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Drag reduction on aircraft configurations with adaptive lifting surfaces

Aaron A. Cusher [1], Ashok Gopalarathnam [*,2]

Department of Mechanical and Aerospace Engineering, Box 7910, North Carolina State University, Raleigh, NC 27695-7910, USA

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ABSTRACT

An approach, applicable to multiple-lifting-surface fixed-wing aircraft operating at subcritical Mach numbers, is presented for minimizing induced and profile drag with a constraint on the pitching moment. The approach allows the designer to select surface incidence, twist, and flap angles as variables for the optimization. The numerical formulation uses superposition to construct the spanwise lift distribution from basic and additional loadings, and decomposes the flap-angle distributions for each surface into mean and variation distributions. Together, these elements enable the solution of the problem using semi-analytical methods that also provide insight. Results are presented for a three surface aircraft which highlights low drag possibilities with positive static margins, presents the trade-offs between induced and profile drag, and provides insight into the aerodynamics of multiple lifting surface configurations.

1. Introduction

Aircraft configurations with adaptive lifting surfaces offer the capability for in-flight alteration of the aerodynamics to suit different flight conditions. The resulting drag-reduction and load-alleviation possibilities could translate to potential benefits in reduced fuel burn and emissions. Adaptive, or morphing, wing and aircraft technologies therefore is an active area of research interest within aircraft aerodynamics and design [5,36,37]. Multiple trailing-edge flaps distributed along the aircraft surfaces offer a simple method of aerodynamic adaptation, as it allows for the in-flight redistribution of spanwise lift for minimum drag. Benefits of such approaches have been shown in several studies for drag reduction and load alleviation [33,35,7,34,25], and adaptive trailing-edge flaps are used frequently on high performance sailplanes today. Recent research at North Carolina State University has shown benefits from multiple trailing-edge flaps on both tailed [14] and tailless [9] configurations with constraints. The current study presents a similar optimization method for use on multiple surface configurations with trim constraints. As an example application, a three surface configuration with trailing edge flaps and twist-distribution control sections is shown in Fig. 1.

Multiple surface configurations have been studied extensively. Prandtl's biplane equation [29], which assumes elliptically loaded surfaces, served as an early approach for induced drag prediction. However, subsequent studies have shown that elliptical distributions on each surface, particularly those operating in the downwash field of another surface, do not necessarily result in minimum induced drag. Several researchers have provided modified

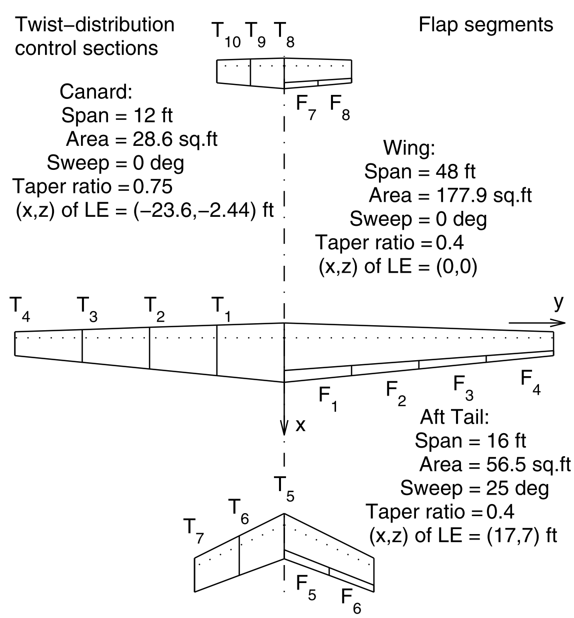

Fig. 1. Planform for example aircraft. The left side shows sections used for defining twist relative to wing root. The right side shows flap locations.

* Corresponding author.
E-mail address: ashok_g@ncsu.edu (A. Gopalarathnam).
[1] Graduate Research Assistant; currently Senior Aerodynamics Engineer, UTC Aerospace Systems, Burnsville, MN, USA.
[2] Associate Professor.

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versions of Prandtl's equation [24,20,21] for multiple surface configurations, each presenting steps forward in understanding optimal spanwise lift and surface lift ratios. The study by Kroo and McGeer [18] on conventional, tailed and canard configurations has provided much inspiration for this work, as comparisons of surfaces twisted for minimum induced drag and trim have highlighted shortcomings of canard configurations. Three surface configurations provide unique opportunities for aerodynamic analysis, as the availability of three surface-lift variables opens up the possibilities for satisfying longitudinal trim, thus allowing for optimal lift and trim to occur simultaneously. This redundancy in design variables has increased interest in three surface aircraft, as indicated by several references [17,26,31,13].

The current methodology builds on earlier work by the authors [9] and differs from earlier approaches for multiple-surface optimization [24,20,21,18,17,26,31,13] in the use of basic and additional loading to formulate the optimization problem. Also, profile drag is considered. The formulation allows for minimization of induced drag with or without trim constraints, with design variables that include incidence, twist, and flap angles. In addition, the method allows for some flap angles to be set for profile drag reduction. The method is very efficient and requires only the solution of simple matrix equations. Further, the information for these equations can be obtained using standard vortex-lattice type methods.

2. Background

The following three subsections briefly provide background material for the methodology developed in the paper.

2.1. Basic and additional lift distributions

The concept of basic and additional lift distributions is described in several references [4,1,19]. As explained in detail in a recent article on multiple TE flaps [14], the use of this concept enables the determination of flap angles using a simple, semi-analytical approach. In this subsection, the highlights of this concept are briefly presented. For further details and an example showing the accuracy of the approach, the reader is referred to [14].

Within the assumption of linear aerodynamics (linear C_l–α variation and linear C_l–Γ relationship) and so long as the component of the induced velocities along the freestream direction are small compared to V_∞, the spanwise distribution of the section lift coefficient, $C_l(y)$, can be written as a sum of two contributions: (1) basic distribution, $C_{lb}(y)$, and (2) additional distribution, $C_{la}(y)$. The basic distribution is the C_l distribution at $C_L = 0$, and is the result of spanwise variations in geometric twist, aerodynamic twist due to camber, and flap deflections. The additional C_l distribution, C_{la}, is due to changes to α for the wing with zero geometric and aerodynamic twist.

The advantage of using the linear superposition concept is that the net C_l distribution for a particular configuration with N independent variables, δ (which can be TE flap angles, δ_f, or twist angles, δ_t), at a given C_L can be posed in terms of the unknown flap/twist angles:

$$C_l = C_L C_{la,1} + C_{lb,0} + \sum_{j=1}^{N} C_{lb,j}\delta_j \tag{1}$$

where, $C_{lb,0}$ is the basic C_l distribution of the configuration due to given baseline spanwise distributions of twist and camber with all flaps set to zero, and $C_{lb,j}$ is the basic C_l distribution due to a unit deflection of flap j or unit angle for twist variable j. It is noted that twist at any section, as used in this paper, is defined relative to the wing's root chord. Thus, twist of sections on the canard or tail includes the incidence of that surface.

For a given bound-circulation distribution the induced drag, D_{ind}, can be obtained by integration along the wake trace in the Trefftz plane (see Refs. [30] or [16]). In non-dimensional form, the induced drag coefficient, $C_{D ind}$, can be written as:

$$C_{D ind} = \frac{1}{2S_{ref}} \sum_{k=1}^{M} \int_{-\frac{b}{2}(k)}^{\frac{b}{2}(k)} c(y)C_l(y)\frac{w(y)}{V_\infty}\,dy \tag{2}$$

where the summation accounts for an M-surface configuration, $\frac{b}{2}(k)$ is the half-span of lifting surface k, and $w(y)$ is the Trefftz-plane downwash distribution. As shown in Ref. [14], the total induced drag coefficient for a configuration with N flaps/twist variables can be expressed as follows:

$$C_{D ind} = \mathbf{f}^T\mathbf{D}\mathbf{f} \tag{3}$$

where $\mathbf{f}^T$, the transpose of $\mathbf{f}$, is written as:

$$\mathbf{f}^T = [\,C_L \quad 1 \quad \delta_1 \quad \dots \quad \delta_N\,] \tag{4}$$

and the drag-coefficient matrix, $\mathbf{D}$, is written as:

$$\mathbf{D} = \begin{pmatrix} C_{Daa} & C_{Da0} & C_{Da1} & \dots & C_{DaN} \\ C_{D0a} & C_{D00} & C_{D01} & \dots & C_{D0N} \\ C_{D1a} & C_{D10} & C_{D11} & \dots & C_{D1N} \\ \vdots & \vdots & \vdots & & \vdots \\ C_{DNa} & C_{DN0} & C_{DN1} & \dots & C_{DNN} \end{pmatrix} \tag{5}$$

in which, for each element of the $\mathbf{D}$ matrix, the first subscript indicates the source of the $c(y)C_l(y)$ distribution and the second subscript indicates the source of the $w(y)/V_\infty$ distribution. As an illustration, C_{Da0} is written as:

$$C_{Da0} = \frac{1}{2S_{ref}} \sum_{k=1}^{M} \int_{-\frac{b}{2}(k)}^{\frac{b}{2}(k)} c(y)C_{la,1}(y)\frac{w_{b,0}(y)}{V_\infty}\,dy \tag{6}$$

The elements of the $\mathbf{D}$ matrix can be pre-computed using any wing analysis method such as a panel, vortex-lattice, Weissinger-type, or lifting-line method that outputs the spanwise C_l and w/V_∞ distributions at a specified C_L.

2.2. TE flap for drag-bucket control

For flight at low subsonic Mach numbers, wing profile drag is dominated by skin-friction drag when there is no separated flow and associated pressure drag. To minimize profile drag, airfoils are often designed to have significant regions of favorable pressure gradient on both upper and lower surfaces to support laminar flow. Such a natural laminar flow (NLF) airfoil typically has a distinct low-drag range, or drag bucket, which is the range of lift coefficients over which low drag is achieved. To extend the range of lift coefficients over which low drag is achieved, a trailing-edge "cruise" flap is often used [27,28,22]. First introduced by Pfenninger [27,28], it has since been used on several airfoil designs [32,23,3,11,6,2], especially on airfoils for high-performance sailplanes [6,3].

Fig. 2 illustrates the effect of a trailing-edge flap on the low-drag range of the NASA NLF(1)-0215F airfoil [32], chosen here purely for illustration. It is seen that low profile C_d is thus achieved over a larger C_l range using a TE flap than without the flap. This benefit is limited to a small range of flap angles, typically close