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ABSTRACT: Numerical Investigation of the Effects of Bumps on Inflatable Wing Profiles

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The need for wings that can be stored in a relatively small volume and then have the capability to be unfolded, inflated, or by other means extruded to a significant span has been of much interest in the field of planetary exploration. There are also military interests in the technology associated with compact, lightweight UAVs that could be a direct result of such technology. One of the major manufacturers in soft goods for the United States military and of NASA is ILC Dover. ILC Dover also supplies inflatable wings to the University of Kentucky for research purposes including the development of lightweight UAVs, wing warping technology, dynamics of inflatable structures, and research associated with aerodynamic effects of inflatable wing profiles. The wing profiles associated with inflatable wings is bumpy compared to ideal wing profiles. This paper wishes to investigate the effects of bumpy profiles through the use of two and three dimensional simulations with a viscid, incompressible CFD code called UNCLE. The aerodynamics of smooth airfoils at low Reynolds numbers is very much different than that at high Reynolds numbers. The incorporation of bumps on these smooth airfoils tends to delay the onset of separation which would typically cause an increase in drag and a decrease in lift on the ideal airfoil. The focus of this paper is to investigate the effects of the bumps through a range of angles of attack and Reynolds numbers with an array of different bump configurations.

Nomenclature

α	=	angle of attack	L/D	=	lift to drag ratio (i.e. C_l/C_d)
c	=	chord length	P	=	static pressure
Re	=	Reynolds number based on chord length	P^*	=	dimensionless pressure
C_d	=	drag coefficient	t	=	time
C_l	=	lift coefficient	t^*	=	dimensionless time
C_m	=	moment coefficient	U_∞	=	free-stream velocity
C_p	=	pressure coefficient	u^*	=	dimensionless x component of velocity
δ/c	=	dimensionless boundary layer thickness	x^*	=	x coordinate dimensionless length
L'	=	lift per unit span	y^*	=	y coordinate dimensionless length

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I. Introduction

There has been much investigation into the uses of inflatable wings for various applications such as that of lightweight UAVs.[1] The uses for lightweight UAVs include surveillance for homeland security, military applications, and exploration in conditions in the higher altitudes of earth similar to that of other planets such as Mars.[2,3,4,5] These inflatable wings inherently possess bumps which modify their baseline profile and is a by-product of the manufacturing techniques used to construct them. Not only do inflatable wings possess the ability to be packaged in a relatively small space,[6] they have the ability to implement wing warping technology as a method of roll control.[7]

Some of the problems that are inherent to flight in low Reynolds numbers are the formation of the separation bubble on the upper surface which is due to the adverse pressure gradient. After the separation bubble forms, the pressure tries to recover past half chord of the airfoil in doing so the laminar boundary layer tends to separate from the surface. This separation is the source for the large increases in pressure drag. Depending on the specific configuration the flow can continue to evolve into a number of different possibilities. In some instances it can re-attach and form a turbulent boundary layer and in other cases the boundary layer remains unattached.[8] There have been other efforts to implement flow control by means of controlling the boundary layer such as piezoelectric actuators, plasma actuators, and morphing wings.[9,10,11]

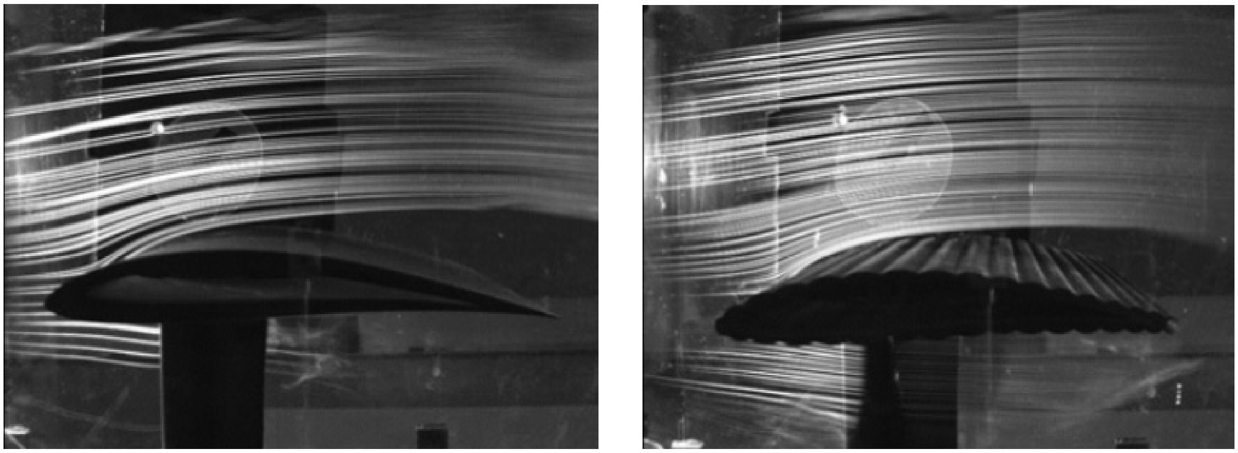
The present paper focuses on the effects of bumps on the airfoil surface, a passive boundary layer control device, to trip the flow into turbulence and thin the boundary layer reducing the possibility of separation on the later half of the airfoil. The aerodynamic effects due to the bumps on the surface of these wings has been shown to be favorable in terms of wing performance at Reynolds numbers in the range of 10,000 to 200,000.[8] Qualitatively, the bumps on the wing surface serve well as a passive boundary layer control mechanism. Thus far, there has been two primary wing profiles investigated. One is based on the Eppler 398 profile and consists of bumps that have a radius $\sim 2\%c$. Second is based on the NACA 4318 profile and consists of bumps with a radius of $\sim 1.5\%c$. Examples of the MIAV (NACA 4318) inflatable wings can be seen in figure I.

Due to changes in manufacturing at ILC Dover the profiles of the inflatable wings available for testing has moved from the Eppler 398 profile to a NACA 4318 profile. ILC Dover moved away from the Eppler 398 Profile when it moved from inflatable rigidizable technology to that of relatively high pressure soft goods like that of the FASM wing. The FASM wing is constructed of rugged Vectran. The Vectran material used in the construction of the FASM wings was left over material from the Mars Lander air bags. Inside the Vectran outer shell is a polyurethane bladder that, without the rigidity of the Vectran shell, could not withstand the inflation pressures needed to make the wings fully rigid. The MIAV wings that are based on the same NACA 4318 profile as the FASM wings, but are made of rip-stop nylon and are a fraction of the cost. The MIAV wings are considerably lighter in weight, but cannot withstand the high inflation pressures used for the FASM wings.

Figure 1. MIAV inflatable wings with bumpy NACA 4318 profiles courtesy of ILC Dover.

A. Motivation for Numerical Investigation

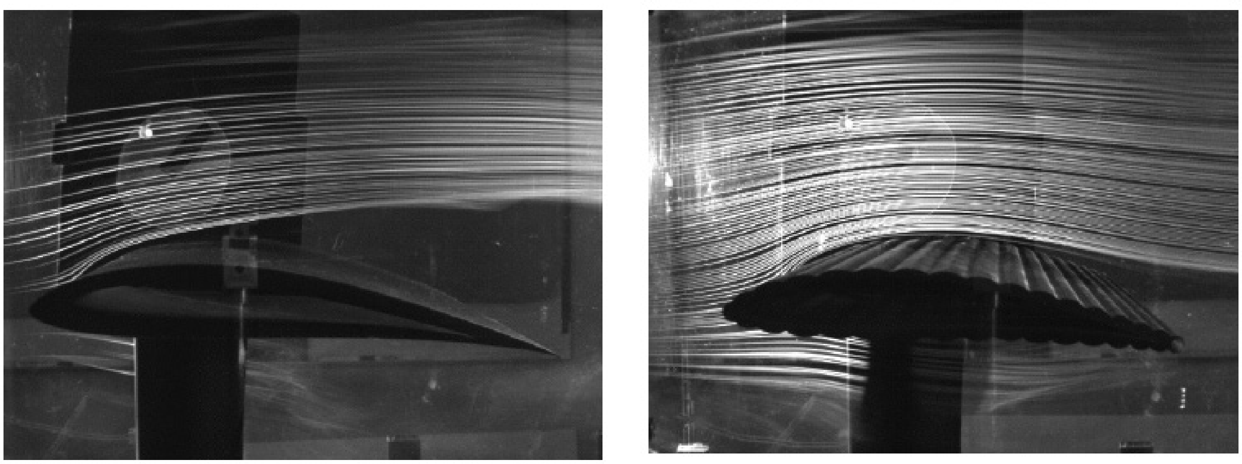
The reason for the interest in numerical simulations of airfoils with bumpy profiles is the phenomena observed from experimental results. Previously, there have been wind tunnel experiments that have focused on the effects of the bumps on the Eppler 398 airfoil.[8] PIV instrumentation was used to gather flow data. Below in Figures(2 a,b), we can see the difference in the flow regime between the ideal and bumpy profiles. In these low Reynolds number regimes we can see that the bumps play a significant role in the delay of separation (Figures 3 a,b). Qualitative results like those seen in the figures are the primary reason for investigating the results numerically.



(a) Eppler 398 Ideal Profile

(b) Eppler 398 Bumpy Profile

Figure 2. Experimental Results for Eppler 398 $Re = 2.5e4, \alpha = 0^o$[8]



(a) Eppler 398 Ideal Profile

(b) Eppler 398 Bumpy Profile

Figure 3. Experimental Results for Eppler 398 $Re = 5e4, \alpha = 4^o$[8]

II. Numerical Scheme

UNCLE is a two/three-dimensional, finite-volume, unstructured incompressible Navier-Stokes solver for steady and unsteady flow fields. UNCLE relies on a cell-centered pressure-based method based on the SIMPLE algorithm with second order accuracy in both time and space. In order to compute numerical flux on interfaces, a second order upwind scheme is adopted to compute advection terms and second order central difference scheme is used for diffusion terms. A collocated grid system with the Rhie and Chow momentum interpolation method[12] is employed to avoid the checkerboard solution of the pressure based scheme. Fluxes on the volume faces are determined through interpolation of cell-centered values. The time discretization is a second-order fully implicit scheme. The version of UNCLE used to generate the results seen in the following section implements the SA turbulence model. This turbulence model has been proved very effective in the simulation of airfoils. This code also includes the capabilities to utilize MPI parallel computing on both 32-bit and 64-bit architectures. It does so by partioning the generated grid into smaller grids and sending them to individual computers. The grids used are generated in Gambit; the popular commercial grid generation software used primarily with the commercial CFD code Fluent.

III. Computational Setup

The present results were obtained through the use of Kentucky Fluid Cluster 3 (KFC3) which employs 32 Pentium 4 2.4Ghz nodes. Ongoing work will be performed on KFC4 which contains 40 AMD Athlon XP 2000+ processors, KFC5 which contains 40 AMD Athlon 64 3200+ processors, and KFC6 which contains 24 AMD Athlon 64x2 4600+ processors and 24 Intel Core 2 Duo e6400 processors.

IV. Results

A. Numerical Results

Preliminary results include the simulation of two different smooth airfoils. These two airfoils are based on the wing profiles that ILC Dover supplied the Fluid Mechanics Lab and the Dynamic Systems Lab at the University of Kentucky. The first profile is based on the Eppler 398 ideal profile and the second is based on the NACA 4318 profile. The inflatable-rigidizable wings are based on the Eppler 398 profile[13] whereas the FASM and MIAV wings are based on the NACA 4318 profile. All numerical results will be obtained through the use of UNCLE. All the results listed below will be based on two-dimensional simulations utilizing the SA turbulence model. Following are dimensionless parameters used for analysis.

The static pressure is non-dimensionalized with ρU_∞^2 with

$$P^* = \frac{P - P_\infty}{\rho U_\infty^2}. \tag{1}$$

The x component of velocity is non-dimensionalized with the freestream velocity.

$$u^* = \frac{U_x}{U_\infty} \tag{2}$$

Time is non-dimensionalized with the velocity and chord length.

$$t^* = \frac{U_\infty t}{c} \tag{3}$$

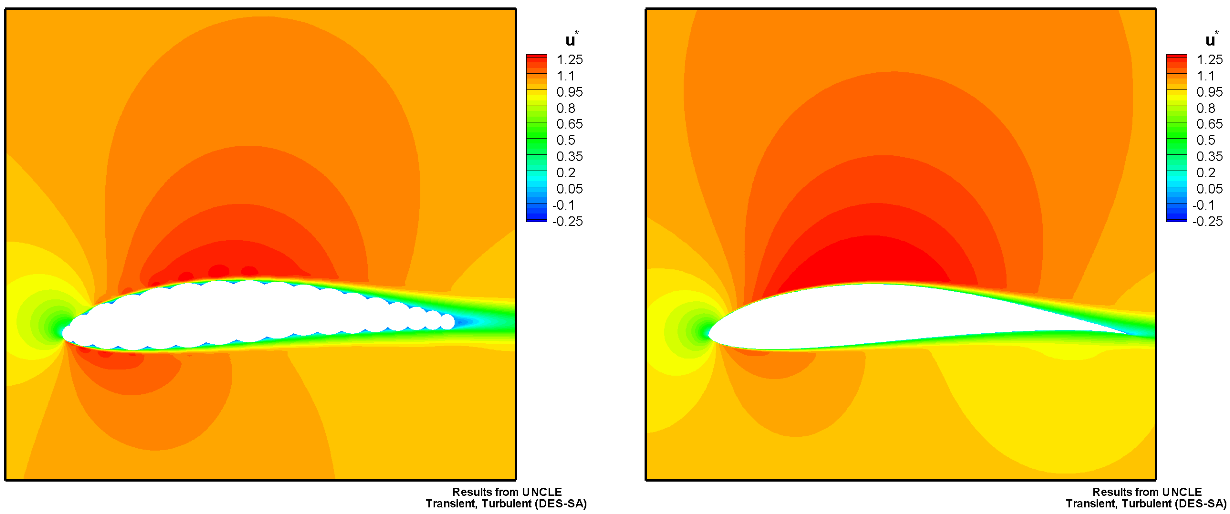
The x and y coordinate length scales are non-dimensionalized with the chord length.

$$x^* = \frac{x}{c} \qquad y^* = \frac{y}{c} \tag{4}$$

The focus on the Eppler 398 profile was to investigate the effects of flow due to the perturbations on the upper and lower surface. These effects have been shown to increase the amount of lift while reducing the amount of induced drag on the airfoil. In figures 4 & 5 we can see the difference in the u^* flow field due to these perturbations. The effects that the bumps have on boundary layer thickness is also of interest and the experimental results suggest that the perturbations would cause the boundary layer to become less thick than that of the smooth airfoil at low Reynolds numbers. As the flow is increased to Reynolds numbers on the order of $1.0e6$ this effect is diminished. It is difficult to quantify the effects of the vorticies that form within the bumps without further analysis of the velocity profiles on the upper and lower surfaces of the airfoil. The vorticies that form in the crevices between the bumps act as a mechanism to delay the onset of separation on the upper surface of the wing at low Reynolds numbers. A more focused view on the activity between the bumps can be seen in Figure 6.

Preliminary Results from the simulations of the Eppler 398 profile at Re = 200,000 suggest that there is no significant increase in performance by implementing the bumpy profile instead of the ideal profile.

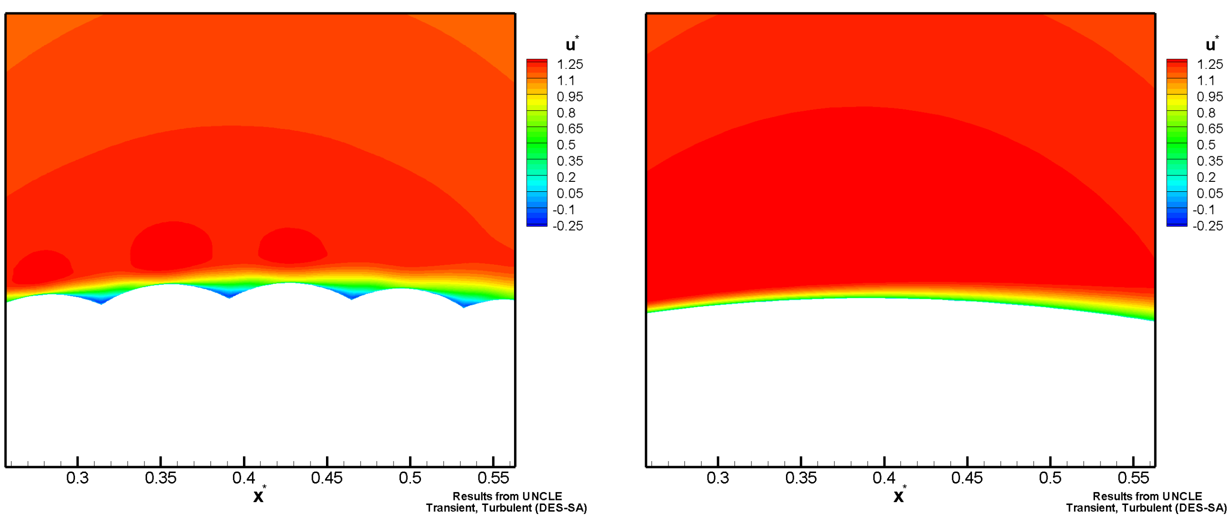
However, in the final paper the investigation of the effects at lower Reynolds number aims to provide results that suggest significant reduction in boundary layer thickness, flow separation, and drag, while offering an increase in lift. The final paper will also include results at higher Reynolds number that will serve to reinforce the fact that the bumpy profiles offer no significant advantage to that of the ideal profile.



(a) Eppler 398 bumpy profile.

(b) Eppler 398 ideal profile.

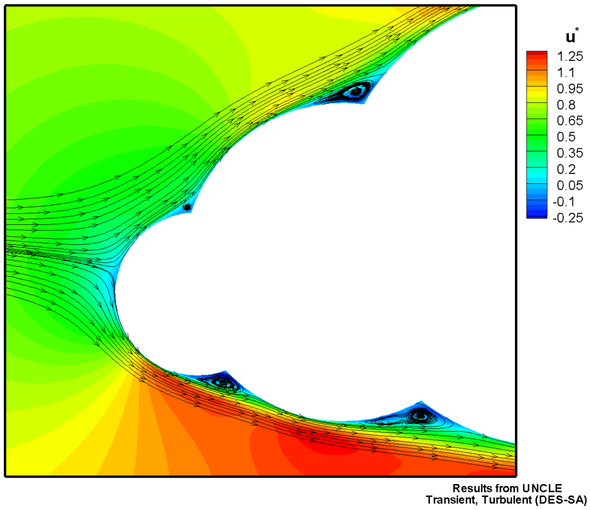
Figure 4. Dimensionless x component of velocity for Eppler 398 profiles Re=200k, $\alpha = 0^o$.



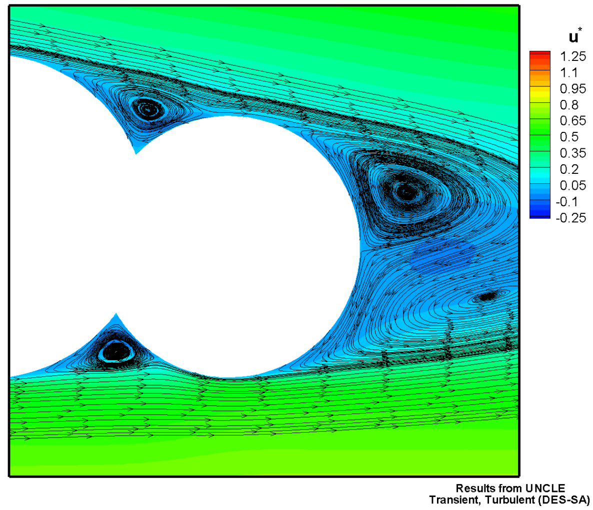
(a) Eppler 398 bumpy profile focus.

(b) Eppler 398 ideal profile focus.

Figure 5. Focused x-velocity for Eppler 398 profiles Re=200k, $\alpha = 0^o$.

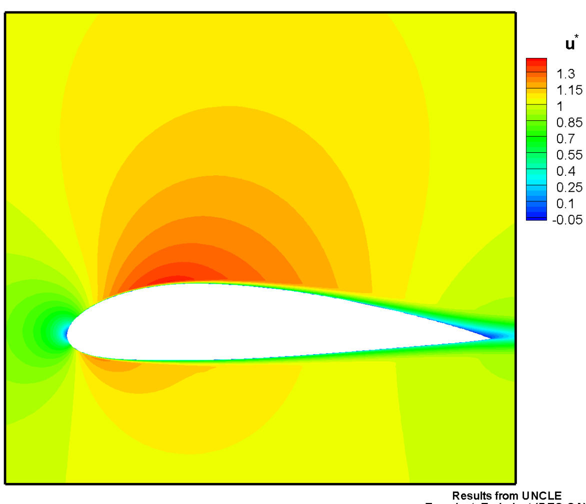


(a) Leading edge of E398 bumpy profile.

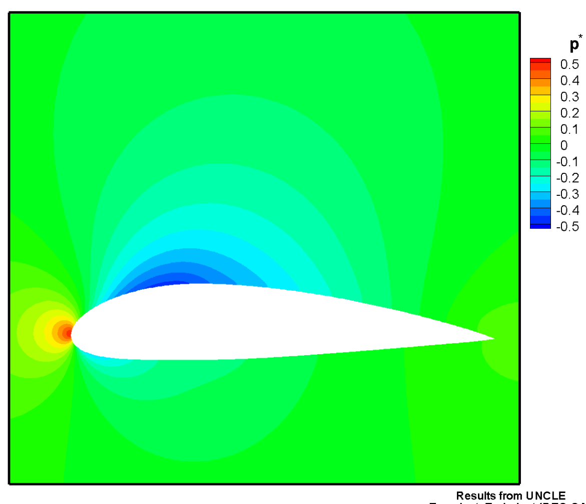


(b) Trailing edge of E398 bumpy profile.

Figure 6. Leading and trailing edge x-velocity contours with streamlines for Re=200k, $\alpha = 0^o$.



(a) u^* Dimensionless x component of velocity contour.



(b) Dimensionless pressure contour.

Figure 7. Contours for NACA 4318 ideal profile for Re=200k, $\alpha = 0^o$.

V. Preliminary Conclusions

From the results obtained thus far, we can conclude that the effects of the bumps on the Eppler 398 airfoil do not have a drastic effect on the performance of the airfoil in Reynolds numbers in the range of Re=200,000 (results for Re=1,000,000 have also been completed and likewise show little effect). Further simulations will investigate the effects of bumps as a way to improve the performance of the airfoils at lower Reynolds numbers. Numerical results will be compared to experimental data like that found in ref[8].

VI. Ongoing Work

Due to the vast number of geometries that can be constructed using bumpy profiles there are ongoing simulations that wish to determine the optimum configuration for a given application. Through the use of data obtained from a large number of simulations the optimum configuration for bump height, bump radius, and the number of bumps can be determined. To do so, adequate data needs to be obtained for various airfoil configurations at various angles of attack and Reynolds numbers.

Acknowledgments

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References

[1]A. Simpson, J. Jacob, S. Smith "Flight Control of a UAV with Inflatable Wings with Wing Warping" AIAA Paper 2006-2831, 24th AIAA Applied Aerodynamics Conference, San Francisco, California, June 5-8, 2006.

[2]P. Kenney, M. Croon "Simulating the Ares Aircraft in the Mars Environment" AIAA Paper 2003-6579, 2nd AIAA "Unmanned Unlimited" Conf. and Workshop and Exhibit, San Diego, California, Sep. 15-18, 2003.

[3]M.D. Guynn, M.A. Croon, S.C. Smith, R.W. Parks, P.A. Gelhausen "Evolution of a Mars Airplane Concept for the Ares Mars Scout Mission" AIAA Paper 2003-6578, 2nd AIAA Unmanned Unlimited Systems, Technologies, and Operations - Aerospace, San Diego, CA, September 15-18, 2003.

[4]J. Lede' and R. Parks "High Altitude Drop Testing in Mars Relevant Conditions for the ARES Mars Scout Mission", AIAA Paper 2003-6609, 2nd AIAA "Unmanned Unlimited" Conf. and Workshop and Exhibit, San Diego, California, Sep. 15-18, 2003.

[5]J. Lafleur, J. Olds, R. Braun "Daedalon: A Revolutionary Morphing Spacecraft Design for Planetary Exploration" AIAA Paper 2005-2771, 1st Space Exploration Conference: Continuing the Voyage of Discovery, Orlando, FL, Jan. 30 - Feb. 1, 2005.

[6]D. Cadogan, T. Smith, F.Uhelsky, M. MacKusick "Morphing Inflatable Wing Development for Compact Package Unmanned Aerial Vehicles" AIAA Paper 2004-1807, 45th AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics and Materials Conference, Palm Springs, CA, Apr. 19-22, 2004.

[7]A. Simpson and J. Jacob "Aerodynamic Control of an Inflatable Wing Using Wing Warping" AIAA Paper 2005-5133, 35th AIAA Fluid Dynamics Conference and Exhibit, Toronto, Ontario, June 6-9, 2005.

[8]A. Santhanakrishnan, J. Jacob "Effect of Regular Surface Perturbations on Flow Over an Airfoil." AIAA Paper 2005-5145, 35th AIAA Fluid Dynamics Conference & Exhibit, Ontario, June 6-9 2005.

[9]A. Santhanakrishnan, J.D. Jacob "Flow Control Using Plasma Actuators and Linear/Annular Plasma Synthetic Jet Actuators" AIAA Paper 2006-3033, 3rd AIAA Flow Control Conference, San Francisco, CA, June 2006.

[10]A. Vorobiev, R. Rennie, E. Jumper "An Experimental Investigation of Lift Enhancement and Roll Control Using Plasma Actuators" AIAA Paper 2006-3383, 37th AIAA Plasmadynamics and Lasers Conference, San Francisco, California, June 5-8, 2006.

[11]A. Santhanakrishnan, N. Pern, K. Ramakumar, and J. Jacob "Enabling Flow Control Technology for Low Speed UAVs" AIAA Paper 2005-6960, Infotech@Aerospace, Arlington, Virginia, Sep. 26-29, 2005.

[12]Chen, H., Huang, P.G., and LeBeau, R.P., "A Cell-Centered Pressure Based Method for Two/Three-Dimensional Unstructured Incompressible Navier-Stokes Solver", AIAA-2005-0880, 2005.

[13]D. Cadogan, W. Graham, T. Smith "Inflatable and Rigidizable Wings for Unmanned Aerial Vehicles" AIAA Paper 2003-6630, 2nd AIAA "Unmanned Unlimited" Conf. and Workshop and Exhibit, San Diego, California, Sep. 15-18, 2003.

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