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AERODYNAMIC INTERFERENCE BETWEEN PUSHER PROPELLER SLIPSTREAM AND AN AIRFRAME – LITERATURE REVIEW

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Abstract

In the article, an aerodynamic interference between pusher propeller slipstream and the airframe of the aircraft powered by it has been presented, based on a literature study. A pusher propeller is one of popular types of the airplane propulsion. It is applied mainly in light sport aircrafts, in the UAVs (Unmanned Aerial Vehicles), unorthodox vehicles, like compound helicopters, canard and joined wing aircrafts etc. The main advantage of pusher propeller is that the engine with the pusher propeller does not affect the visibility from the cockpit and allows placing an electronic equipment in the front part of the UAV's fuselage. Furthermore, reduced cabin noise and increase in stability due to acting normal force aft of the centre of gravity are other benefits of this configuration. The pusher propeller impact on the airframe, especially on the wing, is qualitatively different from the tractor configuration. Main differences between both propulsions has been discussed, as well as aerodynamic benefits of the pusher propeller – like reduction of separated flow area and extending area of laminar boundary layer. However, an application of pusher propeller may have also negative impact, especially lower performance than tractor propeller. In the article the reasons of this suppression has been briefly discussed.

Keywords: *air transport, air propulsion, pusher propeller*

1. Introduction

Propeller is the oldest type of propulsion used in aviation. Although its application is nowadays limited for low-speed (subsonic) aircrafts, recent growth of oil prices caused that the knowledge of propeller phenomena is of interests again [12]. It is related with its efficiency, which is 10-30% higher than turbojets and high bypass turbofans, with slightly lower cruise speeds [15, 18].

One of commonly used configuration of the propeller propulsion is the pusher propeller. It is a propeller mounted behind engine so that drive shaft is in compression [7]. Advantages of this propulsion, according to [6], is unobstructed forward view, reduced cabin noise, increased stability due to acting normal force aft of the centre of gravity etc.

The pusher propeller is not so popular propulsion, as tractor one, however, there are some areas in aviation history, where this propulsion was commonly used, i.e.:
- early fighters (World War I),
- late propeller-powered military aircrafts (late 1940s),
- ultralight aircrafts (1970s-1990s),
- motor gliders (1920s – nowadays),
- seaplanes,
- unorthodox aircrafts, i.e. canards,
- unmanned air vehicles,
- light autogyros and powered hang gliders,
- compound helicopters (1950s, nowadays).

One of the most important disadvantages of pusher propellers is that the fuselage ahead of the propeller may distort flow inside the streamtube, causing asymmetric disc loading and increased blade stresses. This distortion may affect the propeller's performance [6]. A propeller efficiency may be reduced by up to 15% for the pusher propeller, while the efficiency of a tractor propeller decreases only by 10% (see Fig. 3). The graph presented in Fig. 3 includes an axisymmetric nacelle only. It should be noted that the pusher propellers usually have small diameter, because of construction constrains and due to small distance from the ground during take-off and landing, when the angle of attack is high. In this case, the influence of the fuselage is significant [13].

Fig. 1. Quad City Challenger light aircraft, 1983 (left), Beech Starship GA aircraft, 1986 (right) [22, 23]

Fig. 2. MQ-1 Predator UAV, 1994 (left), Sikorsky X-2 - compound helicopter, 2008 (right) [24, 25]

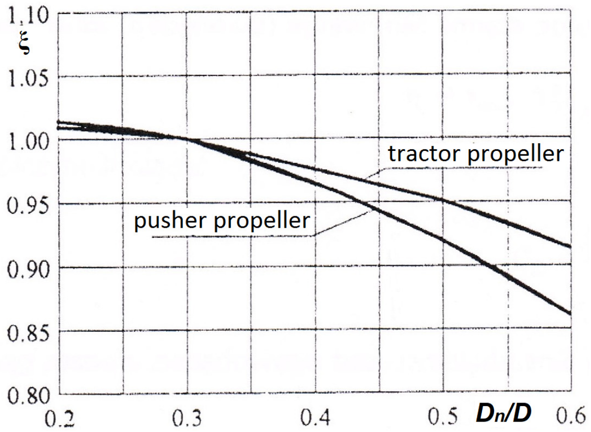


Fig. 3. Correction factor of tractor and pusher propeller efficiency (ξ – relation between propeller efficiency with and without a nacelle, D_n – nacelle diameter, D – propeller diameter) [8, 20]

For several years, one could observe the lack of interest in propeller research, which results with limited availability of experimental results [12]. However, in recent years some new experiments have been performed, focused on the model or its propeller [3, 5] or on the slipstream of the propeller [12, 17]. It should be noted that experiments concerning the slipstream usually requires fast response of the measurement equipment, which is related to high revolution speed of propeller. It also may be connected with large amount of data recorded during the experiment. Thus, the hardware significantly limited the experimental investigation of the propeller slipstream.

Hardware limitation is noticeable also in case of numerical investigation, which is a result of complexity (three-dimensionality and unsteadiness) of the propeller flow. As a result, some simplifications in the calculations have to be made, such as modelling the propeller as an actuator disc, neglecting of the viscosity [2] and difficulties in wake modelling [4]. Another simplification, shown by several authors [9, 10], as acceptable for practical applications, is treating the unsteady flow in the slipstream as a time-averaged. This approach can also be found in some investigations focused on the propeller-powered object [1, 5, 19]. Other problems are the distinction between numerical dissipation and turbulence decay [16] and the computational costs of performing 3-D unsteady propeller calculations.

2. Interference between a propeller slipstream and a wing

An aerodynamic impact of the propeller slipstream, both pusher and tractor, has been investigated mostly for propeller-wing interference. A comparison between tractor and pusher propeller has been described i.e. by Zalewski [21], based on CFD calculations of a twin-engine, unmanned aircraft with electric drive. It has been presented that the influence of pusher propeller is qualitatively different from tractor propeller. In the latter case, the swirl of the slipstream disturbs the span wise distribution of local angle of attack. It has been explained by Veldhuis [19] for different areas of a wing, as it is presented in Fig. 4.

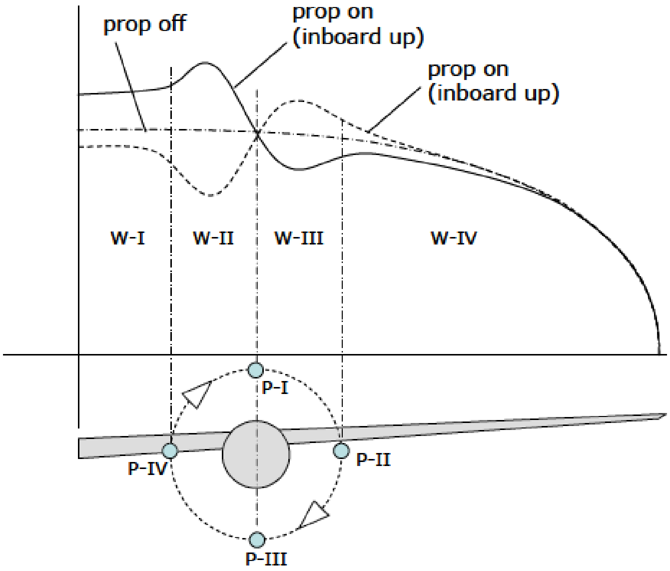


Fig. 4. Influence areas related to propeller-wing interaction based on the loading distributions [19]

One can observe that the angle of attack of the wing behind the blade going up is increased because of the swirl, which causes an increment of lift. Similarly, behind the blade going down the angle of attack of the wing (and thus the lift) is decreased. This effect does not appear in case of the pusher propeller. However, in both cases the slipstream causes an increment of the axial velocity of the flow, which increases drag. It can be observed on the span wise distribution of local drag coefficient, plotted for the aircraft investigated in [21] with pusher propeller, tractor propeller and without any propeller as a reference (Fig. 5). The right half of investigated aircraft has been presented above the graph.

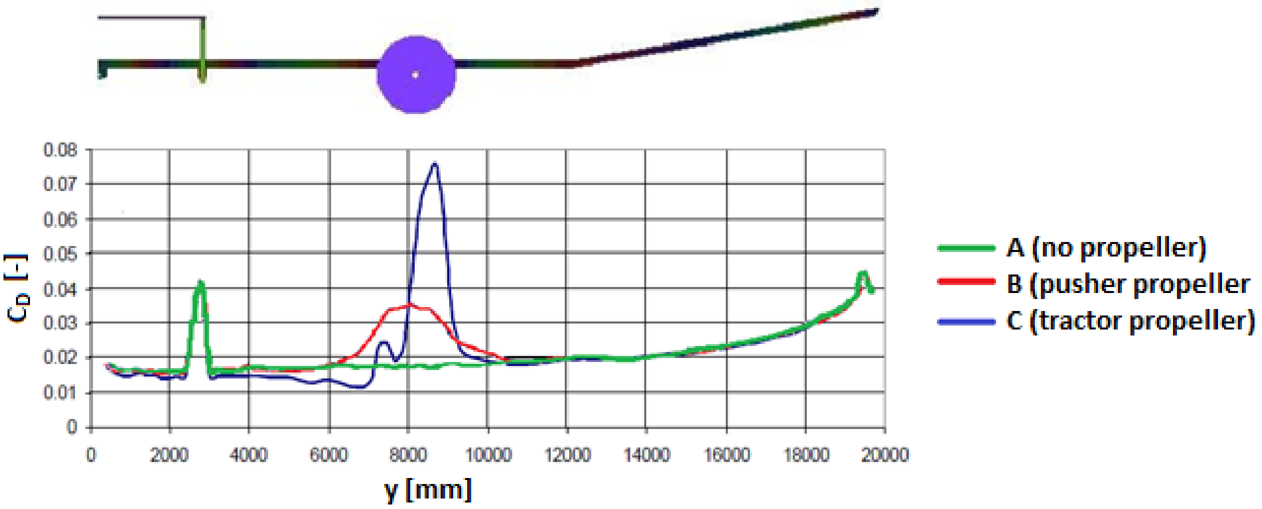


Fig. 5. Span wise distribution of the local drag coefficient (based on data from [21])

For the investigated case (cruise conditions, i.e. α = 0°) the lift in case of pusher propeller is nearly equal to the lift in 'no propeller' case. It may be explained by similar increment of the airflow speed on lower and upper surface of the wing (in investigated position of the propeller). Meanwhile, in case of tractor propeller a slight gain of lift coefficient can be achieved, due to disturbance of local angles of attack. Taking into account that the drag coefficient increases similarly for both kinds of propeller, one can note that the lift-to-drag for tractor propeller may be greater than for the pusher one. It has been illustrated in Tab. 1, where differences between a 'propeller' (tractor on pusher) configuration and 'no propeller' configuration, related to 'no propeller' values, has been presented. Tab. 1 contains changes of lift coefficient C_L, drag coefficient C_D and lift-to-drag ratio L/D obtained for the unmanned aircraft investigated in [21] for cruise conditions.

Tab. 1. Change of aerodynamic coefficients for the aircraft with tractor and pusher propeller, α = 0° [21]

	Pusher propeller	Tractor propeller
ΔC_L	+0.87%	+4.71%
ΔC_D	+9.21%	+8.33%
Δ(L/D)	–7.59%	–3.25%

It must be underlined that the lift increment for the pusher propeller may be increased by shifting the propeller axis upwards. It has been illustrated by Catalano [3] with the wind tunnel investigation of the wing and various tractor and pusher propellers. The lift coefficient increases of about 0.25 in the linear range of the $C_L(\alpha)$, as it has been presented in Fig. 6. The result of this benefit, according to [3], is the increase in effective incidence and camber influenced by the propeller inflow, which in turn causes an increased suction on the upper side of the airfoil. However, the increased suction appearance in the proximity of trailing edge results also with an increased drag. The influence of pusher propeller becomes more significant for high angle of attack. In Fig. 6, one can observe a strong delay of the stall. While the wing with propeller stopped has its maximum lift coefficient of 1.75 (for α = 12.5°), the propeller slipstream increases it to over 2.20 (for α > 20°). This effect is obviously related with the movement of the separation point downstream, caused by the suction of the propeller, which reduces a pressure gradient.

Location of the flow separation point for various angles of attack has been presented in Fig. 7. It is clearly visible that the propeller shifts the separation point forward for over 10% of the chord, nearly independently from the angle of attack.

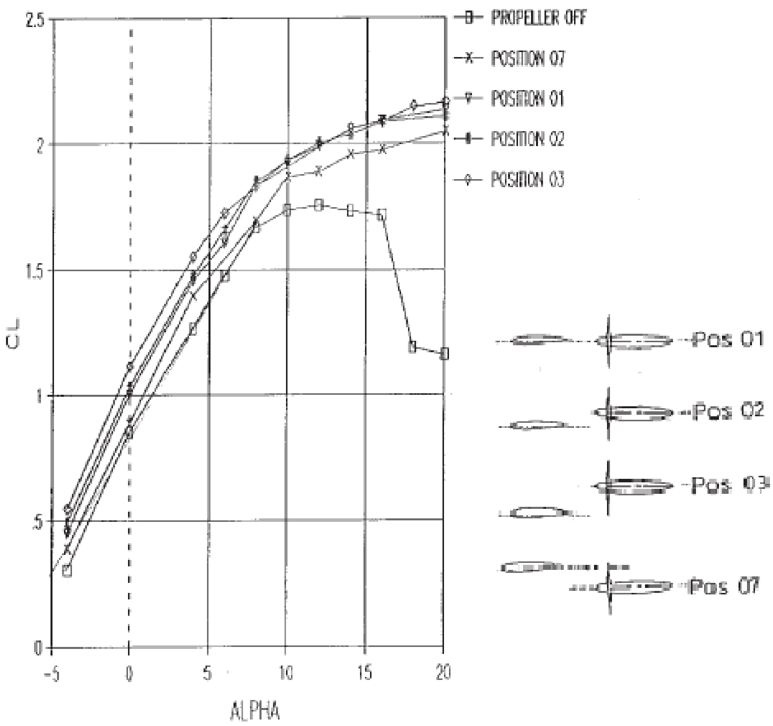


Fig. 6. Lift coefficient versus angle of attack for various positions of pusher propeller [3]

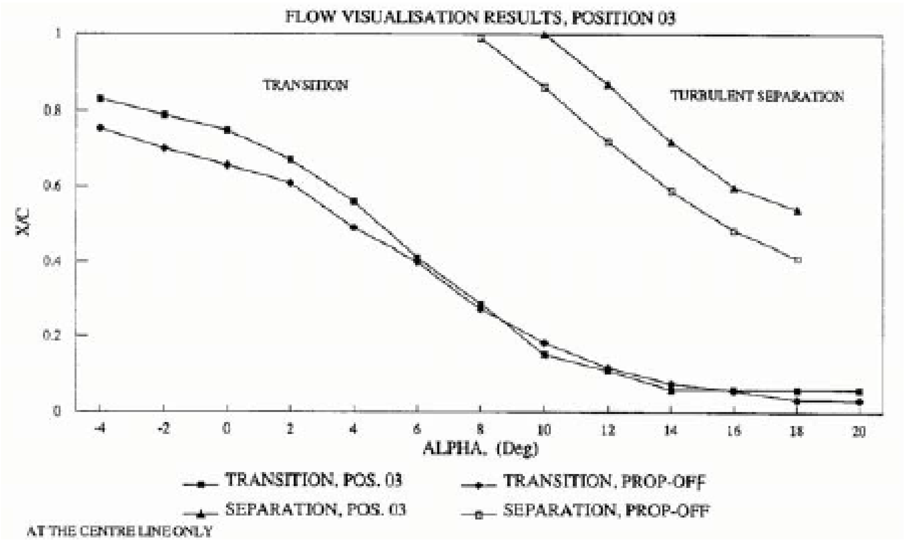


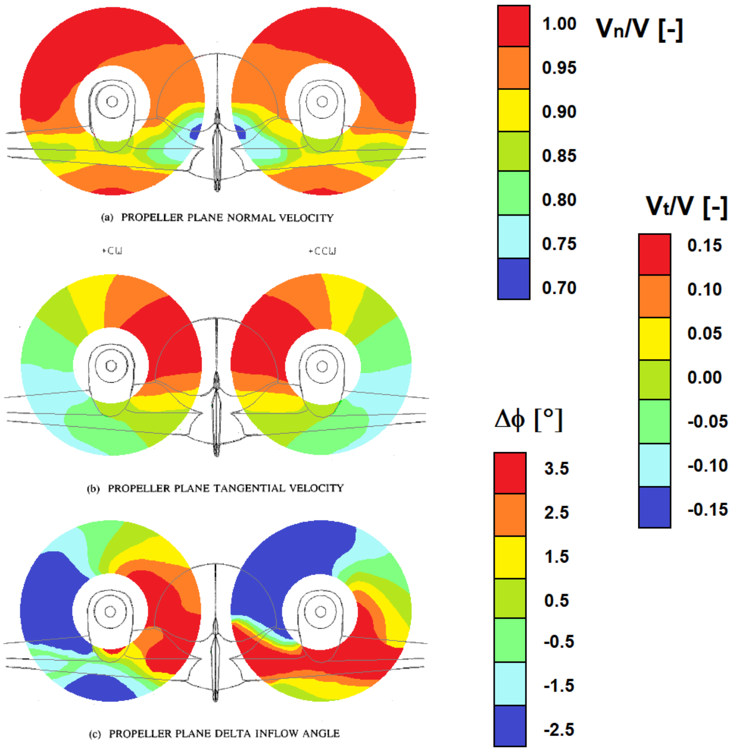
Fig. 7. Location of flow separation point and laminar-turbulent transition point [3]

In Fig. 7, the location of transition point has been also presented. It should be noted that the propeller slipstream might slightly increase the area of laminar boundary layer, for lower angle of attack values (below 6-8°, depending on vertical position of the propeller). It may partially compensate the increment of pressure drag related to the suction in the area of trailing edge. The drag decreases also due to a shift of the resultant force forward, which will thus produce a small thrust force. On the other hand, for higher angles of attack the transition point may be shifted forwards in comparison with ‘propeller off’ case – especially if the propeller axis lays above the wing. The resultant increase in drag is however significantly lower than benefits of flow separation delay.

In case of tractor propeller, laminar boundary layer is significantly reduced (even up to 80%), because the tractor propeller acts in an unsteady fashion, due to the propeller wake and tip vortex crossing the wing surfaces [3].

2. Interference between the propeller slipstream and a fuselage

The interference between pusher propeller slipstream and the wing, described above, is relatively well known. Meanwhile only a few publications can be found in the literature that discusses the issue of an impact of the propeller on the fuselage or other elements of the aircraft, and vice-versa. It may be surprising, because many pusher-propeller aircrafts has the propeller close to the fuselage (Fig. 1 and 2). This may be however caused by a fact that, as found Pfeiffer in [11], pusher propeller aircraft can have very non-uniform inflow velocity fields due to the disturbances from the aircraft surfaces upstream. Wing, flap, canard, tail and pylon wakes can all have variations for general pusher configurations. In Fig. 8 an exemplary distributions of normal velocity, tangential velocity and inflow angle has been presented. These distributions were obtained during wind tunnel tests of the model of Beechcraft Starship (Fig. 1), described in [11]. One can observe that the normal velocity is significantly – up to 30% – reduces behind fuselage, wing and engine nacelles. The tangential velocity may also achieve large values, up to 15% of the flight speed. Both distributions are symmetrical for both propellers, but the distributions of inflow angle are asymmetrical, because both propellers rotate counter-clockwise. It should be noted that the inflow angle changes in wide range (up to 3.5°) and this angle might change very steeply.


(a) PROPELLER PLANE NORMAL VELOCITY

(b) PROPELLER PLANE TANGENTIAL VELOCITY

(c) PROPELLER PLANE DELTA INFLOW ANGLE

Fig. 8. Flow field parameters at propeller disks of Beechcraft Starship (based on [11])

Another drawback for airframe – propeller interference investigation is that even small change of the aircraft geometry may significantly change the inflow velocity field. In [11] such changes concern nacelles (including direction of propellers' axes) and the trailing edge of wing to improve the uniformity of all presented distributions. It has to be noted that change of direction of propeller axis may be advantageous, because normal/tangent velocity components are changed. The total velocity vector remains the same or it is only slightly changed. The flight tests proved that better uniformity of the flow field means better performance and reduced propeller stresses.

The introduced changes cover only aft part of the aircraft, which suggests that this part is responsible for the flow field on the propeller, much more than the front part. It is confirmed by good agreement of pusher propeller test results described in [14]. These tests were consisted of two parts. First part concerned a full joined-wing aircraft, powered by a pusher propeller. The second part covered the pusher propeller in presence of aft part of the airframe (including root part of aft wing). The difference between thrust values obtained in both parts was below 10%; however, the repeatability of measurements was insufficient.

Conclusion

A pusher propeller is a popular solution of the propeller propulsion, which may be beneficial due to some design aspects. This type of propulsion also can be beneficial because of reduction of the separated flow zone or enhancement of the area of laminar boundary layer on the wing. However, its aerodynamic properties are relatively complex, because the aerodynamic interference between the propeller slipstream and the airframe plays an important role. The interference effect is quantitatively different from in the tractor propeller configuration because of no swirl of the slipstream and because of elements of the airframe placed in front of the propeller. The latter one causes significant disturbance of the flow field on the propeller disks. This disturbance is sensitive even for small changes of airframe geometry, thus it is difficult to analyse it in a theoretical way.

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