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Lear Fan Propulsion System

Daniel E. Cooney

LearAvia Corp.

A PUSHER PROPELLER, centerline thrust, and twin turbo-shaft engines are the key components in a propulsion system being developed for the Lear FanTM airplane (Fig. 1). The goals of the design are improved operational safety and greater aircraft efficiency.

ADVANTAGES OF A PUSHER PROPELLER

Although the concept of a pusher propeller airplane is as old as the Wright Flyer, the full potential of the concept has remained unexploited. An airplane which has a propeller on the nose or in front of a wing accelerates a stream tube of air which passes over and around the fuselage or wing. This situation causes increased drag on those surfaces and results in a loss of propeller efficiency generally attributed to "nacelle blockage effect." Furthermore, a propeller located forward of the aircraft center of gravity is destabilizing in pitch and yaw. This is due to a normal force generated whenever the propeller axis of rotation is inclined to the relative wind (1)*. A reduction in interior noise level is an added benefit of a pusher propeller.

ADVANTAGES OF CENTERLINE THRUST

Centerline thrust in a twin engine airplane is a feature which can lead to a substantial increase in safety when coupled with a good rate of climb during single engine operation. Minimum controllable airspeed (Vmc) is the speed below which a conventional twin will yaw uncontrollably because of asymmetric thrust. Accident statistics reveal that conventional twin engine aircraft are involved in approximately 0.21 accidents per 100,000 flight hours due to loss of aircraft control below Vmc after loss of power on one engine. Further examination reveals that poor handling qualities and climb performance after loss of one engine results in an additional 0.66 accidents per 100,000 flight hours (2). This type of accident is occassionally aggravated by the pilot's failure to feather the propeller on the inoperative engine.

Centerline thrust can also lead to performance gains because of the absence of engine nacelles on the wings. The decrease in drag due to mounting the engines in the tailcone, and the increased propeller efficiency described above have resulted in 30% range and fuel efficiency improvement over an identical configuration with wing mounted engines.

A two-engine/single-propeller centerline thrust configuration also can provide a weight decrease compared to a conventional wing mounted installation. The weight decrease is a result of lighter engine reduction gearboxes, lower nacelle weight, lower engine mount weight, and reduced total propeller weight. A weight reduction of approximately one-hundred pounds has been achieved in the Lear Fan propulsion system.

LEAR FAN OPERATIONAL CHARACTERISTICS

The late William P. Lear had advocated the twin engine, single propeller configuration for many years (3) (4). Recent advances in turbine engine and drive system technology, particularly in larger helicopters, have demonstrated the design techniques required for this configuration. Rising fuel prices and the need to improve on the safety record of conventional twin-engine aircraft led to Mr. Lear's decision to develop the Lear Fan.

The safe operational characteristics of the Lear Fan will lead to an improvement in the twin-engine aircraft safety record. In the event of engine failure, a pilot is not required to cope with asymmetric thrust or propeller feathering. This is due to one-way (sprag) clutches located on the gearbox input shafts which automatically disengage when either engine is shut down. Furthermore, engines are sized for cruise speeds over 350 knots at over 30,000 feet, resulting in a large amount of excess horsepower at sea level and single engine rate of climb of over 1500 feet per minute (Fig. 3). These characteristics will greatly reduce the incidence of accidents involving Vmc and poor single engine performance. *Numbers in parentheses designate Reference at end of paper.

ABSTRACT

An aircraft propulsion system for Mach .6 flight is being developed which utilizes two turboshaft engines driving a pusher propeller through driveshafts and a combining gearbox. Thissystem will provide greater operational safety as well as improved aircraft efficiency. This report describes design features, installation considerations, and operational characteristics of the system, and reviews methods of system analysis.

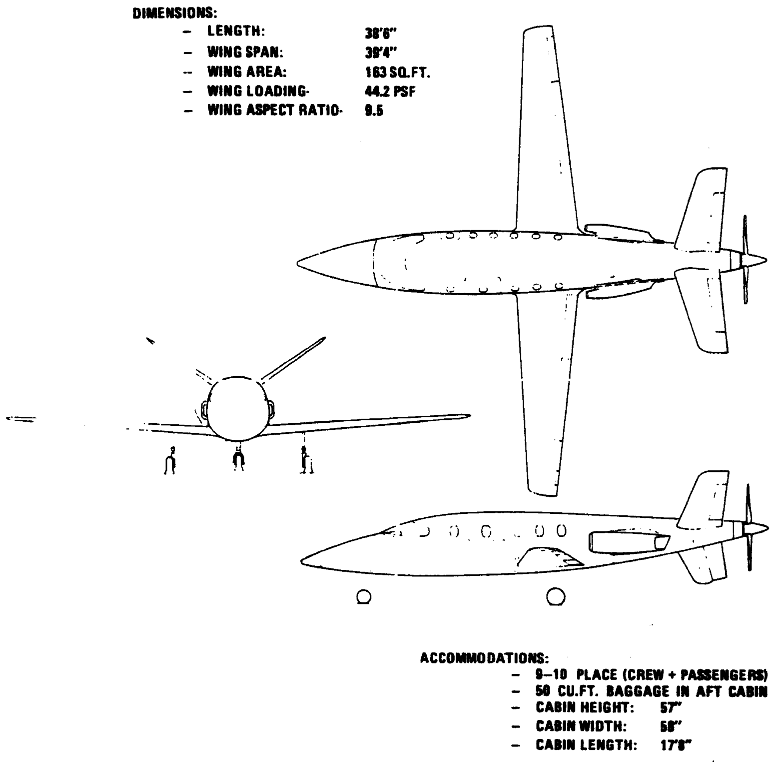

Fig. 1 - Lear Fan Model 2100 Airplane

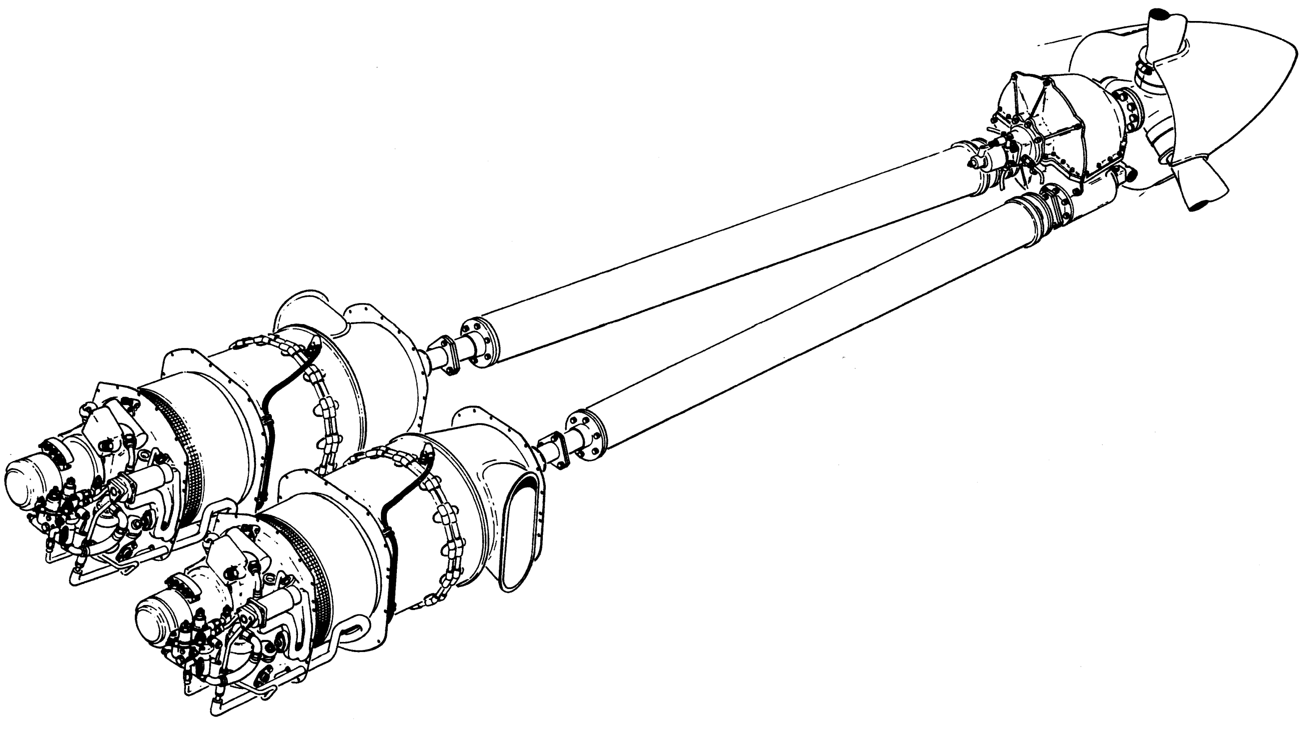

Fig. 2 – Lear Fan Propulsion System

ENGINE INSTALLATION

The Pratt and Whitney of Canada PT6B-35F engine utilized in this system is an assemblage of major components from other production models of the PT6 (Fig. 4). The major differences from other PT6 turboprops are the single stage planetary reduction gearbox and the single side port exhaust, which result in approximately 30 pounds weight saving per engine as compared to similarly rated turboprops. The engines are capable of 850 shaft horsepower output but are flat rated and certified at 650 shaft horsepower. This enables consistent takeoff performance at any altitude and temperature condition.

The inlet system is designed for high efficiency at cruise, having a long conical diffuser section leading to a plenum. An inertial separator system is used during icing conditions to prevent ice particles and water droplets from entering the engine.

These particles and droplets are unable to make the 90-degree turn into the engine plenum, and exit through the by-pass duct. Two electrically actuated doors control this action. The inlet lip is deiced by a pneumatic boot, and the broken fragments of ice also exit through the by-pass duct.

Maximum Speed @19,000 feet	360 kts
@31,000 feet	351 kts
@39,000 feet	326 kts
Fuel Mileage	1.36 n.m./lb. 10.5 s.m./gal.
Range @304 kts	2,000 n.m. (45 min. reserve)
Ceiling	41,000 feet 29,000 feet, single engine
Cabin Pressure	8.3 psi differential (8,000 feet cabin at 41,000 feet)
Rates of Climb, feet per minute	3550 two engine 1650 single engine

Fig. 3 - Lear Fan Performance Specifications

Engine and oil cooling during ground operation is provided by a hydraulically driven fan, which forces air through the engine compartment and oil cooler. Air flow through the cooler is modulated according to oil temperature by an automatically controlled exit door. In flight, ram air provides cooling airflow.

Shielding of the composite structure airframe from engine compartment fire is achieved by various firewall materials on all six sides of each engine. Where needed, insulation materials prevent structure from exceeding a 1800 F limit.

The engine mount is a stainless steel tube design comprised of a torque ring at the aft mount, and a steady rest at the front. The front steady rest allows the engine to grow in length from thermal expansion without creating structural stresses or drive train misalignment. A bracket is mounted on the top of the engine directly above the steady rest to which support braces attach for pivoting the aft end of the engine out of the airframe during ground maintenance (Fig. 5). In this manner, hot section inspections, servicing of fuel nozzles, igniter plugs, etc., are easily accomplished without disconnecting the engine accessories on the forward end of the engine. Engine removal and installation is also facilitated by this feature, since a simple hoist can be attached to the engine center of gravity when in the "swung" position.

Engine controls are completely independent and have no interconnection between engines. Drive train components are not adversely affected by unbalanced engine torques, and therefore a torque equalizing system is not needed. A power turbine speed synchronization system is also not needed, since the power turbines are directly geared together through the combining gearbox. A single cable runs from each engine to the control pedestal for control of power and start functions.

PT6B-35F ENGINE

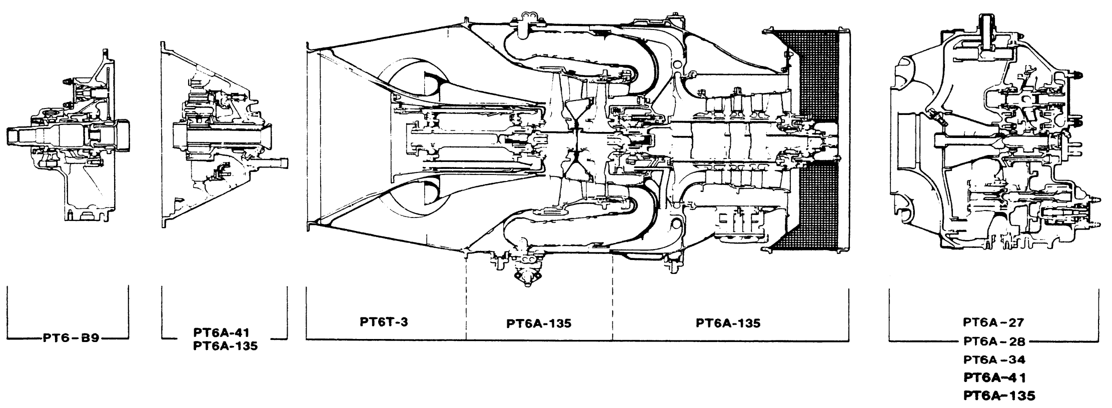

Fig. 4 – Pratt & Whitney PT&B-35F Engine

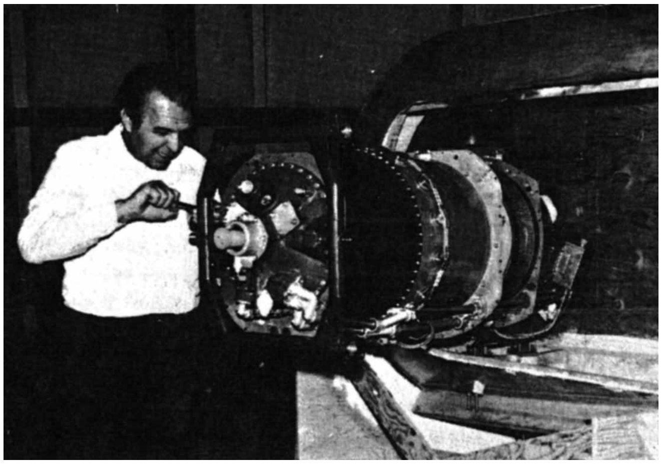

Fig. 5 - "Swing-Out" Engine Mount System

The engine start is semi-automatic. A single button is depressed to initiate the start cycle, and the only other action required is advancing of the power lever when 12 percent gas generator speed is reached. Ignition and starter/generator are automatically cycled

DRIVESHAFTS

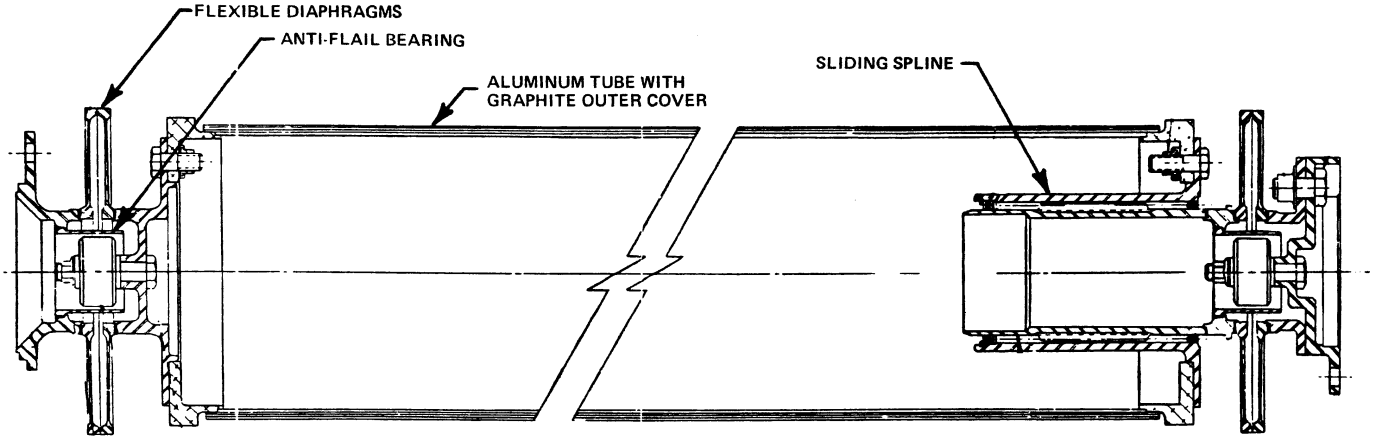

Fig. 6 - Drive Shaft

The driveshafts, manufactured by Bendix Corporation, are constructed of aluminum tubes with outer layers of axially oriented graphite fibers. The graphite provides lateral stiffening of the tube which raises the natural frequency to a point well above the normal operating speed. The ends of the tube are attached to steel diaphragms having hyperbolically shaped cross-sections which evenly distribute stresses induced by axial and angular displacement of the drive shaft. These diaphragms prevent excessive drive shaft stresses caused by thermal expansion, airframe deflections, and installation misalignment.

A large diameter sliding spline enables the shaft to be disconnected from the engine and pushed back during an engine swing-out operation, and also accommodates manufacturing tolerances and severe thermal expansion conditions (Fig. 6).

Safeguards include spherical bearings at the center of each diaphragm pack to provide shaft piloting in the event of diaphragm failure, and closely fitted shaft bulkhead passages to safely limit shaft excursion in the event of overspeed.

GEARBOX

An intensive design and development program initiated with Western Gear Corporation in late 1978 has resulted in a power transmission gearbox which provides the key component to the success of the propulsion system. Reliability and safety were the guiding principles in this design. Statistical studies revealed that the highest reliability was to be achieved by the simplest design, one having a single bull gear in mesh with two pinions. Each input shaft connects to a sprag clutch unit which transmits torque in one direction, and completely releases in the other direction. With this feature, an engine is automatically disengaged when shut down, and causes no drag on the rest of the system (Fig. 7).

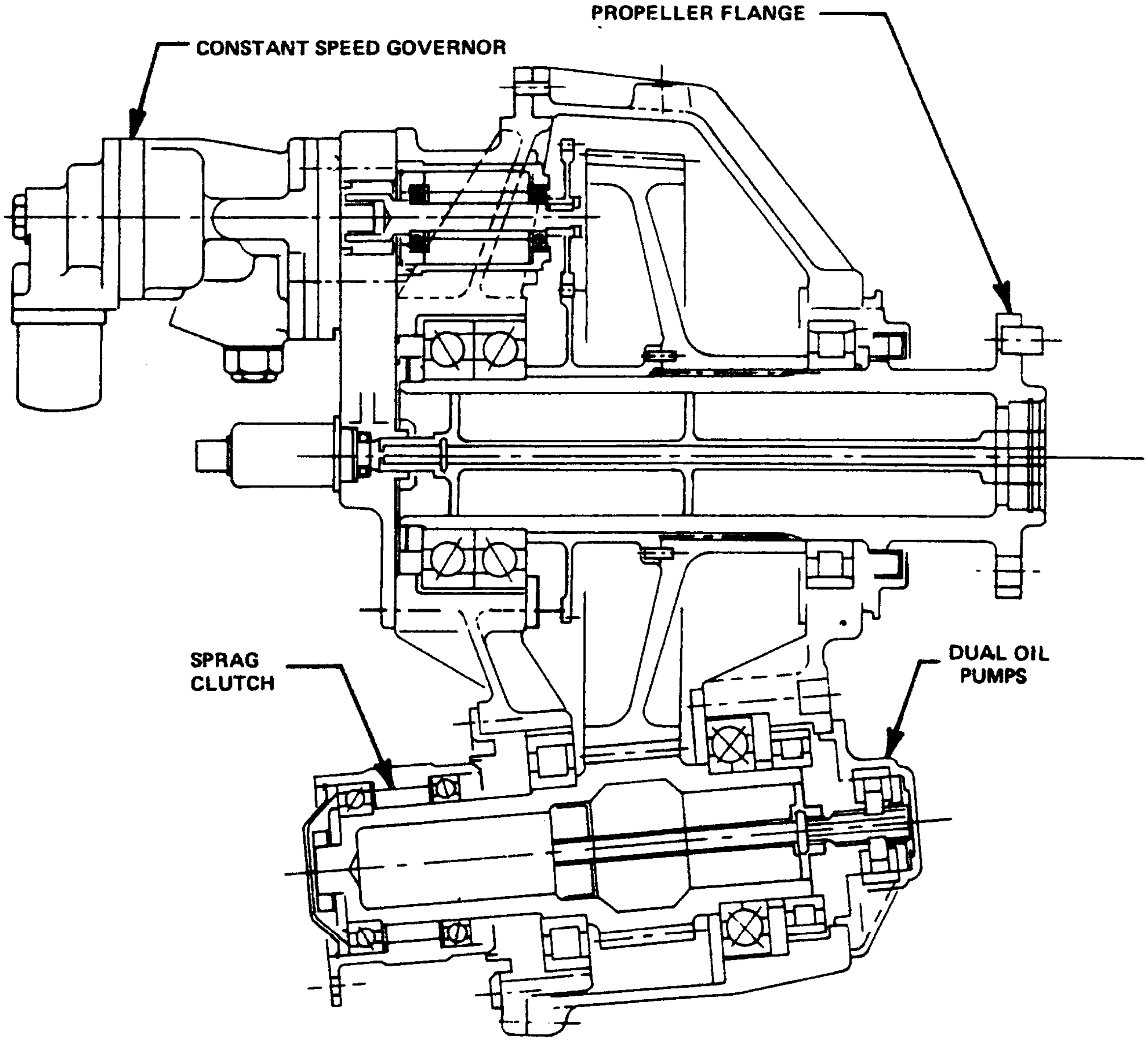

Fig. 7 - Propeller Gearbox

Each clutch unit drives a pinion gear having spiral bevel tooth form. The spiral bevel teeth selected have a contact ratio of over 2.0, which ensures quiet operation and implies that the gears can continue driving even after suffering the loss of a tooth. Computer analysis of many gear designs enabled optimization of efficiency, with resulting minimal heat rise in the gear mesh, and an overall energy loss of less than one percent in the gearbox.

The gearbox lubrication system is comprised of two parallel oil pumps drawing oil from the integral sump, a filter with bypass circuit and impending bypass (differential pressure) indicator, and a distribution system directing oil to the bearings, gear meshes, clutches, and propeller governor. A temperature transducer, pressure transducer, and chip detector provide signals for cockpit monitoring of gearbox operation. For operation at 41,000 feet, the oil system is aided by a differential pressure vent system which maintains 2.5 psi differential pressure in the gearbox, thus ensuring proper intake of oil by the pumps.

The gearbox is designed to operate at reduced power settings for several hours after loss of oil. The bearings are of a special type developed for helicopter transmissions. Silver-plated steel cages and increased clearances are used, which permit operation under the elevated temperatures associated with loss of oil pressure. At these temperatures, wax contained in the pinion and prop shafts melts and sprays onto the gear meshes and bearings, thus providing emergency lubrication.

PROPELLER AND PROPELLER CONTROL SYSTEM

A fiber composite construction four-blade propeller will be evaluated during the flight test program. Composite construction was chosen for its light weight and tolerance to damage without propagating cracks.

Each blade is protected from water and gravel erosion by a stainless steel leading edge, which also acts as a lightning path from the tip to the hub. Blade pitch is limited to a range between approximately 30 and 65 degrees, and is hydraulically controlled by a conventional Woodward constant speed governor.

In the event of loss of governor control oil pressure, over-speed limiting is provided by a hydraulic pitch lock system. In this situation, the propeller will behave as a fixed pitch propeller with RPM varying with power setting.

METHODS OF SYSTEM ANALYSIS

PROPELLER VIBRATION

Although a pusher propeller airplane has inherent advantages over a tractor type, special design attention must be given to many installation aspects which, if unproperly treated, can result in unsatisfactory characteristics. Of prime concern is the flow field through the propeller disc in all of the various flight regimes. To investigate this flow field and its effects on propeller vibration and stress, wind tunnel yaw probe and total pressure probe measurements were taken throughout the plane of the propeller to determine local flow angles and velocities encountered at critical flight conditions. Conditions investigated included flaps extended, elevators deflected, gear down, and various speeds and lift coefficients (Fig. 8). This data, in the form on non-uniform flow velocities, was then input to a computer program which utilized strip theory to calculate blade forces and moments for a range of blade azimuths. These forces were then subjected to a Fourier analysis to determine the blade loads and propeller shaft bending, shear, and torsional loads. The analysis was performed for both three and four blade propellers in a range of critical flight conditions.

Results have demonstrated a very low level of vibration, with the four blade propeller having lower amplitudes of vibration thanthe three-blade propeller. Maximum vibratory loads are encountered at full elevator deflection at maneuvering speed, but these momentary loads are only of a magnitude commonly encountered in conventional twin-engine aircraft during climb at high angle of attack.

PROPELLER PERFORMANCE

Performance aspects of the propeller have been evaluated using a program developed by LearAvia which incorporates various aspects of blade strip theory and vortex theory, along with adjustments for boundary layer energizing due to centrifugal effects, compressibility losses at high Mach numbers, and Reynolds number effects. In investigating the problem of absorbing the power of two engines with one propeller, a three blade high activity factor propeller and four blade low activity factor propeller were found to give good cruise and climb performance, but suffered loss of thrust during takeoff runs due to stalled blades, particularly at high altitude airports on hot days

Analysis of a four-blade propeller showed that a 140 to 160 activity factor alleviated the takeoff problem and offered improved cruise and climb performance. A design study is currently underway to develop a blade airfoil shape which will reduce efficiency loss from operating at high CL's and high Mach numbers, a condition encountered at 41,000 feet cruise.

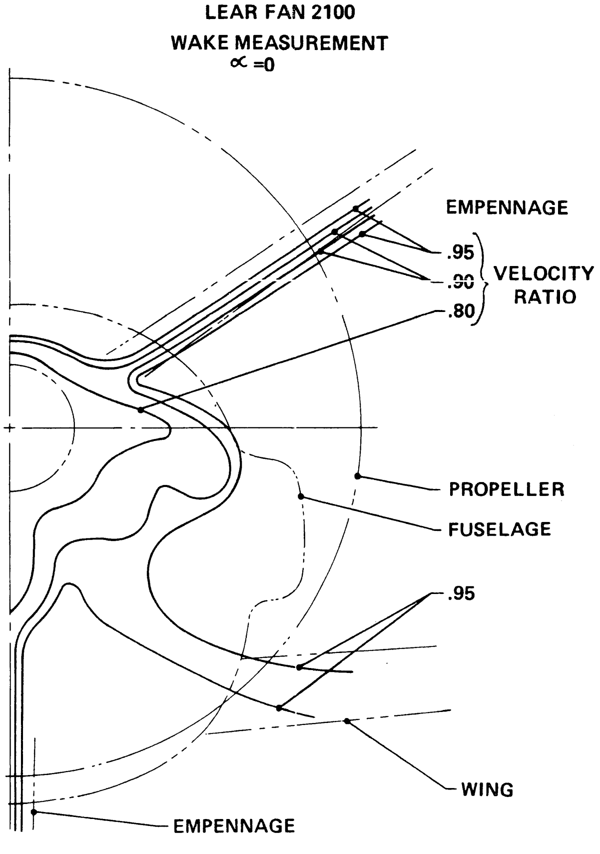

Fig. 8 - Wind Tunnel Data, Propeller Flow Field

WHIRL FLUTTER

Propeller whirl mode flutter is a phenomenon affected by stiffness and inertia properties of the propeller and mounting structure, and interaction with the flow field. The analysis of whirl flutter results in determination of a speed above which whirl flutter may be encountered. The dynamics of this phenomenon are documented in Reference (5).

TORSIONAL VIBRATION

Torsional dynamics of the drive train are analyzed to determine if any frequencies of torsional excitation will excite natural torsional frequencies. To determine system natural frequencies, a computer model of the drive train comprised of inertias connected by torsional springs is subjected to an iterative analysis (6). System excitation by the propeller is known from the propeller vibration analysis described above. The meshing frequencies of gear teeth are the main other excitations. Comparison of the natural frequencies and excitations reveals whether there is a tendency for fatiguing cyclic torsional loads to develop.

DYNAMIC TORQUE OVERSHOOT

On a drive train having two branches where one branch can be rotating at a constant speed while the other branch is accelerated and suddenly engages while accelerating, the magnitude of dynamic torque overshoot must be determined. The above mentioned computer model can be used to investigate this situation, or a formula relating system inertias, stiffnesses, backlash, and steady state torque can be used to analyze simple systems having two main inertias (7).

SHAFT CRITICAL SPEED

The critical speed of a drive shaft is that which corresponds to its installed lateral natural frequency. The lateral natural frequency must lie above the normal speed range, or provisions must be made for passing through the critical speed. This can be accomplished by installing an excursion limiter which will prevent excessive shaft deflection while passing through the critical speed.

The Lear Fan propulsion system contains two 6-foot sub-critical drive shafts which have excursion limiters to allow safe passage through critical speeds in the event of system overspeed.

As a general rule, a shaft should be run at or below 70 percent of critical speed in order to assure smooth operation. However, a finely balanced shaft can run closer to critical speed before encountering vibration which increases exponentially as critical speed is approached. An excellent balancing technique for this type of shaft is an analytical dynamic balance, in which measurements are made along the entire length of the shaft, and weight is added along the length in the amount and at the azimuth which will place the center of mass on the axis of rotation.

SYSTEM RELIABILITY AND SAFETY

A technique known as Fault Tree Analysis can be used to quantitatively determine system safety and identify causal relationships (8) (9). The analysis starts by listing undesired events, such as "an accident," and then listing all possible avenues to this event. These avenues lead to basic events and conditions, for which probabilities are determined from component reliability data and other statistical data. The fault tree is then reduced to equivalent Boolean algebra expressions which are used to calculate the probability of the undesired events, and identify the specific basic events which are most critical in causing the undesired events. This technique has been used for comparing the Lear Fan propulsion system safety and reliability to that of conventional twin engine aircraft. Preliminary results are revealing a twenty percent greater level of overall safety and the incidence of loss of control accidents cut by fifty percent, with further improvement expected as the design is refined.

SUMMARY

In quest of improved aircraft operational safety and efficiency, an aircraft propulsion system is being developed which incorporates a pusher propeller, centerline thrust, and twin engines. Problems associated with this type of design in the past are being solved by "state of the art" methods of system analysis.

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