PROPULSIVE EFFICIENCY OF BOUNDARY LAYER INGESTION PROPELLERS

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Abstract

The pursuit of lower fuel consumption for aircraft is promoting a departure from contemporary arrangements. One example is the development of more synergetic airframe and propulsion system designs, which are expected to increase significantly aircraft efficiency mainly by means of boundary layer ingestion. By integrating propulsion and airframe, both systems will significantly impact each other. This mutual interference requires the development of novel performance evaluation methods that consider such effects. This manuscript introduces a propulsive efficiency equation for boundary layer ingestion propellers based on the power balance method. Two formulations are presented for numerical and analytical evaluations. The equation is bounded between 0 and 1 and allows a meaningful evaluation of shaft to propulsive powers conversion, which results in an accurate determination of thrust and drag. This manuscript is the first advance of a project that will develop an optimizing tool for boundary layer ingestion propellers based on computational fluid dynamic simulations. The results will be presented in subsequent manuscripts.

1 Introduction

The increasing amount of flights over the last decades and in the foreseeable future emboldens constant progress towards reducing fuel consumption and emissions. Aircraft manufacturers are driven to meet strict environmental regulations set over the past decades, which promotes a departure from contemporary arrangements [1]. For instance, the classical separation of airframe and propulsion systems is shifting towards more synergetic designs in which the aircraft components experience beneficial interactions [2]. One example is the development of a fuselage encircled by a propulsion system, known as propulsive fuselage [3].

The propulsive fuselage arrangement benefits from Boundary Layer Ingestion (BLI). When a propulsion system ingests the wake produced by a body upstream, the aircraft forward speed can be maintained with a lower outflow velocity magnitude. Thus, the body wake is regarded as a power input for the propulsion system [4]. Moreover, the closely integrated design reduces the surface area 'wetted' by the air, reducing the overall drag and to some extent the weight [5]. The BLI concept has been extensively applied to naval vessels; for aircraft, the fuel consumption reduction enabled by BLI has been recognized since the 1940s [6]. However, complications related to non-uniformity of the propulsion system inlet flow and high development cost undermined the applicability of BLI for aircraft. Although a 18% power saving has been obtained experimentally [7], the potential benefit is highly dependent on the configuration [8].

The traditional approach to aircraft design relies on calculating the airframe drag and sizing the propulsion system accordingly. The calculations are based on a system of thrust and drag accounting, appropriately called bookkeeping, to ensure that no force component is overlooked or counted twice [9]. This standalone approach works well for freestream propulsion systems as it is reasonable to assume that the interaction between airframe and propulsion is neglectable [10]. However, for BLI configurations, the airframe affects the propulsion system and conversely to a significant extent. The conventional subtraction of gross thrust from ram drag cannot be employed to BLI aircraft [5].

The synergetic design of airframe and propulsion system implicates in a mutual interference. Comparing traditional and propulsive fuselage, the latter presents a higher drag since the propulsion system induces a lower pressure at the rear of the body, which will increase the pressure drag due to a larger pressure difference along the body and the profile drag due to a higher flow velocity near the body [11]. On the other hand, BLI enhances the propulsion system performance. Therefore, it is noticeable that part of the drag and thrust are induced by the propulsion system and fuselage, respectively. The conventional bookkeeping performance calculations must be modified accordingly.

According to Drela [12], the performance calculations of BLI aircraft can be accomplished by focusing on mechanical power and kinetic energy flow. This power balance method waives the definition of thrust and drag, which is especially useful to evaluate tightly integrated propulsion systems. The goal of this manuscript is the development of an equation to calculate the propulsive efficiency of BLI propellers through power balance, which allows the determination of drag and thrust.

2 Power Balance Method

The traditional performance calculation of aircraft focuses almost exclusively on the momentum analysis to obtain relations between aerodynamic lift and drag; the propulsive power is then determined by multiplying engine thrust by flight velocity [12]. In contrast, the power balance method relates the mechanical power with energy dissipation through a mechanical balance equation. This relation is especially applicable for the evaluation of tightly integrated propulsion systems.

The first step toward defining the mechanical energy equation is the determination of the control volume, seen in Fig. 1. The boundaries are partitioned into an outer boundary (S_O) and an inner boundary lying on the body surface (S_B). In order to simplify the integral expressions derived, the Trefftz plane and the side cylinder, respectively, will be assumed perpendicular and parallel to the incoming flow. The fuel mass flow will be considered negligible.

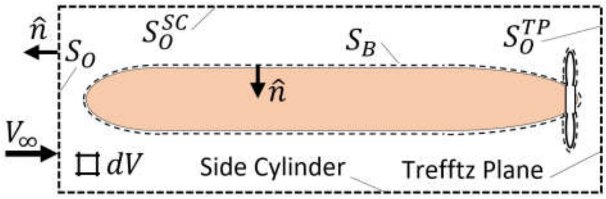

Fig. 1 Control volume definition.

By integrating the mechanical energy over the entire control volume, the power balance equation is obtained (Eq. 1);

$$P_S + P_V + P_K = \dot{\varepsilon} + \Phi \qquad (1)$$

where P_S is the net shaft power for all components covered by S_B, P_V is the volumetric expansion power within the control volume, P_K is the net mechanical power rate across S_B, $\dot{\varepsilon}$ is the mechanical power leaving through S_O, and Φ is the rate at which kinetic energy of the flow is converted into heat within the control volume.

The left side of Eq. 1 represents the mechanical power supply, production, and inflow, respectively. The right side represents the outflow and lost powers. The power balance is valid for steady flow. This concise equation relating power sources and sinks is fully consistent with previous analyses based on momentum and avoid the definition of often ambiguous thrust and drag forces [12].

Considering the five components of the power balance equation, only two of them will be explicitly presented in this manuscript, namely the net shaft power in Eq. 2 and the net mechanical power rate in Eq. 3, since the other terms will not be required to derive the propulsive efficiency;

$$P_S = \oiint (\tau - p\hat{n}) V \, dS_B \qquad (2)$$

where $\hat{n}$ is the vector normal to the boundary, τ is the surface viscous stress vector ($\bar{\tau} \cdot \hat{n}$), p is the static pressure, and V is the flow velocity;

$$P_K = \oiint -p_0 V \cdot \hat{n} \, dS_B \tag{3}$$

where p_0 is the stagnation pressure.

3 Propulsive Efficiency

The propulsive efficiency indicates the amount of shaft power that will effectively become propulsive power. Viscous and shock losses at the blades, kinetic energy downstream of the propeller in a direction either than axial, and induced losses due to the finite number of blades are some of the reasons why part of the energy is lost in the transformation of shaft to propulsive powers. The propulsive efficiency, therefore, accounts for all the losses in this transformation process.

Several studies regarding BLI propulsion systems were published in the past; however, the definition of the propulsive efficiency remains controversial. Smith [13] acknowledged that by calculating the propulsive efficiency of BLI systems according to the traditional Froude formulation, the result could exceed unity, which lead to application of the term propulsive coefficient instead. The critical condition for propulsive coefficients greater than one is when the wake entering the propulsion system is larger than the wake leaving it [4]. The misrepresentation of the propulsive efficiency is related to the fact that BLI propulsion systems inlet velocity is lower than freestream velocity. Therefore, considering the propulsive power as thrust multiplied by freestream velocity will result in an unrealistically high value. The reduced velocity at the propulsion system inlet must be considered instead to achieve values below unity [14].

According to Drela [12], several studies calculate the power saving of BLI propulsion systems by assuming that the ingested airframe boundary layer is the same as calculated by the standalone airframe. However, the presence of a propulsion system downstream will increase both profile and pressure drag, altering the boundary layer wake. For this reason, the estimation of BLI benefits is complex and highly dependent on the configuration.

3.1 BLI Propellers

The first step toward defining the propulsive efficiency formulation of BLI propellers regards the volumetric expansion power within the control volume (P_V). This power source will have a significant impact whenever heat is added at a high pressure, such as within a combustion chamber [12]. Moreover, the volumetric expansion power contribution for turbofans is about 5% and is not the dominant physical mechanism when evaluating BLI propulsion systems [15]. Therefore, it is reasonable to assume that the volumetric expansion power within the control volume is negligible for propeller driven aircraft.

Considering the alternative control volume inner boundaries depicted in Fig. 2, the left one integrates all surfaces while the right one disregards the propeller surfaces, bounded by the inlet and outlet planes and the height of the blade. When integrating the left surface, the only source of the power balance equation (Eq. 1) will be the shaft power (P_S). On the other hand, when integrating according to the right surface, the only power source will be the net mechanical power rate crossing into the control volume (P_K), which accounts for the propulsive power.

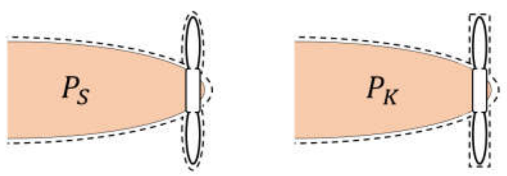

Fig. 2 Shaft power and net mechanical power rate control volumes.

Considering the propulsive efficiency as propulsive power divided by shaft power, Eq. 4 is obtained;

$$\eta_P = \frac{\oiint -p_0 V \cdot \hat{n} \, dS_{P_K}}{\oiint (\tau - p\hat{n}) V \, dS_{P_S}} \tag{4}$$

where η_P is the propulsive efficiency.

4 Discussion

In the past decades, computational fluid dynamics has matured to such an extent that it can provide reliable information regarding aircraft performance [16]. Moreover, the simulation is cost effective when compared to wind tunnel testing and enables an insightful evaluation of loss mechanisms. Eq. 4 is readably applicable to a computational solution. However, another equation will be presented to assess the propulsive efficiency analytically. By considering that the mechanical power leaving through S_O ($\dot{\varepsilon}$) is the same for both control volumes presented in Fig. 2 and applying the power balance (Eq. 1), another propulsive efficiency formulation is presented by Eq. 5;

$$\eta_P = 1 - \frac{\Phi_{P_S} - \Phi_{P_K}}{\Phi_{P_S} + \dot{\varepsilon}} \tag{5}$$

Noticing that $\Phi_{P_S} - \Phi_{P_K}$ is equal to the rate at which kinetic energy of the flow is converted into heat by the propeller and that $\Phi_{P_S} + \dot{\varepsilon}$ is equal to the shaft power, some remarks were drawn regarding the propulsive efficiency:

- The result is bounded between 0 and 1;
- $\eta_P = 0$ indicates that the blades are responsible for all the friction loss and that mechanical power is not leaving the control volume;
- $\eta_P = 1$ indicates that the blades friction loss is 0 since the rate at which energy of the flow is converted into heat is equal for both control volumes;
- The propulsive efficiency is inversely proportional to the blades friction loss and directly proportional to the shaft power.

Considering that the power balance equation is valid for steady flow, thrust will be assumed equal to drag. Multiplying the shaft power by the propulsive efficiency results in the propulsive power, which divided by the freestream velocity will be equal to the drag.

The formulation presented will be employed to evaluate the performance of a propeller driven propulsive fuselage. The blade geometry will be optimized based on computational fluid dynamic simulations to handle the distorted boundary layer flow. Considering the mutual interference of airframe and propulsion system, the process is strictly iterative since designing the propeller requires knowledge of the boundary layer, which depends upon the installed thrust. The optimal design relies on a careful balance between aerodynamic and propulsive considerations [17]. The results will be presented in subsequent manuscripts.

5 Conclusion

A propulsive efficiency equation for BLI propellers based on power balance method has been introduced. Two formulations were presented for numerical and analytical evaluations. The equation is bounded between 0 and 1 and allows a meaningful evaluation of shaft to propulsive powers conversion, which results in an accurate determination of thrust and drag. The equation presented will be employed in posterior manuscripts to evaluate BLI propellers.

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