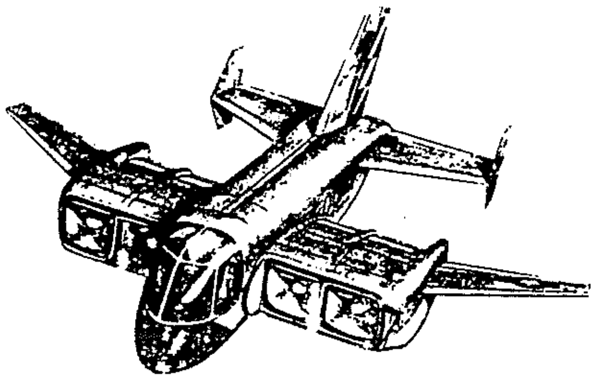


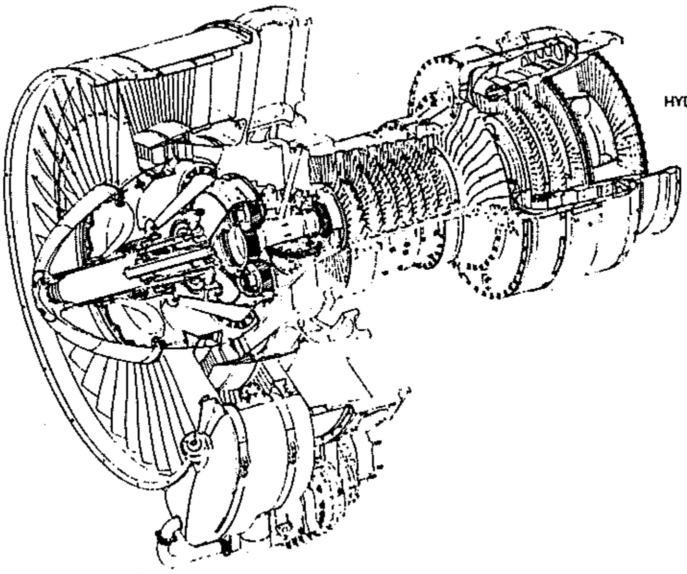
TYPICAL CONVERTIBLE ENGINE POTENTIAL APPLICATION
BELL CONCEPT - FOLDING TILT ROTOR

Figure 1



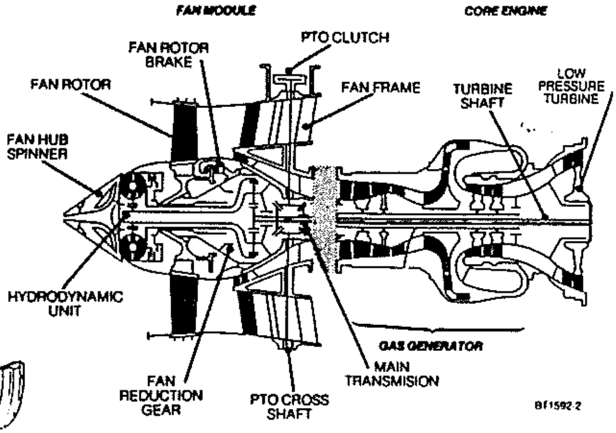
TYPICAL CONVERTIBLE ENGINE POTENTIAL APPLICATION
GENERAL DYNAMICS A311-A "ABLE"

Figure 2



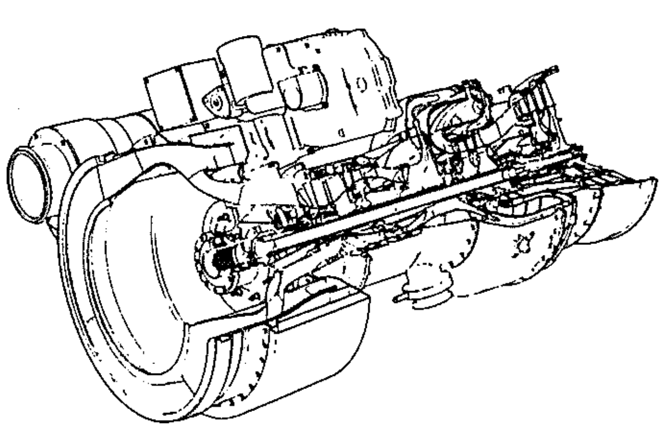
TYPICAL GEARED TURBOFAN ENGINE
TEXTRON LYCOMING ALF 502

Figure 3



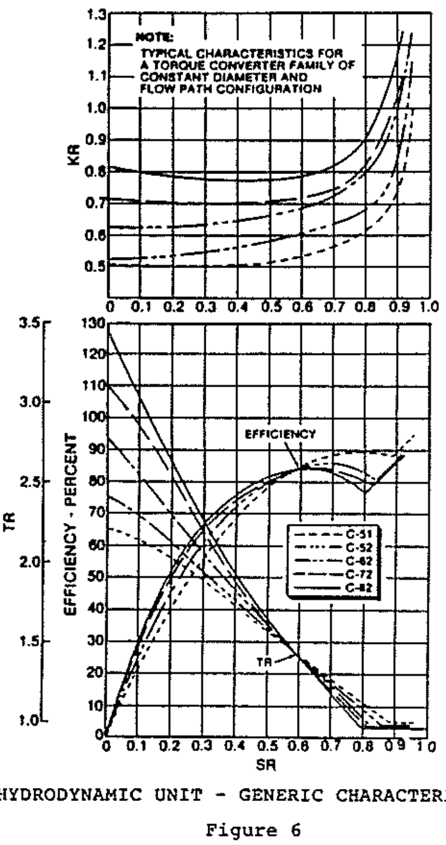
HYDRODYNAMIC CONVERTIBLE ENGINE COMPONENTS

Figure 4



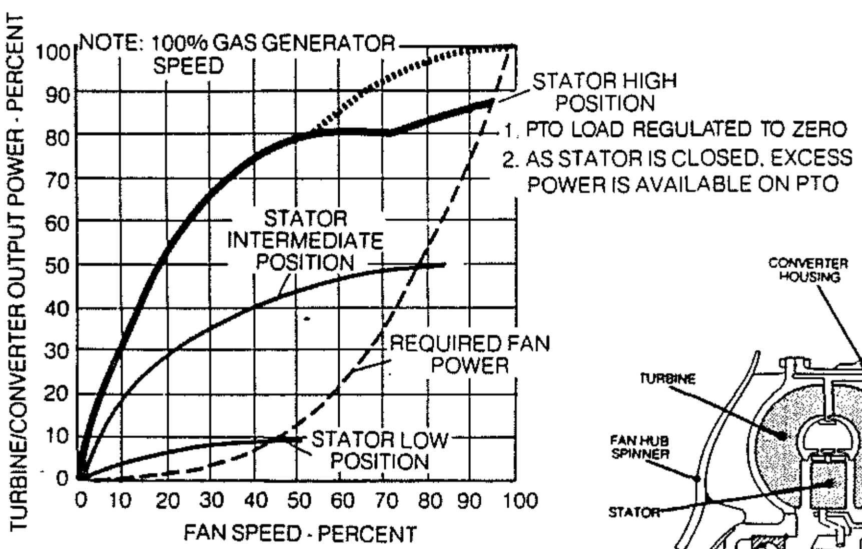
TEXTRON LYCOMING / PRATT&WHITNEY
T800-APW-800 TURBOSHAFT ENGINE

Figure 5



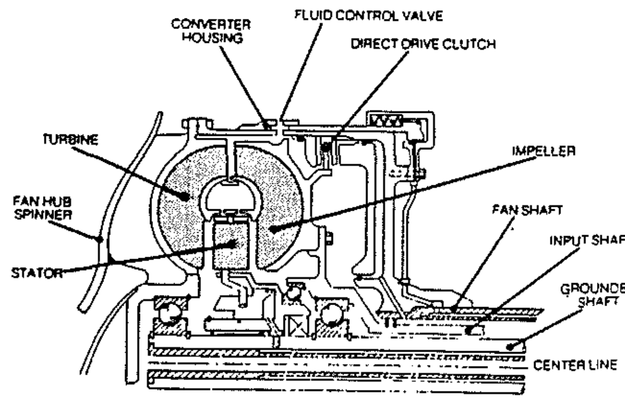
HYDRODYNAMIC UNIT - GENERIC CHARACTERISTICS

Figure 6



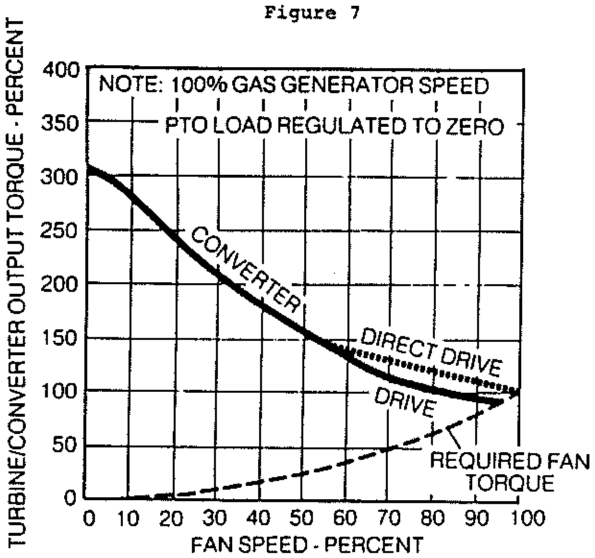
TYPICAL POWER AVAILABILITY
FROM HYDRODYNAMIC UNIT

Figure 7



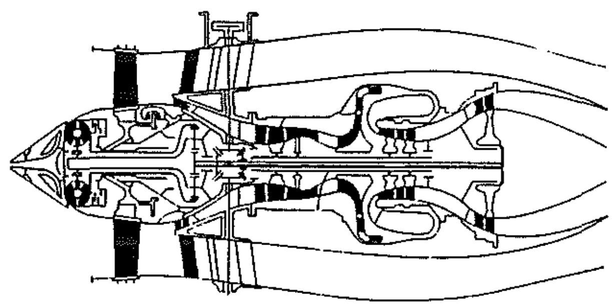
HYDRODYNAMIC TORQUE CONVERTER

Figure 8



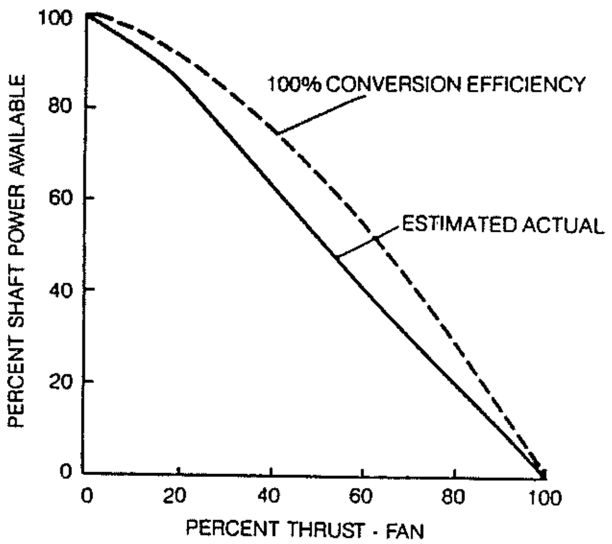
TYPICAL TORQUE AVAILABILITY
FROM HYDRODYNAMIC UNIT

Figure 9



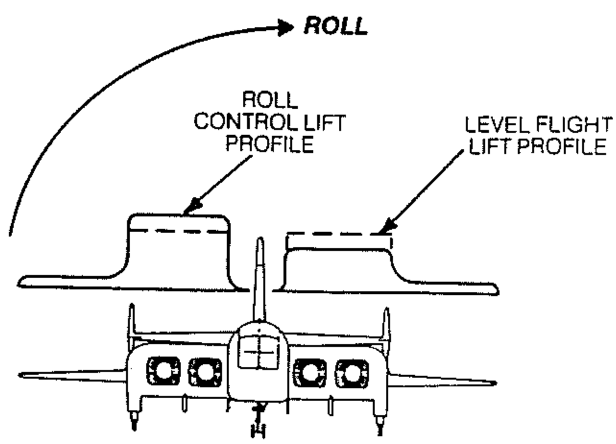
HYDRODYNAMIC CONVERTIBLE ENGINE ASSEMBLY

Figure 10



CONVERSION CHARACTERISTICS

Figure 11



ROLL CONTROL USING CONVERTIBLE ENGINES

Figure 12