Wing Pitching and Loading with Propeller Interference

R. M. Ardito Marretta,* G. Davi,† and A. Milazzo‡
Universitá degli Studi di Palermo, Viale delle Scienze, Palermo 90128, Italy
and
G. Lombardi§
Universitá degli Studi di Pisa, Via Diotisalvi 2, Pisa 56126, Italy

Introduction

THE wing loading variation and shifting of the c.p. generated by the interaction with a propeller are the subjects of this numerical investigation. This problem involves a time-dependent loading variation on the wing when positioned behind the wake of a propeller. The focus of this paper is to numerically model and analyze the behavior and the mechanism of mutual interference between the two wakes, both for the propeller and the wing on which it is mounted. The investigation considered here is purely computational and it is assumed that the flow is ideal and inviscid. The free wake analysis (FWA), as confirmed by new experimental results obtained from tests performed on a scale model in subsonic wind tunnels,[1,2] is successful in numerically determining the wing–propeller interference. The mechanism of the interaction between wing and propeller has been described by Witkowski et al.,[3] by assuming that the flowfield is inviscid and quasisteady behind the propeller, whereas Cho and Williams[4] and Rottgermann and Wagner[5] focused on the problem of the dominant frequencies in unsteady flows. The results presented by Catalano,[6] who made use of Konig's theory, highlighted the behavior of the coupling of a two-dimensional smooth wing and a pusher propeller. The isolated propeller was analyzed by Kinnas and Hsin,[7] by means of the boundary element method (BEM), and by Graber and Rosen,[8] who presented an effective method of calculating the axial and radial components of the velocities induced by semi-infinite helical vortex filaments. More recently, Yamaguchi and Bose[9] and Bose,[10] using a two-dimensional time-domain panel method, analyzed the behavior of a propeller in oscillatory motions, as well as under chordwise deflection of large amplitude. Meanwhile, the measurement of helicopter rotor flow at hover flight has been carried out by Müller et al.,[11] through a flow visualization gun time-line technique. Without compressibility effects on the blade, results show that the conclusions obtained by using the quasi-steady model are similar to those of the more complex unsteady one. Using this as basis, the wakes and the three-dimensional components of the induced velocity have been investigated and calculated by a hybrid FWA–BEM approach. The numerical procedures usually involve a discretization into a large number of panels for both the wing and the blades; in this case, however, for the interference of a wing and a tractor propeller, a single line vortex is sufficient to correctly model each blade of the propeller. Following Chiaramonte et al.,[1] Favier and Maresca,[12] Favier et al.,[13,14] Ardito Marretta and Lombardo,[15] Ardito Marretta,[16] and, more recently, Ardito Marretta et al.,[17] in the present work the isolated propeller and the wing in a freestream are modeled by FWA and BEM, respectively, and an algorithm based on the hybrid FWA–BEM approach[18] is applied to find the mutual influence of the wing and propeller and its effects on aircraft performance. A previous analysis for the tractor configuration, based on the FWA, allows the wake and propeller blades to be represented by lifting lines,[19] and more detailed results become available for the flow past the propeller. Moreover, to improve accuracy in describing the effects of the superposition of the propeller velocity field on the isolated wing circulation, instead of the classical Prandtl scheme, the theory owing to Pistolesi–Weissinger[20] is employed; in this theory the bound vortex is placed at the wing quarter chord line and the velocity tangency condition to the surface is imposed at the three-quarter chord line, using the approach described by Prossdorf and Tordella[21] and Chiocchia and Pignataro.[22] Additionally, to provide more effectiveness to the approach of the mutual interference of the wing with the propeller and its wake, a lifting surface model, based on a three-dimensional BEM formulation for the isolated wing, previously developed at the Department of Mechanics and Aeronautics of Palermo,[23] was employed. By developing a hybrid FWA–BEM numerical procedure, this may be applied to the wing and propeller.[3,4,22] The procedure was validated by means of the experimental results of Chiaramonte et al.[1] It may be worth noting that for estimating the loads on a wing of high aspect ratio, the flow close to the wing tip is of the utmost relevance. Additionally, the results obtained by Lombardi and Cannizzo[24] indicate that the formation of the tip vortex of a high aspect ratio wing could significantly affect the evaluation of the wing loads (particularly the torque and the bending moment at the wing root), particularly for swept wings. In the present work, the variations of the wing circulation are developed in terms of the wing angle of attack. Meanwhile, the new wing loads, which are dependent on the mutual interference with the propeller, are related to the altered freestream condition to allow convergence through iteration. The results demonstrate that, compared with the isolated configuration, variations in pressure distribution and lift can be large and a considerable shifting of the c.p. occurs, giving a change in overall aircraft pitching moment.

FWA Propeller Model

Following previous authors' works,[16–18] the wake from the propeller blades is considered and the FWA approach is first applied to an isolated propeller. This iterative method is based on a convergence criterion imposed on the sheet of vortices leaving each blade to form the propeller wake, which is made up of all the vortex lines starting from the points on the blade. Following Graber and Rosen,[8] Favier and Maresca,[12] and Favier et al.,[13,14] the tip vortex line radial contraction, r_t, and axial convection, x_t, are related to the wake azimuth, ψ, and are valid in the region near the propeller disk, the so-called *near wake*. Beyond a value ψ_s (far wake), the flow becomes unstable. For the propeller wake, the convergence criterion stops the description of the helicoidal vortex sheets at a certain downstream distance (assigned through a particular value ψ_s, for which a dependence on the advance ratio J and the number of blades B is also provided, based on experiment). Farther downstream, the wake is considered to be an infinite solenoid having a constant diameter (Fig. 1). The equations relating the value of ψ_s to J, β, r_t, and x_t, and the number of blades B are those of Refs. 14–18. The velocities u, v, and w induced by the wing and its wake at any point on the blade, P, may be calculated by relating the wing lift coefficient, C_l, to the wing and wake vortex strengths.[14–17] Through Biot–Savart's law, applied to the blade circulation $\Gamma(\xi)$ and to the trailing-wake vortices,

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*Research Engineer, Department of Mechanics and Aeronautics; currently at the Department of Aerospace Engineering, Pisa, Italy. Member AIAA.

†Associate Professor, Department of Mechanics and Aeronautics. Member AIAA.

‡Ph.D., Department of Mechanics and Aeronautics. Member AIAA.

§Assistant Professor, Department of Aerospace Engineering. Member AIAA.

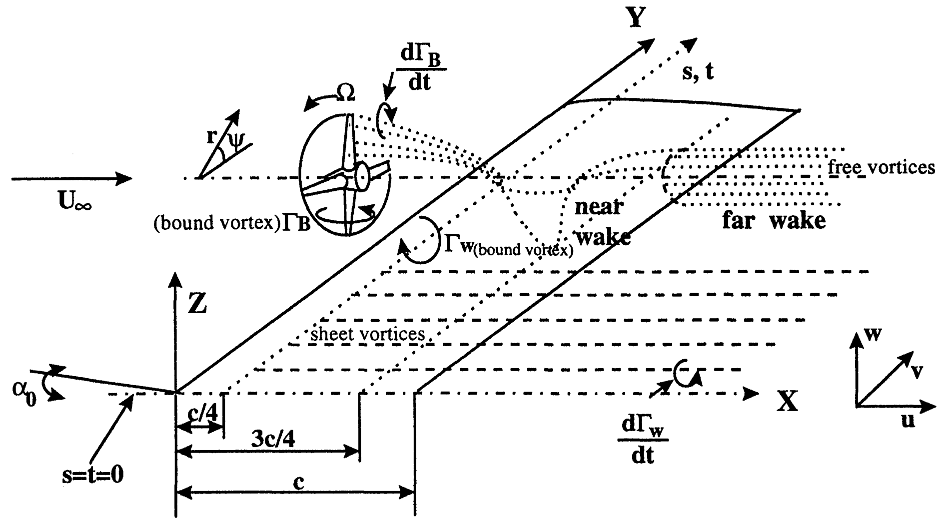

Fig. 1 FWA wake configuration of wing–propeller coupling.

one obtains the induced velocity at any point in the wake as follows:

$$V_P = \frac{1}{4\pi}\int_{R_0}^{R}\Gamma(\xi)\,\frac{\mathrm{d}\boldsymbol{l}\wedge\boldsymbol{r}}{|\boldsymbol{r}|^3} + \frac{1}{4\pi}\int_{\xi_0}^{1}\left[\frac{-\mathrm{d}\Gamma(\xi)}{\mathrm{d}\xi}\int_{L(\xi)}\frac{\mathrm{d}\boldsymbol{l}\wedge\boldsymbol{r}}{|\boldsymbol{r}|^3}\right]\mathrm{d}\xi \tag{1}$$

In Eq. (1), $\boldsymbol{r}$ represents the position vector of a space point P in the vortex coordinates system, $L(\xi)$ is the vortex filament leaving the point ξ of the blade, and $\mathrm{d}\boldsymbol{l}$ is the vector parallel to the direction of the bound vortex in the first integral and to the trailing vortex filaments in the second one. We assume the bound vortices influence may not be large and $\mathrm{d}\boldsymbol{l}\wedge\boldsymbol{r}$ vanishing. Having evaluated the circulation, Γ, from Eq. (1), the velocity induced at the point P by the sheet vortices may be written as a superposition, on each blade, of each integral:

$$V_{ia}(P) = \frac{1}{4\pi}\sum_{p=1}^{B}\int_{\xi_0}^{1}\Gamma(\xi)\,\frac{\boldsymbol{\tau}_p\wedge\boldsymbol{r}_p}{|\boldsymbol{r}_p|^3}\,\mathrm{d}\xi \tag{2}$$

where $\boldsymbol{\tau}_p$ is the unit vector parallel to the direction of the sheet vortex filament. Therefore, the velocity V_{il}, induced by the free vortices at point P, may be written in the form:

$$V_{il}(P) = \frac{1}{4\pi}\int_{R_0}^{R}\frac{\mathrm{d}\Gamma(\xi)}{\mathrm{d}\xi}\,\boldsymbol{G}(P,\,\xi)\,\mathrm{d}\xi \tag{3}$$

where the influence coefficients $\boldsymbol{G}(P,\,\xi)$ are those of Ref. 17.

Wing–Propeller Model and Coupling

In Refs. 15–17 and 22, the performance was calculated for a propeller with a given number of blades with specified dimensional and design characteristics, i.e., the geometric twist, β, the diameters, R and R_0, the freestream velocity, U_∞, and the rotational speed, Ω. The present work takes into account the strength of the three-dimensional induction of the wing and its interaction with the propeller in terms of the variations of wing circulation and lift and, finally, the wing quasisteady distributions of the chordwise pressure. The location of the center of lift along the wingspan is also calculated to provide the pitching moment characteristics of the aircraft. Based on the available literature concerning numerical results and experimental data,[2,12–14,16] the aerodynamic characteristics of the blade airfoil section can be introduced into the numerical process. For the tractor configuration, by assuming a rectangular wing with a coplanar wake, under the hypotheses of quasisteady and inviscid flow, negligible effects of vortex roll-up, an integro-differential equation containing the circulation, with its relative boundary conditions $\Gamma = 0$ at wing tips, is obtained:

$$2\alpha_0(s) = \frac{1}{\pi}\int_{-1}^{1}\frac{\mathrm{d}\Gamma_w}{\mathrm{d}t}\,\frac{\mathrm{d}t}{s-t} + \frac{1}{\pi}\int_{-1}^{1}T(s,t)\Gamma_{w(t)}\,\mathrm{d}t, \qquad -1\le s\le 1 \tag{4}$$

where $T(s,\,t)$ is given in Ref. 17. The system of wing wake vortices is assumed to be adequately represented by a set of free vortices lying in the wing plane, parallel to the freestream and trailing downstream from the three-quarter chord line. This set of vortices may be seen as free when the geometry of the vortices is considered to be determined by use of the self-induced wake velocity. The bound vortex circulation $\Gamma_w(s)$ varies along the nondimensional wingspan s, whose tips are at $s = \pm 1$, and is of such a magnitude that its own induced velocity added to that given by the trailing vortices results in the flow velocity being tangent to the wing three-quarter chord line. Suitable mathematical procedures[16,22] applied to Eq. (4) lead to a numerical solution for the circulation, which can be expressed as follows:

$$\Gamma_{w(t)} = (1 - t^2)^{1/2}\sum_{j=1}^{N}\varpi_j\,\frac{U_N(t)}{(t-t_j)U_N'(t_j)} \tag{5}$$

where ϖ_j are a set of unknown coefficients, $U_N(t)$ ($N = 1, 2 \ldots$) are the Chebyshev polynomials of the second kind, and t_j are their zeros.

Calculations

A rectangular wing of aspect ratio AR = 6.6 is considered. The wing has an RA1843N1L1 airfoil and negligible dihedral angle. Furthermore, a four-bladed coupled propeller, having a hub and overall diameter of 0.196 and 0.833 of wing chord, respectively, and a constant NACA 64A408 airfoil section, is considered. The input parameters are the same of those of Ref. 1. The simulation technique permits positioning of the propeller anywhere along the wingspan and it was positioned near the wing tip with a distance between the propeller disk and the wing leading edge of 0.25 wing chord. The output of the model gives the velocity field, circulation distribution, wake geometry, as well as the performance characteristics of the propeller, without and with wing induction.[15–17] The calculated induced velocities are computed for the mutual influence of the wing on the propeller and vice versa. By doing so, the pressure coefficients are calculated through an iterative scheme based on a BEM approach. As mentioned previously, the ultimate goal of this work was the inclusion of the aircraft pitching moment and loads corresponding to the altered aerodynamic characteristics of the wakes by propeller interference. According to the previously mentioned hypotheses and following the procedures identified by Favier and Maresca,[12] Favier et al.[13,14] and Davi' et al.,[22] a three-dimensional BEM formulation was employed for the wake past the wing. The main body of the hybrid FWA–BEM approach used contains a general potential-based formulation through boundary integral equations for the analysis of quasisteady three-dimensional low-speed, inviscid, attached-flow problems. The uniqueness problem for three-dimensional flows and the removal technique of the trailing-edge singularity are shown in Ref. 18. The Kutta condition is applied to resolve the problem of determining the distribution of circulation around each wing section.

Results

Figure 2 plots interesting results for the rectangular wing of AR = 6.6 for α = 4 deg. The effect of the influence of the propeller slipstream on the wing loads has been obtained and has given, for the same advance ratio, a more significant variation at lower incidence (α = 0 deg) than at higher ones (α = 4 deg) (see Ref. 18). This is related to the strength of the wing downwash velocity component: it makes this variation more predominant as angles of attack are increasing. For isolated and coupled configurations, the detailed spanwise variation of the local lift coefficient was computed and is shown in Fig. 3a. From wing root to the tip, ΔC_l ranges from 1.4 to 12%, depending upon the blade up–inboard instantaneous azimuthal position and the angle of attack. This may be explained if one considers that once J, U_∞, and α are fixed, the most significant variations of lift coefficient occur close to the propeller operating position and, more effectively, near the zone of the 70% blade radius. Finally, Fig. 3b shows the spanwise variation of center of lift respective to the quarter chord. As a consequence of movement of the center of lift, significant variations in rolling and pitching response of the aircraft occur. This shift is more marked close to the propeller area of aerodynamic influence.

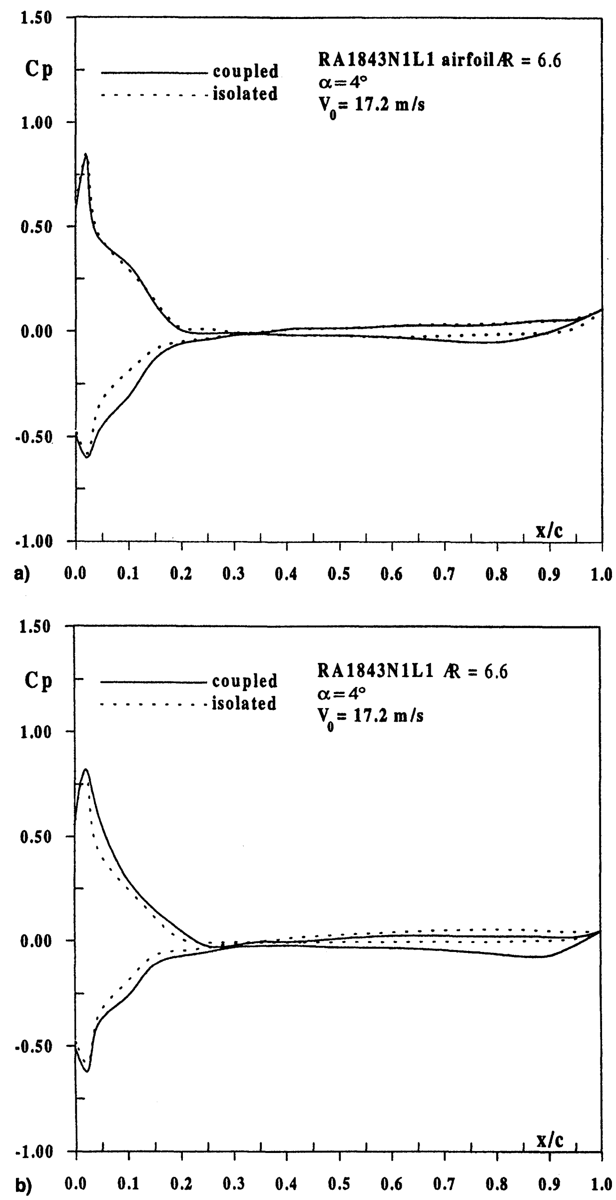

Fig. 2 Wing (isolated and coupled) pressure distribution at spanwise stations; AR = 6.6, α = 4 deg. $2y/b$ = a) 0.16 and b) 0.60.

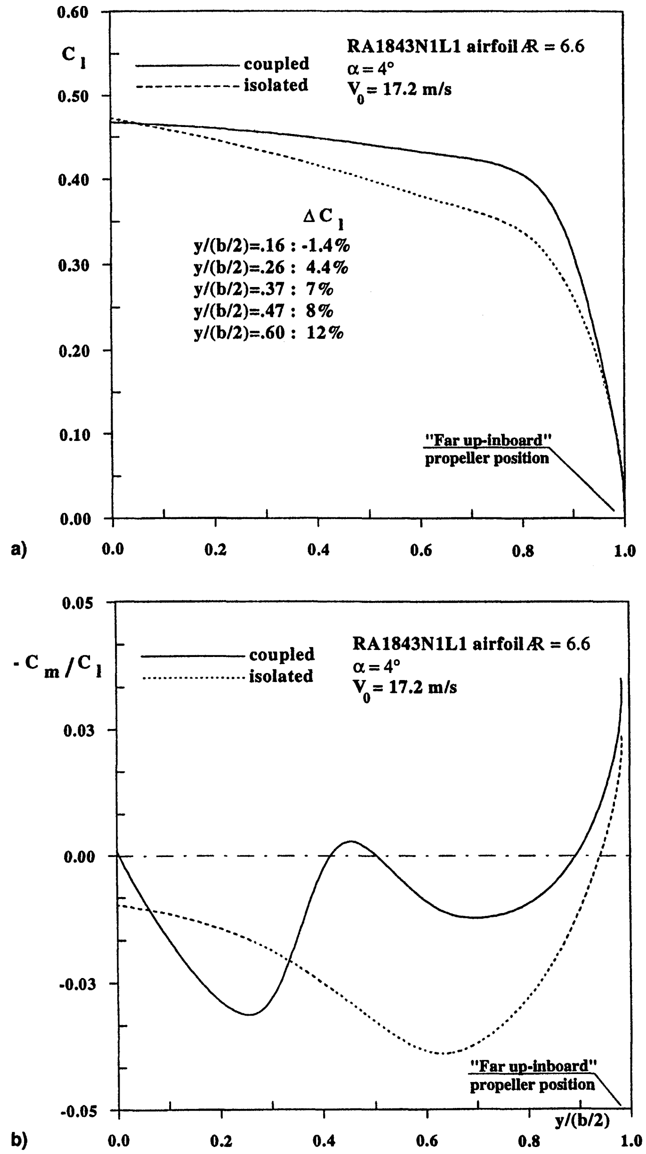

Fig. 3 Half wing (isolated and coupled) a) lift coefficient distribution and b) center of lift variation.

Conclusions

A method to analyze the variation of aerodynamic load on a wing operating in the wake of a tractor propeller, using a hybrid computational scheme based on FWA and BEM approaches, has been analyzed. Computations performed for an untapered and unswept rectangular wing show variations of the pressure coefficient distribution and the lift point of application along the wingspan. The resulting calculations of this reciprocal aerodynamic influence of the propeller and the wing have exhibited and confirmed quasisteady typical variation. The results displayed by the present hybrid numerical scheme applied to isolated wing and propeller, in quasisteady flow conditions, as well as to coupled configurations, show that the close vortex wing surface interaction gives rise to a low-pressure peak on the wing upper surface, which produces an increase in the positive local lift area near the trailing edge. From a merely computational point of view, the present method has demonstrated its capability to process higher-order mesh refinement and to give accurate results with very low computational effort.

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Stall Resistance Features of Lifting-Body Airplane Configurations

Joseph Katz* and Shaun Byrne†
San Diego State University,
San Diego, California 92182
and
Robert Hahl‡
Redwood Aircraft Corporation,
Falls Church, Virginia 22046

Introduction

THE lifting-body airplane concept, pioneered in the early 1920s, seems to fascinate every generation of airplane designers.[1-3] The basic concept, shown in Fig. 1a, postulates that the traditional cylindrical fuselage can be replaced by an airfoil-shaped body that contributes to the airplane lift. The design allows for larger cabin volume and, possibly, less wing loading during takeoff and landing because of the additional lift of the body. The generic model of Fig. 1a depicts the features of the early designs, which had small aspect-ratio airfoil-shaped fuselages (when viewed from the side) and a quite angular rectangular shape (when viewed from the top). The sharp side edges of those early designs created sizable vortex lift at the higher angles of attack, and the resulting large drag increase may have hurt the appeal of the concept.

Another approach to airplane design is based on eliminating the fuselage entirely, leading to the flying wing concept. This approach allows a spanwise continuous wing without interruptions by fuselage junctions. However, for small airplanes, the small wing thickness severely limits cabin heights. Therefore, for such a design to be practical, only large airplanes can be considered. Recent studies of such large transport aircraft[4] propose the blended wing concept, which, in essence, is a com-

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*Professor, Department of Aerospace Engineering and Engineering Mechanics. Associate Fellow AIAA.

†Student, Department of Aerospace Engineering and Engineering Mechanics. Member AIAA.

‡President and CEO.