Proposed Arrangement to Improve Turboprop Efficiency

W S Gearhart*
Pennsylvania State University State College, Pennsylvania

Renewed attention has been focused on the efficiency of aircraft propulsion as the cost of fuel has risen Studies conducted by NASA to obtain fuel efficient aircraft have considered relatively highly loaded turboprop systems The disk loadings of the propellers being as much as four times higher than those on present turboprop aircraft The higher disk loadings result in greater slipstream swirl and higher energy losses Of primary im portance is the radial distribution of the energy losses across the slipstream due to the tangential and axial velocities This study presents the results of analysis defining the various sources of energy loss resulting from a swirling slipstream downstream of a propeller Experimental data are presented demonstrating the presence of such losses and a propeller configuration is discussed which offers improved propulsive performance when relatively highly loaded propellers are employed

Nomenclature

A_p	= propeller disk area
A_S	= slipstream cross sectional area
D_p	= propeller diameter
g	= gravitational constant
J	= advance ratio V_∞/nD_p
n	= shaft speed rps
p	= freestream static pressure
Q	= volumetric flow rate
R_p	= propeller radius
T	= thrust
U	= peripheral velocity of propeller
U_T	= tip velocity of propeller
V_Θ	= tangential component of velocity
V_∞	= forward speed of craft
λ	= density of fluid
ρ	= mass density of fluid λ/g

Introduction

THE function of any propulsive system is to provide a forward thrust along its axis The design objective is to obtain a maximum in propulsor thrust with a minimum of shaft power while satisfying practical limits of propulsor size and shaft speed The generation of thrust requires that some kinetic energy be lost in the propulsive slipstream These losses are associated with both axial and rotational velocity components in the slipstream In addition the presence of rotational velocity in the slipstream results in a low pressure region in the far wake that reduces the net effective thrust generated by the propulsor Propellers that ingest large mass flows and place a small amount of energy per unit mass in the flow have a relatively small amount of slipstream swirl However the trend now is toward more heavily loaded propulsors having lower shaft speeds and heavier blade loadings Thus a reevaluation of the relative magnitudes of the losses associated with the velocity components in the propulsive slipstream is necessary

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*Associate Professor of Engineering Research Applied Research Laboratory

Sources of Losses in the Propeller Slipstream

The sources of energy losses in the propeller slipstream are shown in Fig 1 and consist of 1) tangential kinetic energy loss 2) axial kinetic energy loss and 3) a low pressure in the slipstream due to swirl which reduces the thrust of the propeller

The tangential kinetic energy loss arises from the swirl component of velocity that is placed in the slipstream As noted in Fig 1, which shows a typical radial distribution of swirl downstream of a propeller the swirl velocity is highest near the axis of rotation Therefore greater gains in efficiency per unit mass of fluid can be achieved by removing the swirl near the axis of rotation

The axial of kinetic energy loss originates from the axial component of velocity which is typically greater than the forward speed of the ship over the outer portion of the slipstream This is depicted in Fig 1 where the axial velocity is less than ship speed near the axis of rotation and greater than the ship speed over the outer half of the slipstream The axial kinetic energy loss could be reduced if the axial velocity near the axis of rotation could be increased thereby permitting a decrease of velocity in the outer region

The third source of efficiency loss due to slipstream swirl arises from the lower than ambient pressure that must exist across the entire downstream face of the slipstream By the radial equilibrium relationship the static pressure will be ambient at its outer boundary and decrease continuously to a minimum value at the axis of rotation The radial equilibrium equation in conjunction with the swirl distribution can be used to obtain the static pressure distribution across the down stream face of the slipstream Having obtained the static pressure distribution it can be applied over an increment of slipstream cylindrical area to obtain a force The increments of force obtained in this manner can be summed over the entire slipstream to obtain the resultant axial force resulting from the static pressure distribution caused by the slipstream swirl This force acts to reduce the thrust of the propeller This low pressure region can be physically envisioned as a suction or drag force created by swirl that reduces propeller thrust for a given shaft horsepower It shall be shown in a later section that by reducing swirl near the axis of rotation the greatest gains in reducing this drag force can be achieved Figure 2 demonstrates how the existence of a lower than ambient pressure across the face of the downstream slip stream reduces the thrust produced for a given shaft hor sepower This is shown considering a control volume around a propeller and the momentum flux as well as the pressure forces operating on the control volume Applying the radial equilibrium equation when the slipstream has swirl the static pressure (p_l) is less than ambient (p_∞) across the downstream face of the slipstream The energy added per unit mass flow is the same in both cases however the thrust produced by the propeller for a given shaft power is reduced if swirl is present in the slipstream

Some of the advanced propeller driven aircraft proposed for the 1990's are considering using pusher propellers located at the aft of the fuselage This arrangement will result in the propeller ingesting the low momentum fluid from the hull and thereby provide an increase in propulsive efficiency However if proper design is not employed the interaction of the propeller blades with the shear flow from the fuselage will generate secondary flows which will result in higher than desired swirl near the axis of rotation as discussed in Ref 2 The increased swirl near the axis of rotation due to secondary flows will increase the previously discussed energy losses and offset the desired gains in efficiency obtained by ingesting the boundary layer from the fuselage

In summary the preceding indicates that the loss due to slipstream swirl can be reduced most effectively by reducing the swirl near the axis of rotation In other words if the angular momentum is removed from the flow over the inner portion of the slipstream it is possible to achieve larger energy gains than by removing it from the same percentage of fluid near the outer boundary of the slipstream

Predicted Propeller Performance with Slipstream Swirl

An analytical model of the propeller and the described energy losses associated with the slipstream is reported in Ref 3 From these studies it is possible to predict, for a propeller with a given advance ratio and ingested mass flow or diameter the magnitude of each of the previously described sources of slipstream loss as a function of propeller thrust coefficient

It is reported by NASA[1] that the advanced aircraft propellers will operate with a lower ratio of peripheral tip speed to forward speed than present propellers; the nominal value of tip speed to forward speed for conventional tur boprops being 2 0 or greater whereas the advanced prop fans shall approach 1 0 Predictions of propeller slipstream losses using the analysis of Ref 3 and considering propellers of equal diameter but having a ratio of tip speed to forward speed of 2 0 and 1 0 are illustrated in Fig 3 The increment of pressure drag derived and defined in Ref. 3 and shown in Fig 0 originates from two regions of the slipstream The first being the swirling slipstream outside the vortex core and the second from the vortex core region where solid body rotation is approximated

If a propeller thrust coefficient of 0 1 is required in both cases it is apparent that the losses associated with slipstream swirl are significantly greater for the propeller having the lower shaft speed The lower shaft speeds are required to permit air speeds on the order of Mach 0 6 to 0 8 but achieve blade surface velocities which are not excessively high The reduced blade surface velocities obtained by reduced shaft speeds minimize compressibility losses

The significance of Fig 3 is that the axial kinetic energy losses did not change with advance ratio since the propeller diameter and ingested mass are essentially equal for the two cases The energy losses associated with the tangential kinetic energy losses and pressure drag increase by about a factor of four when the lower shaft speed is considered The pressure drag term being the larger of the two energy losses resulting from slipstream swirl Figure 3 indicates that about a 9% loss in efficiency will result for a single propeller at a thrust coefficient of 0 1 if slipstream swirl is not removed This closely agrees with NASA estimates[1] of 8% It is evident from this exercise that the losses resulting from slipstream swirl are

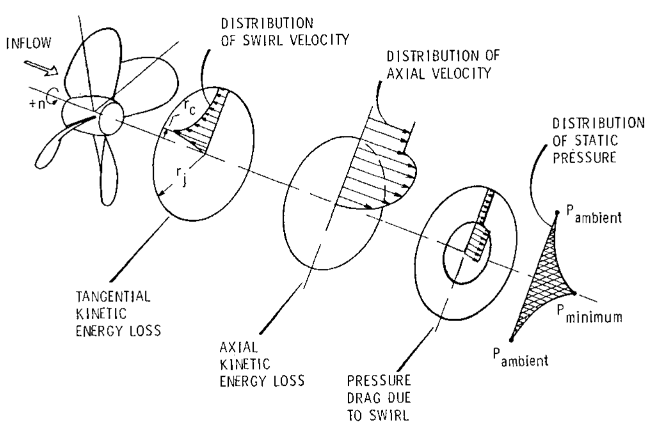

Fig 1 Sources of energy losses in the slipstream

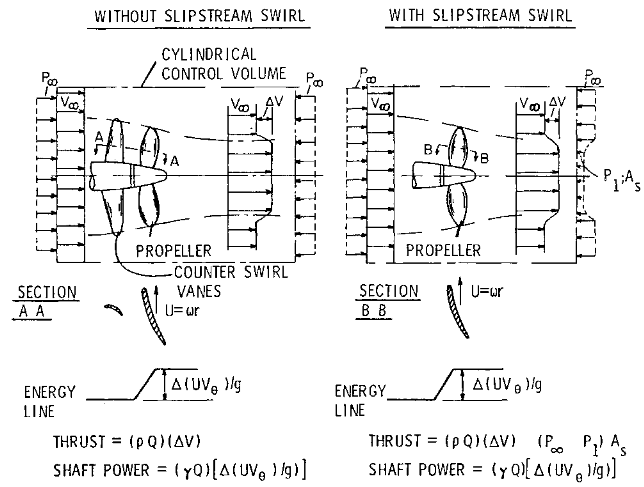

Fig 2 Reduced propeller thrust due to slipstream swirl

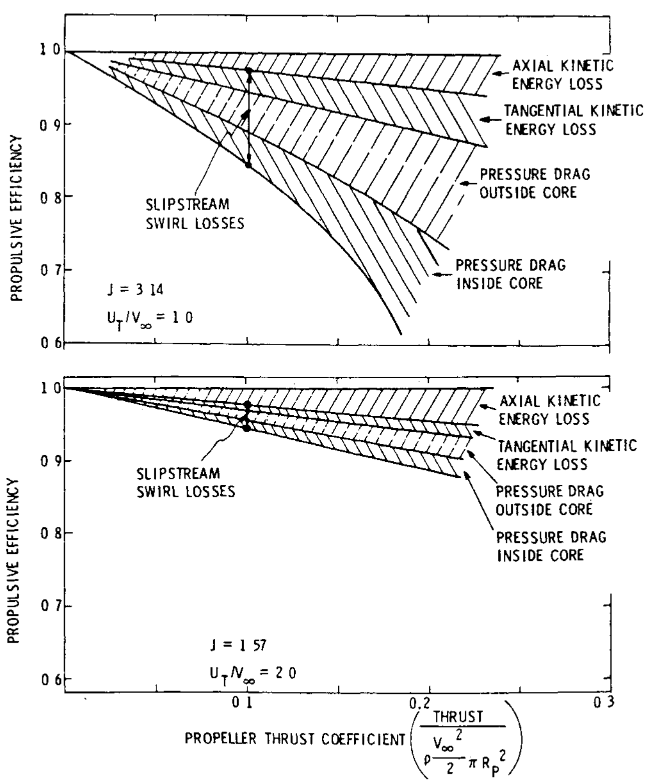

Fig 3 Energy losses with slipstream swirl as a function of advance ratio and propeller thrust coefficient

highly dependent on the propeller thrust coefficient and advance ratio selected in the design

The approach described in Ref 3 for evaluating the losses due to slipsteam swirl is a one dimensional analysis and assumes a free vortex loading on the propeller A more general approach for obtaining the flowfield through the propeller is by means of the streamline curvature flowfield analysis [4 5] The fluid properties of pressure and velocity are derived at selected stations for an arbitrary spanwise blade loading An inflow to the propeller having a nonuniform total energy such as the boundary layer fluid from the fuselage can be used in the solution A control volume is specified as illustrated in Fig 4 and the momentum analysis applied to obtain the net effective thrust generated by the propeller for a given shaft horsepower

Applying the streamline curvature analysis to a free field solution is achieved by initially solving for the flowfield over a relatively large flow area Using the results of the initial solution a smaller flow area is used in a second solution This procedure is repeated until a streamwise boundary as in dicated by SL_n in Fig 4 is obtained A check of the accuracy of the flowfield properties defined can be performed by solving for the force on a control volume which does not encompass any structure The net force on this control volume should be zero

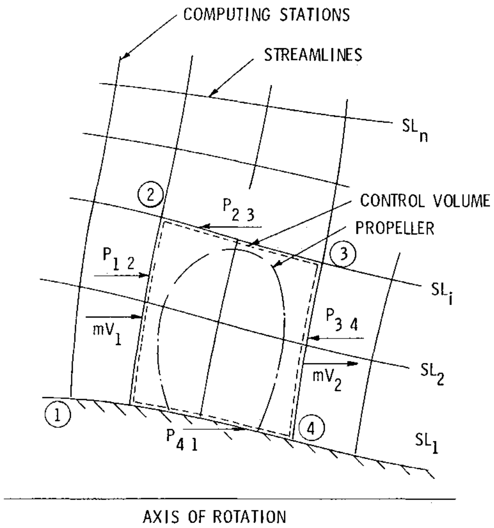

Fig 4 Streamlines and control volume analysis to determine propeller efficiency

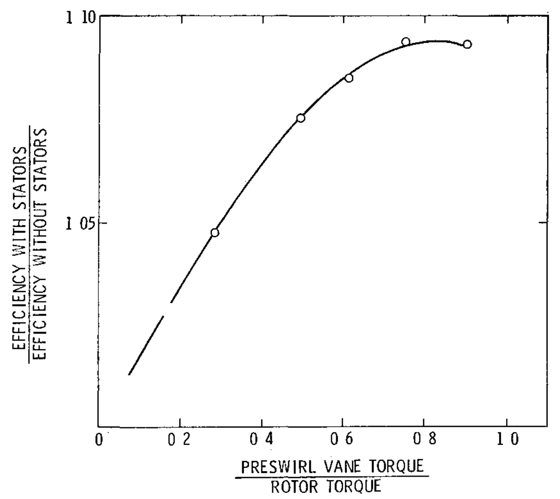

Fig 5 Propeller efficiency as a function of counterswirl

The analysis can be applied to a propeller configuration where stator vanes are placed either upstream or downstream of the propeller Placed in front of the propeller they would place counterswirl in the flow if placed aft of a propeller they would remove swirl placed in the flow by the propeller This technique will permit predictions of performance with stators having varying ratios of span relative to the propeller and which impart angular momentum or torque of some fraction of that supplied by the propeller The results as plotted in Fig 5 indicate the span of stator blades required relative to the propeller to obtain a given increase in efficiency over that of the propeller alone

Experimental Evidence of Reduced Propeller Thrust Due to Slipstream Swirl

The pressure effects of swirl in the slipstream especially near the axis of rotation were experimentally deomonstrated in Ref 6 A backup bar was located behind the propeller hub and supported by a separate strit as shown in Fig 6 The backup bar did not touch the propeller hub Three propellers with different operating advance ratio and, hence different amounts of slipstream swirl were tested with this arrangement When the backup bar was in place the shaft thrust was increased for two propellers by almost 20% and for one propeller by better than 30% as compared with the propeller alone case The shaft torque was unchanged for each propeller with and without the backup bar in place As a check on this measurement the backup bar was removed and a conical tailcone was installed

The tailcone was supported by a separate strain gaged shaft which was located inside the propeller drive shaft The axial

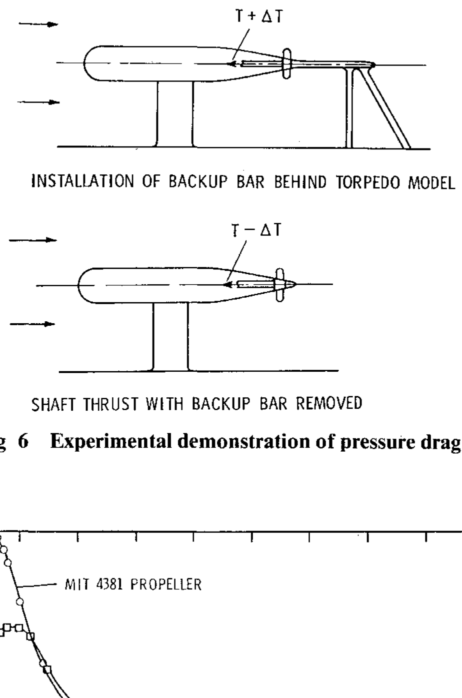

Fig 6 Experimental demonstration of pressure drag

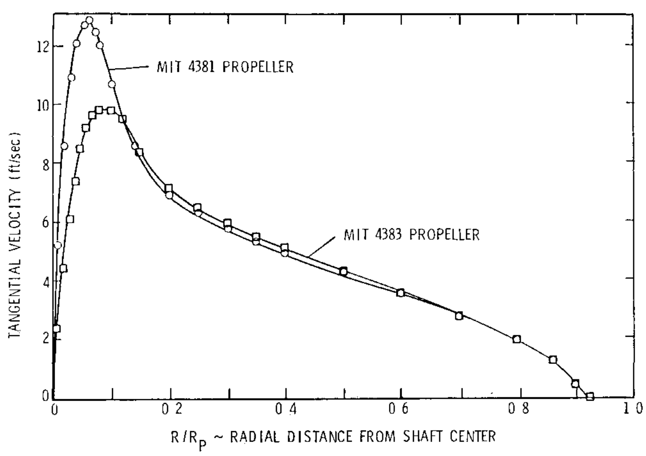

Fig 7 LDV measurements of tangential velocities in MIT water tunnel

force or drag measured on the tailcone was equal to the amount that the shaft thrust was increased with the backup in place The net axial force transmitted to the body in this case via both shafts was (T-ΔT) When the backup bar was in place the net axial force transmitted to the body was ($T+\Delta T$) This experiment demonstrates that the pressure effects of swirl contribute to the reduced thrust of the propeller The shaft power required at a given shaft speed did not change with the presence of the backup bar or the strain gaged tailcone

The experimental measurements described above suggest that significant gains in efficiency can be achieved by elimination of the swirl near the axis of rotation Ex perimental LDV measurements across the slipstream of two separate propellers are reported in Ref 7 These propellers were tested in a water tunnel and were driven by an upstream dynamometer The measured tangential velocity is shown in Fig 7 Applying the radial equilibrium equation and ob taining the static pressure distribution across the slipstream the radial distribution of pressure drag is obtained as in dicated in Fig 8 It is apparent that nearly one half of the energy loss associated with the pressure drag could be recovered if the swirl were removed from the 0 4 i d of the slipstream

The use of short span stators permitting the inboard sec tions of a propeller to carry a heavier loading has a numbr of benefits First it will permit propellers of smaller diameter which result in improved noise The inboard loading reduces blade surface velocities near the tip and also reduces noise as reported in Ref 1 The application of such an arrangement to a pusher-type propeller located at the aft of an aircraft permits placing higher energy into the low momentum fluid from the fuselage which will increase propulsive efficiency as described in Ref 3

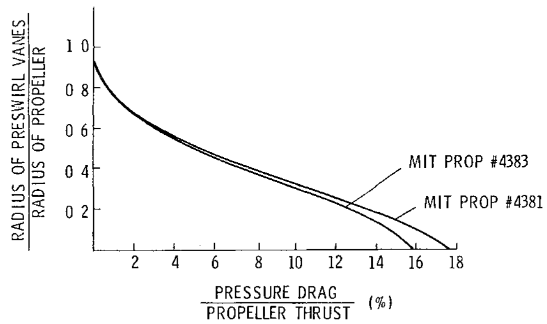

Fig 8 Radial distribution of pressure drag based on experimental tangential velocities

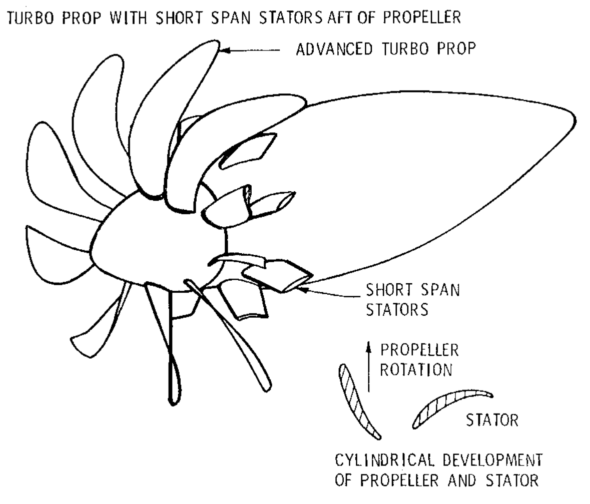

Fig 9 Short span stators on nacelle of tractor type propeller

Proposed Propulsor Arrangement for Aircraft

The prior art in aircraft propulsion has included patents granted for stationary vanes mounted either fore or aft of the propeller Counterrotating propellers have been considered as well as stationary appendages such as the wing or the elevation and direction control surfaces which act as stator vanes Their success and application have been limited by their mechanical complexity The added drag and weight associated with such arrangements also have been prohibitive Interference with controllable pitch propeller performance at other than design conditions also has prevented any practical adaptation These reasons in addition to the relatively lightly loaded propellers used in the past and the small gains that could be achieved if the swirl in the slipstream were removed have provided cause for not applying a stator system

It is proposed that a stator arrangement be considered, as illustrated in Fig 9 where a series of short span stators are mounted on the nacelle of a tractor type propeller Figure 10 depicts the short span stator arrangement for a tractor and pusher type propeller application

The primary advantage of the short span stator arrangement is that the surface area and weight associated with a stator system are minimized while the slipstream swirl is removed from a region where the greatest gains in efficiency are achieved In so doing the noise performance is also improved since tip loadings are reduced The small span of the stator relative to the propeller should permit the use of controllable pitch propellers with little effect on their per formance It is likely that successful application with variable pitch propellers will require that the pitch of the stators also be variable The small planform area of the stator system would have minimal effect on the maneuvering stability and control of the aircraft

The use of such a stator system permits a larger portion of the propeller blade loading to be carried inboard which will increase the propeller efficiency and reduce propeller noise The use of the proposed arrangement permits efficient operation with a smaller diameter propeller A reduced diameter propeller could be of equal efficiency but have improved noise performance reduced weight and be structurally more acceptable Alternately the use of the stator system would permit designing for lower shaft speeds

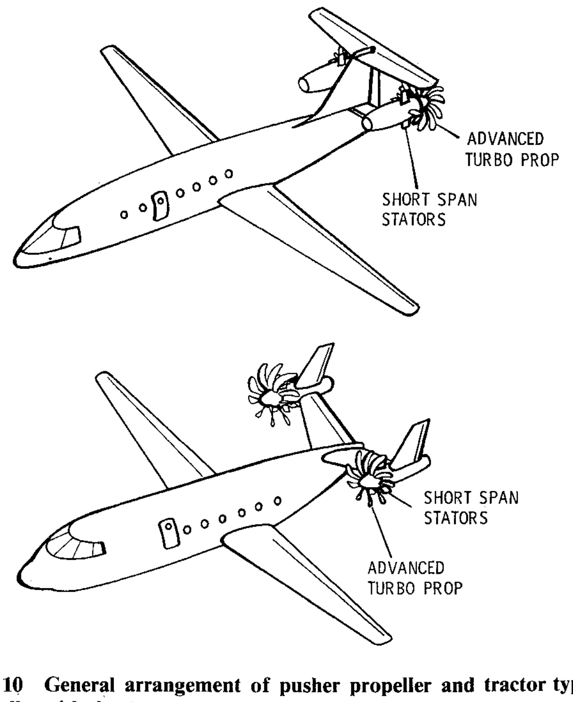

Fig 10 General arrangement of pusher propeller and tractor type propeller with short span stator

resulting in lower blade surface velocities which would reduce noise and compressibility effects

The proposed stator system is estimated to provide ef ficiency gains comparable to those achieved with coun terrotating propellers but without the complexity of coaxial shafting, bearings and seals However by current estimates a counterrotating gearbox will be lighter than a single rotational gearbox On this basis a detailed system analysis relative to counterrotation or single rotation employing some means of counterswirl is required

Summary

The energy losses associated with slipstream swirl are presented The radial distribution of the energy losses indicate that a significant portion of the losses could be eliminated by using some means of counterswirl over the inner portion of the slipstream On this basis short span stators are proposed to achieve the desired counterswirl The result being a gain in efficiency and a potential gain in noise performance

Acknowledgments

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