PAPER NUMBER 60-AV-11



AN ASME PUBLICATION

# The Ducted Propeller for STOL Airplanes[1]

**AUGUST RASPET**
Professor,
Aerophysics Department,
Mississippi State University,
State College, Miss.

The ability of a ducted propeller to provide high thrust at low speeds will moderate engine power makes it ideally suited to STOL airplanes utilizing high-lift boundary-layer control. Problems in the design of efficient ducted propellers are that of preventing separation on the inlet of the duct and that of matching the propeller-pitch distribution to the inflow velocity profile at the propeller plane. The utilization of the stabilization and control, which the duct can provide, requires a pusher configuration. However, an STOL pusher derives the additional benefit of low drag, which is possible since the turbulent propeller slipstream does not impinge on large wetted areas of the aircraft.

80c PER COPY
40c TO ASME MEMBERS





THE AMERICAN SOCIETY OF MECHANICAL ENGINEERS
29 West 39th Street, New York 18, N. Y.

[1] Studies conducted under offices of Naval Research Contract with sponsorship of U. S. Army Transportation Command.

For presentation at the Aviation Conference, Dallas, Tex., June 5-9, 1960, of The American Society of Mechanical Engineers. Manuscript received at ASME Headquarters, April 6, 1960.

Written discussion on this paper will be accepted up to July 11, 1960.

Copies will be available until April 1, 1961.

p.1

Printed in U.S.A.

# The Ducted Propeller for STOL Airplanes

AUGUST RASPET

## Nomenclature

$T$ = thrust, lb

$HP$ = horsepower developed by engine

$\theta$ = angle of climb-out

IAS = indicated airspeed, mph

$U$ = velocity of flow, fps

$R$ = local radius of curvature of wall, ft

$g$ = gravitational constant 32.2 ft/sec$^2$

$\rho$ = density of air for test conditions, slugs/ft$^3$

$\frac{\partial p}{\partial y}$ = static pressure gradient normal to wall, sec$^{-1}$

$a_n$ = normal acceleration away from wall in ft/sec$^2$

$\Delta_p$ in mph = pressure differential with respect to ambient; $\Delta_p = \frac{1}{2}\rho V^2$ where V is in mph

$C_T = \frac{T}{\rho n^2 D^4}$ = thrust coefficient

$n$ = number of revolutions per second

$D$ = propeller disk diameter

$\eta = \frac{Tv}{HP}$ = propulsive efficiency

$\tau = \frac{v}{nD}$ = advance ratio

$v$ = forward speed, fps

Diffusion ratio = $\frac{\text{area at outlet of duct}}{\text{area at minimum diameter}}$

## Introduction

The ducted propeller had its origin in the Kort nozzle used in Germany for tugboat propulsion. In the Kort nozzle a highly convergent nozzle was placed over a conventional propeller on which even the rounded tips were retained. As a result of the large effective tip clearance, the static thrust developed by the Kort nozzle was only 10 to 15 per cent better than an equivalent diameter open propeller. In addition to the large tip clearance, the use of a standard propeller, or screw having blade setting decreasing toward the tip, did not permit operation in a flow field such as to yield the highest thrust, since a good portion of the outer blade radius was immersed in the highly accelerated flow due to the convergent nozzle. The propeller was in effect windmilling toward the tips.

When ducted propellers were first tried in various aircraft applications, some effort was made to retain small tip clearance, although the classically twisted propeller was still used.

Because the ducted propeller offered a considerable increase in static thrust, early at-

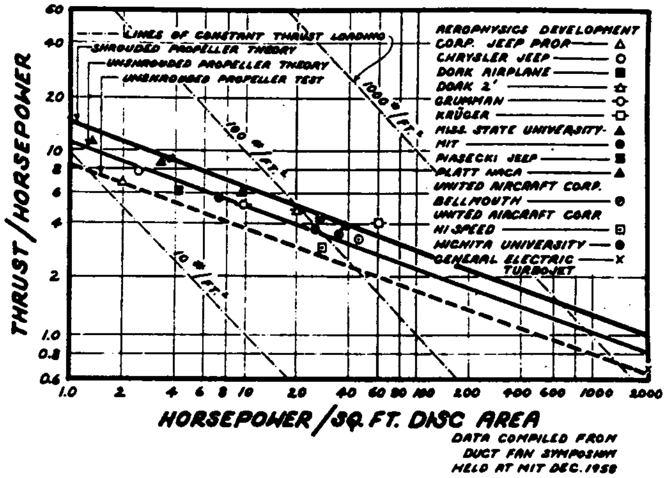


Fig. 1 Ducted propulsor performance

tempts at applying this concept were in the field of vertical lifting machines, such as the flying platforms, and multiple ducted vertical lifting machines. The state of the art in this field is shown in Fig.1. It is quite clear from this illustration that there exists quite a variation in the static thrust attained by various designers. There are a few designs which reached the theoretical limit for the shrouded propeller. These better designs utilized a thin shroud, having chord-to-diameter ratios of 0.25.

By far, the best results were obtained by Kruger,[2] whose ducted propeller was built around a streamline body of revolution. The duct and propeller were mounted at the trailing end of the body, thus providing for additional diffusion of the flow.

Although the applications of ducted propellers to VTOL aircraft have been most numerous, the concept of the ducted propeller, however, offers a real contribution to the highly efficient STOL aircraft. It is this aspect of ducted-propeller technology which will be discussed in this paper.

## Ducted Propeller for STOL Aircraft

The concept of the ducted propeller lends itself admirably to STOL airplanes. The reason for this lies in the fact that an STOL airplane

[2] W. Kruger, "On Windtunnel Tests and Computations Concerning the Problem of Shrouded Propellers," NACA TM 1202, 1949.

by virtue of its high lift also possesses high induced drag, which must be overcome by means of a propulsion unit capable of developing high thrust at low speeds. Since the ducted propeller possesses this feature of developing high thrust at the low forward speeds at which STOL airplanes utilizing high lift boundary layer control fly, it permits matching the propulsor to the airplane without resorting to the usual approach of merely adding a larger engine.

However, when one considers the ducted propeller as a tractor, the idea is immediately thrown out, for the duct acts as a considerable destabilizing element in yaw. This consideration then automatically dictates that the ducted propeller be arranged in a pusher configuration. Arranged thusly, the duct can also be used as the stabilizing element, as suggested by Kuchemann and Weber.[3]

## Concept of High Thrust Combined with High Lift

Assuming that one designed a ducted propeller to develop a thrust equal to the weight of the aircraft, the question then comes up of whether it would not be more feasible to use this thrust to lift the airplane. One can easily resolve this aspect by computing the take-off speed attainable with distributed suction boundary-layer control. With the already attained low stall speed of 35 mph, the take-off run with thrust equal to the airplane's weight comes to a mere 41 ft.

The climb-out with such a high thrust would be almost vertical.

However, one does not need to attain as high a thrust-to-weight ratio as unity. Excellent performance can be obtained with values between 0.6 and 0.8. Such values can be attained with engines of nominal powers of the order of 250 hp for a two-seater airplane grossing 2200 lb.

Since the duct acts as a stabilizing surface both for pitch and for yaw, it is also feasible to Include control surfaces in the duct's after-section, thus providing yaw and Pitch control.

## Aerodynamics of High-Lift STOL Airplanes

It was mentioned previously that high lift implies high induced drag, and that this high induced drag necessitates high thrust at low speeds. In Fig.2, are shown flight-test measurements of the climb-out angle of a Piper Super Cub, which has been fitted with a distributed suction high-lift system. It will be seen that the maximum climb-out angle is obtained with a flap deflection of l/3, and that this climb-out occurs at an airspeed of 48 mph. Yet this airplane is capable of flying stably and under control down to a speed as low as 26 mph.

What these flight-test data clearly show is the need for better propulsion at low speeds on this airplane. Obviously, if this better propulsion can be achieved without increasing the horsepower of the engine, the airplane's design will not suffer a vicious spiral ending in a much larger airplane due to the larger gasoline requirement and higher weight requirement of the larger engine.

## Design Considerations for Ducted Propellers

Obviously, a ducted propeller must be designed with two features In mind:

1 It must provide high thrust at low speeds.

2 It must not possess a high drag in cruising flight.

What these considerations imply is that the thickness of the duct cross section must be kept as small as possible without loss of static thrust.

The usual solution to this problem has been to use a bell-mouth entry for the duct and then complain about the high drag of this configuration, or else to try to make a variable geometry inlet as was suggested by Kruger.2

However, recent studies of viscous flows on curved walls[4] have led to an understanding of the nature of the flow separation on the inlet to ducted propellers.

The usual criteria for laminar separation of viscous flows in adverse pressure gradients completely neglect the effects of centrifugal forces, tending to throw the flow away from the wall. In fact, all of the laminar-separation criteria are based on flat-plate flows.

When the centrifugal forces are given consideration, as they must be for violently curved flows, these simple criteria are not valid.

As an example of a strongly curved flow, let us look at Fig.3. The data for this figure were obtained in flight with a sailplane having

---

[3] Kuchemann and Weber, 'Aerodynamics of Propulsion," McGraw-Hill Book Co., Inc., New York, N.Y., 1953, p.136.

[4] Mathur, Maneshwar Chandra, "A New Simplified Form of Navier-Stokes Equations for Curvilinear Flows." Mississippi State University, Aerophysics Department, Research Report No. 24, May 30, 1959.



AV11

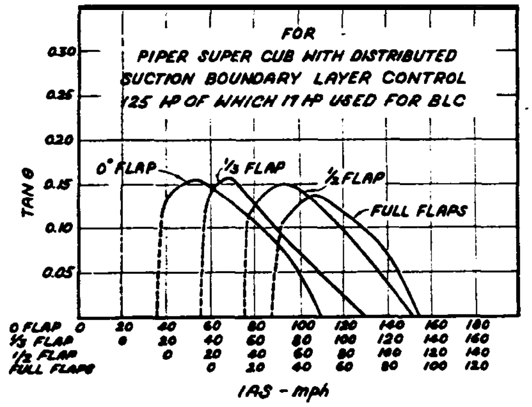


Fig.2 Tangent of climb angle versus indicated air speed

Fig.4 Flow visualization of duct propeller inlet without suction BLC

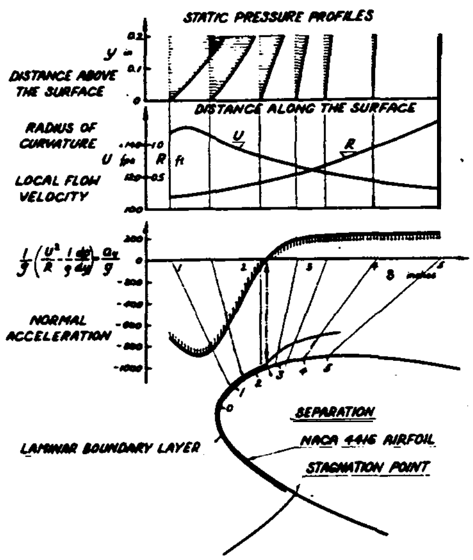


Fig.3 Separation on an airfoil due to forces normal to flow

an NACA 4416 airfoil whose turbulent separation was delayed by distributed suction. The airfoil was capable of developing a maximum lift coefficient of 2.4. Because of this high lift coefficient, the stagnation point lay fairly far back on the bottom surface as shown and the velocity around the nose of the airfoil was actually 3.4 times flight velocity, which is large, but considerably smaller than that expected at maximum lift coefficient for this airfoil.

It will be seen from Fig.3 that separation of the flow takes place at exactly the point where the centrifugal forces exceed the static pressure gradient toward the wall. In other words, the criterion for separation for extremely curved flow fields does not depend on the viscosity of the air nor the boundary-layer thickness, but only upon the balance of centrifugal and pressure gradient forces.

With this concept in mind, one can see that the basis for designing the so-called "high-speed" duct by simply rotating a classical airfoil is bound to lead to difficulties due to flow separation around the leading edge of the duct. The obvious reason for the classical airfoil's failure, when used for this purpose, lies In the fact that the classical airfoil is designed for angles of attack of no more than 30 deg. yet the duct entry must handle a change in flow direction. of 180 deg.

In order to portray how abrupt the centrifugal separation on an inlet to a ducted propeller can become, there Is shown In Flg.4, a liquid-film photo[5] of the flow around the leading edge of a duct having an NACA 4415 airfoil cross section. The liquid-film method consists of allowing a volatile liquid containing a dye to ooze out of a series of holes on a plate erected parallel to the duct section on the leading edge. The wide band of dye on the plate is on the outside of the duct. The area of separation is clearly evident where the dye is no longer deposited In the streamwise direction.

It is apparent from this illustration that the centrifugal separation is very abrupt taking off at an angle of almost 45 deg. It Is also quite evident that the separated area will re-

---

[5] H.M. Claybourne. "Study of a Shrouded Propeller with Distributed Suction on the Inlet Profile," Mississippi State University, Aerophysics Department, Research Report No. 20, January 20, 1959.

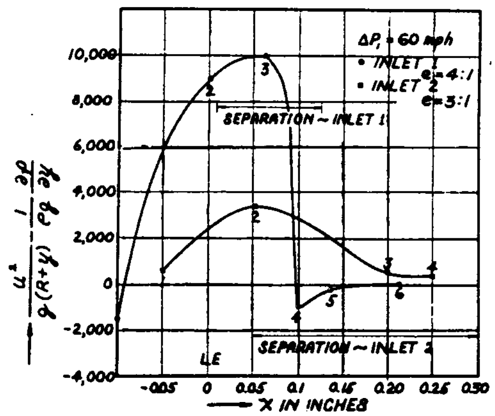


Fig.5 Centrifugal separation parameters for two elliptic inlets

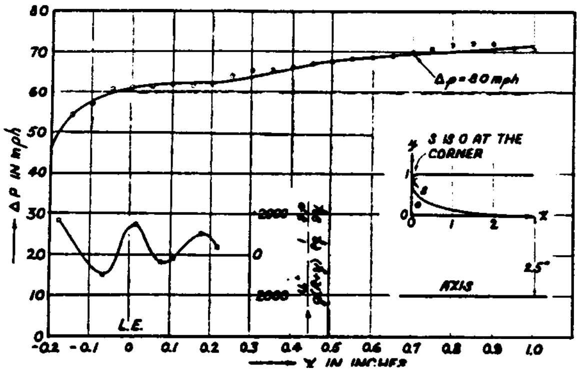


Fig.7 Pressure distribution and centrifugal separation terms along wall at axisymmetric Borda mouthpiece

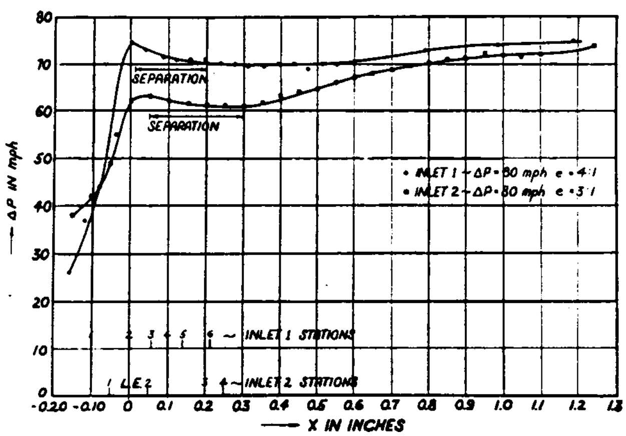


Fig.6 Pressure distribution along walls of two cambered elliptic inlets

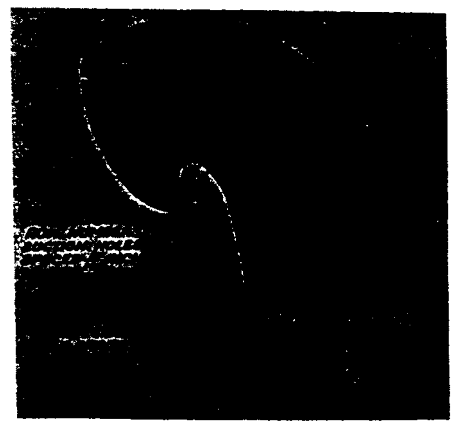

Fig.8 Flow visualization of duct propeller inlet with suction BLC

sult In the propeller tip being stalled since the effective angle of attack of the blade tip is quite large when the flow velocity is low. The stalled propeller tip then results in a tip vortex which Implies large induced drag, thereby resulting in poor propulsive efficiency at low speeds. Furthermore, the separation of the flow on the inlet results in a reduction of the suction pressure peak on the inlet. A large loss of static thrust is then experienced by the Propeller-duct combination.

If then an airfoil shape cannot be used for the duct cross section, what can be said about a better shape? Based on the concept of, centrifugal separation, ye can say that the inlet should be so designed that the centrifugal term $U^2/gR$ is kept as low as possible around the nose. obviously, what is desired is that the flow velocity will be low where the curvature is large. A surface which has such a behavlor is that of a cambered elliptic inlet, with the camber concave outward.

In Fig.5, are shown the results of measurements of two cambered elliptic Inlets. It till be seen that the elliptic inlet of eccentricity 4:l allows unbalanced accelerations of 10,000 g's to be developed in the flow, whereas for an inlet of eccentricity 3:1, this acceleration is down to 3200 g's.

As a matter of fact, the pressure distributions taken along the wall for these two cases, Flg.6, show clearly the pressure peak for the 4:l ellipse to be much greater than that for the 3:l elliptic entry.

It has been possible to design an inlet absolutely free of separation using the concept of transforming the Borda mouthpiece for use in axisgmmetric flow. This was done by Dr. T. Maekawa.[6] Fig.7 shows the pressure distribution

[6] Fulbright Research Professor at Mississippi State University, 1957-1959, Physics Department, University of Hiroshima, Japan.

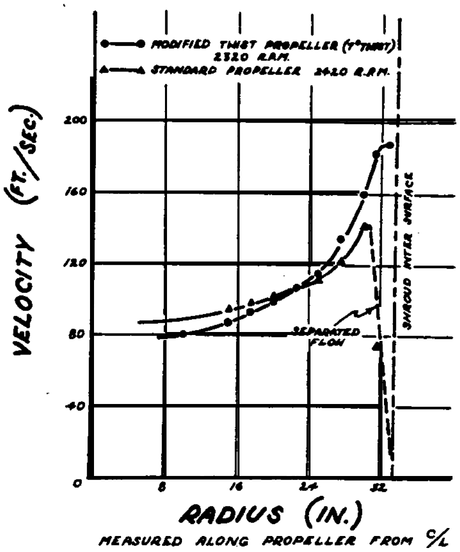


Fig. 9 Velocity distribution ahead of propeller AG - 14 shroud, static

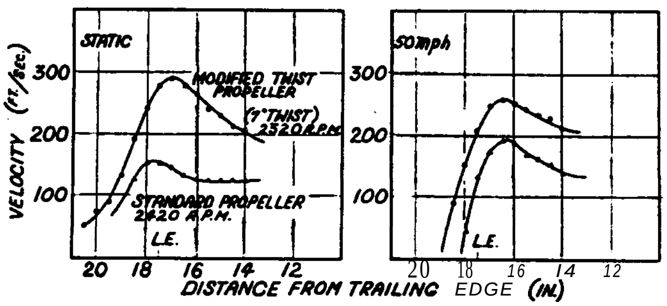


Fig. 10 Typical velocity distributions around leading edge of AG - 14 shroud

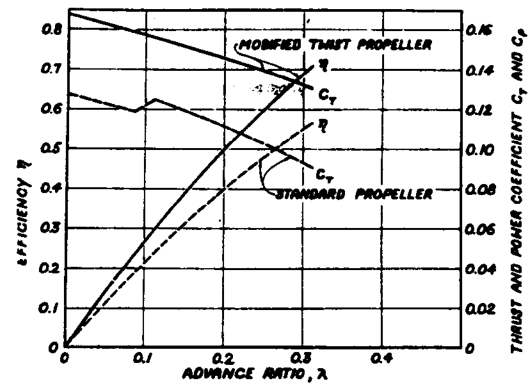


Fig. 11 Performance of standard and modified twist propellers in a 5.5 ft duct 90-hp engine at full throttle

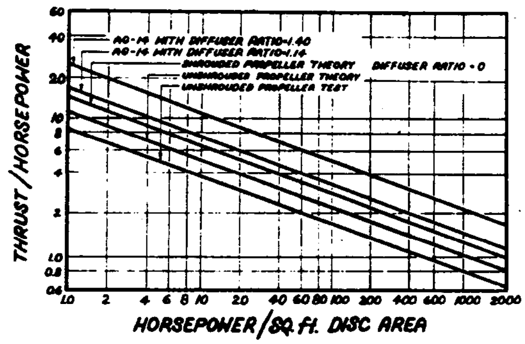


Fig. 12 Ducted propeller performance for various diffuser ratios compared to unshrouded propellers

along the wall for this inlet tested under similar conditions to the elliptic Inlets.

In addition to geometric means for controlling the flow around the leading edge of a duct, there is the possibility of using distributed suction to Introduce an acceleration toward the wall, thereby preventing the occurrence of centrifugal separation. In Fig.8, there is shown a flow similar to that in Fig.4, except that In Flg.8, suction pressure was applied to three lines of holes around the periphery of the nose, through which air was sucked.5 It is clearly evident that the flow is completely attached to the wall of the duct. In fact, the flow is seen to be converging Into a very narrow tube, having extremely high velocities near the wall.

It is this very problem of flow acceleration near the wall of the duct which has resulted In rather poor results being obtained with conventionally twisted propellers when placed In ducts.' This aspect of ducted-propeller design will be discussed next.

## Twist Distribution for Ducted Propellers

In Fig.9 are shown the velocity distributions across the propeller plane for two differently twisted propellers In the same duct.7 The standard propeller is a conventionally twisted propeller originally used In the AG-14 airplane as a pusher. The twist was such that the blade setting at the 0.66 radius point was 4.2 deg, larger than that at the tip. The modified twisted propeller was similar to the former, except that it was made of constant chord and constant angle to within 0.9 radius, where the twist was gradually increased to 7 deg at the tip.

This illustration shows that the convention-

[7] D.E. McNay, "Study of the Effects of Various Propeller Configurations About a Shroud," Mississippi State University, Aerophysics Department, Research Report No. 14, February 1958.

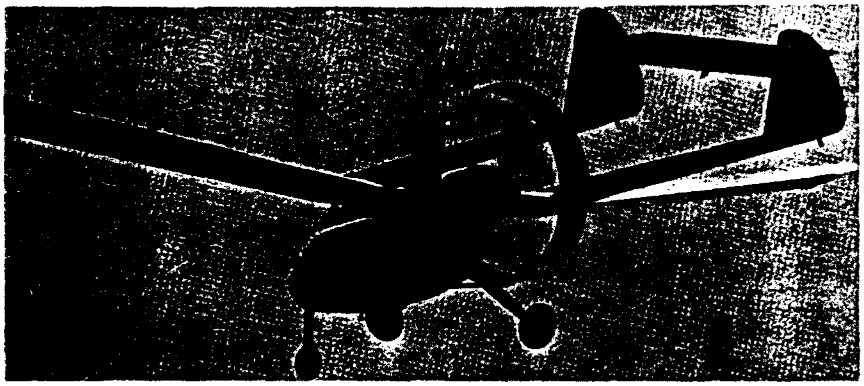

Fig. 13 AG - 14 ducted-propeller research aircraft

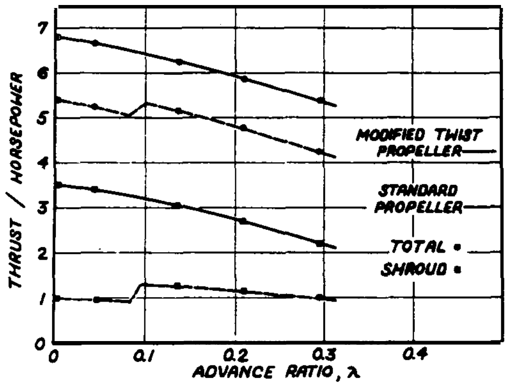


Fig. 14 Thrust per HP versus advance ratio for standard and modified twist propellers in 5. 5-ft duct with 90-hp engine, full throttle

ally twisted propeller suffered from separate flow occurring on the inlet and passing through the propeller. As a result, the peak velocity through the duct was much lower than with the positively twisted blade. The propeller was operating in this separated flow with Its tips stalled.

Fig.10 shows the influence on the flow on the wall of these same two propellers mounted in the same duct. Quite clearly, the modified twist propeller develops a much higher thrust on the duct since the integral in the axial direction of the pressure distribution on the duct is the value of the thrust of the duct.

The over-all behavior of these two ducted-propeller combinations is shown in Fig.11, where the propulsive efficiency and the coefficient of thrust are plotted against advance ratio. The distinct advantage of the positively twisted (modified twist) propeller over the speed range of the measurements is clearly demonstrated. Also, It must be mentioned that it is entirely possible by additional research to improve still further the performance of the ducted propeller throughout its speed range by utilizing the modified twist concept.

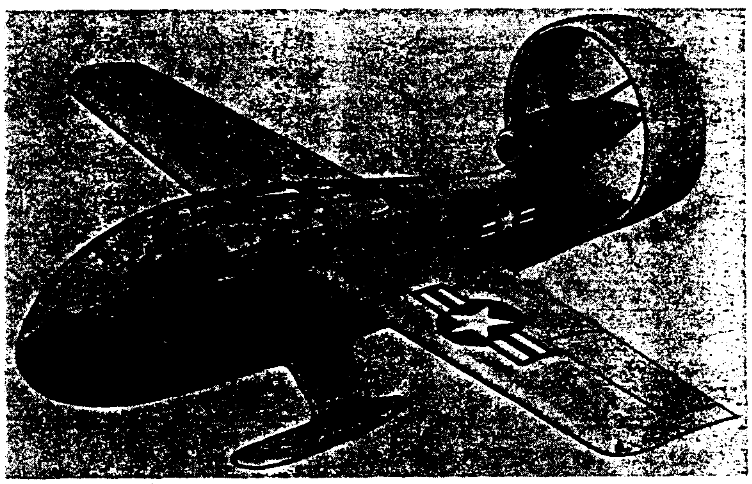

Fig. 15 "Marvel" example of ducted-propeller aircraft utilizing duct for propulsion and for control and stabilization

## Diffuser on Inside Duct

After having designed the proper Inlet, and then having adjusted the propeller twist to match the resultant Inflow velocity profile, there still remains one Problem of the ducted propeller; namely, the diffusion of the flow behind the propeller. If the velocity energy of the flow can be recovered as pressure applied to the inclined Inner wall of the diffuser, one can gain in static thrust for the same power expended in the propeller. Fig.12 shows the plot of theoretical T/HP versus HP/sq ft, for the conventional open propeller, for a ducted propeller of zero diffusion, for the duct with moderate diffusion, before mentioned,5 and for a highly diffused duct which was a modification of the former. It can be seen that there can be made a considerable gain in static thrust if the diffuser flow can be maintained attached. Perhaps by using distributed suction on the diffuser, it would be possible to achieve this gain.

However, to date, such high diffusion ratios on a ducted propeller have not proven useful. In fact, for a STOL airplane, the higher diffusion ratio duct must Inevitably result in a higher drag In cruising flight.

## Practical Applications

A typical experimental airplane on which a ducted propeller was found to yield a large performance improvement in take-off and climb is shown in Fig.13. The duct consisted of an NACA 4415 airfoil modified to a cambered elliptic nose of eccentricity 2.5:1. With the modified twist propeller, the static thrust was 560 lb, using a 90-hp engine. Originally, the open propeller of conventional twist developed a thrust of 265 lb.

The improvement in take-off and climb was quite significant since the thrust at low speed was almost doubled.

However, the cruising performance was not significantly improved because the conventional tail as well as the duct added to the over-all drag at high speeds. Fig.14 does show that the total thrust for the duct shown in Fig.13, even at advance ratios up to $\lambda = 0.3$, is better when a modified twist propeller is used.

## New Design

When the ducted propeller is utilized in an original design to take advantage of its best features, we arrive at an airplane of the configuration shown In Fig.15. Here the ducted propeller is used as a pusher, the duct providing stabilization and control in pitch and yaw. In addition, the airplane shown uses high-lift boundary-layer control, achieved by means of suction through distributed perforations.

Since the static thrust of the ducted propeller driven by a 250-hp gas turbine will be around 1800 lb for an airplane gross weight of 2200 lb, a thrust-to-weight ratio of 0.82 will be attained. Having such a thrust-to-weight ratio means that the airplane can take off on skids from any type of surface; runway, grass, mud, ice or snow, and even plowed fields, with an acceleration of at least 0.4 g. Landing In unprepared fields is made quite safe by the use of skids long enough to bridge ditches, and holes and even cross furrows.

Later on In the development of the STOL shown in Fig.15, research now being carried on will permit the marriage of the high-lift-suction boundary-layer-control system with low drag-suction boundary layer control., Such a combination will permit this airplane to fly at 500 mph on 250 hp at 20,000 ft, whereas without this combination low-drag and hi&-lift system, the top speed at 20,000 ft is 350 mph.

Since Its landing and take-off-will be done at 35 mph, using high-lift boundary-layer control, very short fields will suffice. Estimates of take-off distance over a 50-ft obstacle from grass fields show that the total distance should be around 150 ft. Landing will be a corresponding distance.

## Conclusion

In this paper, an effort is made to show that the ducted propeller provides an Ideal propulsor for STOL airplanes utilizing high-lift boundary-layer control of an energy-conservative type.

It is shown that the design of a ducted propeller for STOL application Involves the correct design of the entry contour as well as a correct matching of propeller-pitch distribution to the Inflow velocity distribution at the propeller plane.

Having designed the ducted propeller with these two considerations, there is left only the problem of diffuser ratio at the aft end of the duct. The choice here depends on the airplane speed ratio. Additional research on this aspect should permit a rational choice to be made.

What recommends the ducted propeller for a high-performance STOL airplane Is Its multiple function of propulsor, stabilizer, and control element. In addition, the freedom from turbulent flow over the fuselage and wing Permits the pusher-ducted STOL to attain high cruising speeds on moderate power.