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Aerodynamic Modeling of Morphing Wings Using an Extended Lifting-Line Analysis

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This paper presents an extension of Weissinger's method and its use in analyzing morphing wings. This method is shown to be ideal for preliminary analyses of these wings due to its speed and adaptability to many disparate wing geometries. It extends Prandtl's lifting-line theory to planform wings of arbitrary curvature and chord distribution and nonideal airfoil cross sections. The problem formulation described herein leads to an integrodifferential equation for the unknown circulation distribution. It is solved using Gaussian quadrature and a sine-series representation of this distribution. In this paper, this technique is used to analyze the aerodynamics of a morphable gull-like wing. Specifically, this wing's ability to manipulate lift-to-drag efficiency and center of pressure location is discussed.

Nomenclature

a = wing curvature parameter
b = wing span
C_l = section lift coefficient
C_d = section drag coefficient
C_L = wing lift force coefficient
C_D = wing drag force coefficient
C_Y = wing side force coefficient
$C_{\mathcal{L}}$ = wing roll moment coefficient
$C_{\mathcal{M}}$ = wing pitch moment coefficient
$C_{\mathcal{N}}$ = wing yaw moment coefficient
C_{l_α} = section lift curve slope
c = local chord length
$\hat{c}$ = local nondimensional chord length
$\bar{c}$ = mean aerodynamic chord
$\hat{\bar{c}}$ = nondimensional mean aerodynamic chord
G = nondimensional circulation
L = wing lift force
l = section lift force/length
M = number of points used in trapezoidal approximation
m = number of points used in sine-series expansion of circulation function
Q = dynamic pressure
$\boldsymbol{r}$ = displacement vector
S = wing planform area
$\hat{S}$ = nondimensional wing planform area
U_∞ = free-stream velocity magnitude
$\boldsymbol{v}$ = wind velocity vector
w = downwash velocity
x_{cg} = position of the wing center of gravity
x_{cp} = position of the wing center of pressure
$x_{c/4}$ = position of the airfoil quarter-chord point
y_0 = wing semispan, y coordinate of wingtip
α = wind incidence angle/angle of attack
α_{0L} = angle of attack for zero lift
Γ = circulation magnitude
Γ = vorticity vector
ε = downwash angle at wing $1/4$-chord line
η = nondimensional spanwise coordinate
Λ = wing aspect ratio
ξ = nondimensional chordwise coordinate
σ = planar density
$\mathcal{L}$ = wing roll moment
$\mathcal{M}$ = wing pitch moment
$\mathcal{N}$ = wing yaw moment

Introduction

THROUGHOUT the history of aviation, very little of man's inspiration for flight has manifested itself in aircraft designs. Indeed, man-made flight bears little resemblance to avian morphologies, which are backed by millions of years of evolution. Birds morph their wings and tail in complex, fluid ways, in contrast to the limited range of motion of an aircraft's control surfaces. Most aircraft deploy flaps and slats during takeoff and landing in order to increase lift at slower speeds. This is an example of a configuration change that occurs continuously during avian flight. A bird's morphology allows it to constantly change its wing and tail shapes to suit flight at a wide range of speeds.

Recently, research and development have begun on a new concept that challenges current designs: morphing aircraft [1]. A morphing aircraft is an aircraft capable of controlled, gross shape changes in-flight, with the purpose of increasing efficiency, versatility, and/or mission performance. Whereas traditional aircraft are designed as compromises of various performance needs, a single morphing aircraft can excel at numerous tasks [2,3]. The same airframe can morph from a highly efficient glider to a fast, high maneuverability vehicle. Whereas a traditional wing is designed for high efficiency over a small range of flight conditions, a morphing wing can adapt to grossly different altitudes and flight speeds. Morphing technologies enable new flight capabilities, such as perching, urban navigation, and indoor flight. These capabilities have heretofore been unrealizable due to technological limitations. Modern development of smart structures, adaptive materials, and distributed and adaptive control theory has opened the door to a host of new aircraft designs and flight capabilities [4].

These new capabilities are realized by the careful manipulation of aerodynamic forces and moments. For example, a long endurance aircraft benefits from a high lift-to-drag ratio, whereas a highly maneuverable aircraft needs high lift and low (or negative) stability margins. Highly efficient cruise can be accomplished by morphing the wing cross sections to maintain high lift-to-drag ratios at various flight speeds and altitudes. New capabilities, such as perching, can be achieved by controlling the degree of separated flow over the

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