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Behaviour of trailing wing(s) in echelon formation due to wing twist and aspect ratio

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A R T I C L E I N F O

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A B S T R A C T

In this paper, a novel decambering technique has been implemented using a vortex lattice method to study the effects of wing twist on the induced drag of individual lifting surfaces in configuration flight including post-stall angles of attack. The effect of both geometric and aerodynamic twist is studied. In the present work, 2D data of NACA0012 airfoil from XFoil at $Re = 1 \times 10^6$ is used to predict 3D post-stall data using geometric twist for a single wing and compared with literature. The effect of aerodynamic twist is implemented by using different airfoils along wing–span and the resulting wing C_L–α and C_{di}–α are compared with experiment. Study of wings of different aspect ratios with & without aerodynamic twist on both leading and trailing wings helps to understand the effect of twist on the lift and induced drag when they are varied on both wings simultaneously and individually.

1. Introduction

Formation flight has seen considerable interest in the research community due to its promise of fuel savings due to reduced drag. In this work, the numerical technique that we use gives aerodynamic data for a wider variety of possibilities in a formation, namely the shape and size of individual wings. The method used works at post-stall angles of attack and interesting behaviour is noted when one or more wings in a formation operates at these regions of flow. The modelling technique used also enables to generate results very quickly.

The drag reduction in a formation is due to the trailing wing operating in the downwash region of the leading wing. In this work, we have used a twisted leading wing to study the effects on the trailing wing. We have also changed the size of the leading wing (aspect ratio) to study its changes on the trailing wing.

Using a twisted leading wing essentially changes the distribution of the effective angle of attack on the trailing wing and using different aspect ratios of the leading wing changes the location of the tip vortices, which effect the behaviour of the trailing wing.

In the present work, analysis at post-stall angles of attack shows that stall can be pre-poned or post-poned depending upon the formation. The objective and motivation for this work stems from the fact that all facets of formation can be analysed and such knowledge and information can serve as the basis of design of formations.

In previous work, we have shown the effect of changing offsets (dx, dy, dz) and angles of attack of the wings on a formation [1].

As per the history of formation flying, the early research started in the year 1914 by Weiselsberger [2] who calculated the induced drag which could be reduced by velocity field and induced by bound & trailing vortices of nearby flock members. The horseshoe vortex of constant strength was replaced by a bird and three birds were considered in a diagonal–line formation. The sample calculation showed that the bird in the middle position gains 15.2% drag reduction.

Schlichting [3] analysed the formation flight and studied the interaction of multiples airplanes using horse shoe vortices for V and inverted V formations. The first calculation on fuel savings have been made in symmetrical formations of airplanes Ju 52 which was used by German airforce during WW II. The rates of energy savings have been calculated for various aircraft numbers and recommended inverted V-formations for practical reasons, i.e. visibility and evenly drag distribution.

D. Hummel [4] conducted a survey on formation flight of birds by doing study on three types problems which turned out all three can't be solved directly by measurements on birds and aerodynamic forces acting on birds in soaring flight or flapping flight can't be determined by wind-tunnel experiments. He also concluded that possible approach is only by quantitative experimental investigation of the position and motion of the birds in flight and subsequent analysis by means of aerodynamic theory.

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Nomenclature

$C_l(sec)$	2D section coefficient of lift
$C_m(sec)$	2D section coefficient of pitching moment
$C_{di}(sec)$	2D section coefficient of induced drag
$C_L(max)$	maximum Lift coefficient
$C_{di}(min)$	minimum Induced Drag coefficient
C_L	3D wing coefficient of lift
C_m	3D wing coefficient of moment
C_{Di}	3D wing coefficient of induced drag
$(L/D)_{max}$	maximum lift-to-drag ratio
c	wing chord length
LLT	lifting line theory
VLM	vortex–lattice method

Subscript

α	angle of attack
$\alpha_{C_{L=0}}$	zero-lift angle of attack
$\Delta C_l, \Delta C_m$	Difference between viscous and potential
δ_1, δ_2	decambering functions
(x_1, x_2)	Cartesian locations of δ_1 and δ_2
(θ_1, θ_2)	spherical locations of δ_1 and δ_2
max	maximum
lw	leading wing
tw	trailing wing
sec	section
$visc$	viscous
AR	aspect ratio
dx	chord-wise offset
dy	span-wise offset
dz	vertical offset

The benefits gained by birds in formation remains same for fixed wing aircrafts. Markus Beukenberg & Dietrich Hummel [5] analysed and proved that when two airplanes Do-28 flies in formation, a maximum flight power reduction of about 15% is achievable for the rear aircraft at very small lateral distances.

In our present work, wing twist is applied in single and multiple wing configurations. The benefits of applying wing twist are studied both by geometric and aerodynamic twist. The further literature shows how wing twist was applied in the past in different applications.

Wing–twist distribution is not the least controversial design parameter and has to be carefully selected so that the cruise drag is not excessive. In a rectangular wing, the washout due to wing–twist causes the root to stall before the wing tips. The solution based on washout optimization using lifting line theory [6] gives the idea of how to minimize the induced drag at a design C_L effectively by using both geometric and aerodynamic twist.

It has been shown that any planform shape may be optimized with wing–twist to reduce the induced drag to an optimum value [7]. They have been shown that the maximum lift–drag ratio increases and the maximum C_L reduces as the distance between the wing root and the twist start line decreases. They also mentioned that twist could be applied only on the area of the wingspan, and the effect of the twist on C_{Lmax} and $(L/D)_{max}$ could be reduced.

Lingxiao Zheng [8] used many models to study the wing and body kinematics of painted lady butterfly. It may be noted that the twist-only-wing (TOW) model recovers much of the performance of observed butterfly wing (OBW) model by demonstrating the wing–twist but, not the camber is the key to forward flight in these insects.

Geoffrey et al. [9] used the LinAir, a discrete vortex Weissenger program to analyze the representative aircraft and formation geometries. In order to get desirable load distributions the wings of three different models were twisted. In LinAir calculations they used the DC-10-30 wing geometry, assumed a streamwise spacing between aircraft of (x/b) = 5.0 and no vertical gap was used.

Ashok Gopalarathnam [10] concluded that to achieve elliptical loading (or any other target loading) when flying in a formation, a wing must have the freedom to adapt its shape via twist or control deflections. He also said that birds are able to achieve this by wing–shape adaptation using some form of aerodynamic sensing.

H.P. Thien et al. [11] used domain discretization and flow field properties evaluation to explain the effect of incidence angle, dihedral angle, aspect ratio and taper ratio in V-formation flight. They found that aspect ratio has a significant effect on increasing the rear wing lift and pitching moment, but seems to be no effect to the drag reduction.

Sara Nichols [12] explains how reduction in washout at the highest rate of wing twist lowers the direct span-wise strains in the outboard section of the rib and the consequent reduced shear strains induced by the coupling terms. They also have explained how aerodynamic subroutine optionally calculates the required amount of twist for various sections along the aerofoil that would achieve an elliptical lift distribution for a given set of user input parameters. Twist changes the structural weight by modifying the moment distribution over the wing.

Kevin et al. [13] introduced a new way of giving aerodynamic twist to the wing by finding the set of spanwise locations and their corresponding design lift coefficients that minimize the error between the C_L distribution achieved by aerodynamic twist and the C_L distribution resulting from the desired lift distribution and planform shape. Similarly, geometric twist is given by superimposing all the $\Delta C_L.c$ distributions due to each twist distribution to calculate the required twist function weights.

The wind-tunnel test was conducted by Vanessa L. Bond et al. [14] to demonstrate the use of wing twist for longitudinal (pitch) control in a joined-wing-aircraft configuration and to validate models that are used in analysis methods. They also investigated the feasibility of incorporating flexible twist for pitch control in the design of a high-altitude long-endurance aircraft.

Ivan Korkischko et al. [15] examined the application of formation flight to micro air vehicles with regard to possible power savings. They also stated that the effect of the induced upwash can be seen as a modification of wing twist, which is used to optimize the spanwise lift distribution on nonelliptic planforms to lower the induced drag for a given lift value.

2. Numerical procedure

A vortex–lattice method algorithm based on the decambering approach [16] is used for predicting formation flight aerodynamics of wings using known section data. Although the numerical code, VLM3D based on this approach was originally developed with a view to predict post-stall aerodynamics of single wings or their configurations, it has been found to be robust and powerful in the analysis of formation flight as well with some modifications.

The ability to change spatial offsets (chord-wise, span-wise and vertical), the ability to change the angle of attack of the trailing aircraft for a particular angle of attack of the leading aircraft and vice versa are incorporated into VLM3D to study formation flight aerodynamics. The unique feature of formation flight is the inter-

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