UNCLASSIFIED
SECURITY CLASSIFICATION OF THIS PAGE

(2)

REPORT DOCUMENTATION PAGE

AD-A200 222

1a. R	1b. RESTRICTIVE MARKINGS
2a. S	3. DISTRIBUTION / AVAILABILITY OF REPORT: APPROVED FOR PUBLIC RELEASE DISTRIBUTION IS UNLIMITED
2b. D	
4. PERFORMING ORGANIZATION REPORT NUMBER(S)	5. MONITORING ORGANIZATION REPORT NUMBER(S): AFOSR-TR- 88-0987
6a. NAME OF PERFORMING ORGANIZATION: UNIVERSITY OF COLORADO; 6b. OFFICE SYMBOL (If applicable)	7a. NAME OF MONITORING ORGANIZATION: AFOSR/NA
6c. ADDRESS (City, State, and ZIP Code): UNIV OF COLORADO, BOULDER, CO 80309	7b. ADDRESS (City, State, and ZIP Code): BUILDING 410, BOLLING AFB, DC 20332-6448
8a. NAME OF FUNDING / SPONSORING ORGANIZATION: AFOSR; 8b. OFFICE SYMBOL (If applicable): NA	9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER: F49620- ~~AFOSR~~ 84-C-0065
8c. ADDRESS (City, State, and ZIP Code): BUILDING 410, BOLLING AFB, DC 20332-6448	10. SOURCE OF FUNDING NUMBERS: PROGRAM ELEMENT NO. 61102F; PROJECT NO. 2307; TASK NO. A3; WORK UNIT ACCESSION NO.

11. TITLE (Include Security Classification)
(U) UNSTEADY SEPARATED FLOWS: STRUCTURES AND PROCESSES

12. PERSONAL AUTHOR(S)
M. LUTTGES, P. FREYMUTH, C.Y. CHOW

13a. TYPE OF REPORT	13b. TIME COVERED	14. DATE OF REPORT (Year, Month, Day)	15. PAGE COUNT
FINAL	FROM 06/84 TO 07/88	08/88	22

16. SUPPLEMENTARY NOTATION

17. COSATI CODES			18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)
FIELD	GROUP	SUB-GROUP	UNSTEADY AERODYNAMICS, DYNAMIC STALL UNSTEADY SEPARATION

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

Experimental, computational and theoretical work was designed to investigate the unsteady separation phenomenon. The experimental investigations used qualitative methods allowing a full characterization of the forcing functions and planforms capable of producing and controlling unsteady flow separations. For select test conditions the characterizations were to employ quantification of the unsteady flow phenomena. In addition, the theoretical and numerical aspects were closely coordinated to study the potential applications in high performance flight vehicles. Keywords: Boundary layer flow separation; Vortices; Boundary layer trips; Viscous flow; Oscillating airfoils; Dynamic stall. (edc)

DTIC ELECTE OCT 0 6 1988 S H D

20. DISTRIBUTION / AVAILABILITY OF ABSTRACT	21. ABSTRACT SECURITY CLASSIFICATION
☐ UNCLASSIFIED/UNLIMITED ☒ SAME AS RPT. ☐ DTIC USERS	UNCLASSIFIED

22a. NAME OF RESPONSIBLE INDIVIDUAL	22b. TELEPHONE (Include Area Code)	22c. OFFICE SYMBOL
HENRY E. HELIN	202-767-0471	AFOSR/NA

DD FORM 1473, 84 MAR 83 APR edition may be used until exhausted. All other editions are obsolete.

SECURITY CLASSIFICATION OF THIS PAGE
UNCLASSIFIED

88 10 5 213

Unsteady Separated Flows: Structures and Processes (F49620-84-C-0065)

Research Objectives

Experimental work was designed to investigate the unsteady separation phenomenon. Such investigations were to use qualitative methods allowing a full characterization of forcing functions and planforms capable of producing unsteady flow separations. For select test conditions the characterizations were to employ quantification of the unsteady flow phenomenon.

(1) Boundary layer separations were to be evaluated to determine how such separations foster unsteady flows. Develop physical models of same.
(2) Vortex production and entrapment characteristics of boundary layer "trip" mechanisms were to be described.
(3) The three-dimensionality of unsteady flows was to be described for sinusoidal, repetitive forcing functions.
(4) Unsteady flows arising from airfoils and plates at various incident angles in starting flows were to be characterized: both uniform acceleration and instantaneous acceleration were to be evaluated. Extend to three-dimensional analyses.
(5) Anemometric measurements, pressure measurements and force measurements were to be coupled with flow visualization, where appropriate, to evolve an understanding of unsteady separated flow physics and generation mechanisms.
(6) Studies and simulations of three-dimensional lifting mechanisms endemic to insect flight were to be conducted for both streaming and hovering conditions. Integrate with mechanical data.

These experimental studies have been a part of the total work package that includes analytic endeavors. These latter efforts include theoretical and numerical analyses of unsteady separated flows on lifting surfaces that may have potential applications in high performance flight vehicles. Specific examples of such analyses are listed below.

(1) Evaluate the effects of surface suctions on vortex entrapment.
(2) Characterize the behavior of a free vortex released above an oscillation airfoil as related to flow stability and load enhancement.
(3) Evaluate lifting surface performance in the presence of a bound vortex.
(4) Evaluate the lifting performance supported by moving vortices of varying magnitudes of circulation.

(5) Conduct numerical simulations of flows about oscillating airfoils and about constant pitch airfoils. Evaluate simulations for airfoils in accelerating flows beginning from rest.
(6) Conduct numerical simulations related to natural flight mechanisms as described in experimental work.
(7) Create an adaptive computational grid simulation of unsteady viscous flows.

Status of Research Efforts

During the funding period all work was successfully completed. More than 50 scientific papers and reports were generated. And, many students received training in this research area. The details of these papers and reports are provided below. A list of professional personnel is provided, as well.

Boundary Layer Separation. Several investigations have been directed toward understanding the role of boundary layer separations in the genesis of unsteady separated flows. The studies have ranged from a broad class of whole lifting surface forcing functions (motion histories, discontinuous motions, differing axis of rotation studies) to lifting surface modifications (deployable spoiler, imposed suction and air pulses, deployable leading edge configuration shifts). In addition, subtle evaluations of boundary layer characteristics have been completed through acoustical analyses of Tolmien-Schlichting wave reinforcement and amplification. Together, these evaluations have been the impetus for renewed interest in highly detailed evaluations of the boundary layer vorticity both near the nacent vortex at the leading edge and near the initiation sites of reverse flow at the trailing edge. The questions remaining focus on how and where vorticity is accumulated in the boundary layer, how the vorticity is transported and finally how the vorticity is normally lost from the boundary layer? Recently, the boundary layer vorticity was thoroughly mapped and tracked over the surface of airfoils for two very different unsteady flow elicitation conditions. The results showed that vorticity distribution varies dependent on extant flow structures and interactions with the free stream. Thus, boundary layer distributions of vorticity prior to unsteady separation dictate the nature of the vortices produced and the growth and convection characteristics of such vortices. Despite the complexities inherent to these interactions, the boundary layer features of unsteady separated flow initiation are highly reproducible on both temporal and spatial scales. This feature has persisted across all test conditions and it remains the basis on which future applications for practical aerodynamics may rest.

Our present concepts of boundary layer separation include a vorticity storage mechanism, limited reverse flow mechanism and a leading edge shadow (from free stream) mechanism. Vorticity storage and production are necessarily in close spatial proximity. The velocity gradients of the accelerating flows near the leading edge generate vorticity that is accumulated in the shadowed region of the pitching test surface. The resultant reduction in boundary layer convection at the leading edge causes a "stretching" of the downstream vortex arising at the time the major leading edge vortex is being formed. Reverse flow and the momentum it carries will push upstream only to the site of boundary layer stretching. At this point the reverse flow can aid in the growth of the downstream vortex. In instances of low pitch rates the upstream, leading edge portions of the boundary layer are longer in the chordwise direction. The rate of vorticity production exceeds the rate of volume increase in the shadowed region. No boundary layer stretching is in evidence and reverse flow proceeds to the major leading edge vortex region. High pitch rates culminating at high angles of attack generate a massive, full chord shadow region and, thus, stores vorticity in the shadowed area based upon the site of vorticity production and the gradient of the vorticity running from maximum production to minimum production sites.

<u>Boundary Layer "Trip" Mechanisms.</u> Studies undertaken to clarify the role and characteristics of boundary layer trip mechanisms included several studies with a deployable spoiler located at 0.12 chord of a NACA 0015 airfoil, a number of slots (18" long, 1/16" wide) located at various chord sites (0.1, 0.2, 0.7 and 0.9 chord) from which air pulses could be delivered and use of the same slots for suction episodes. In addition, the deployable spoiler has been modified to produce a periodically deforming leading edge followed by a reversed step. Air and suction pulses have been combined with sinusoidal pitching of the airfoil.

All of the above trip strategies yielded typical unsteady separated flow characteristics having a prominent leading edge vortex. Each of the mechanisms possessed the capability to maintain flow attachment at angles of attack beyond static stall angles and each, showed dynamic relations (such as the relation of K value to when a leading edge vortex was produced) consistent with common observations of unsteady slow initiation. The sized and effectiveness (in maintaining flow attachment) of leading edge vortices vary. In addition, the evidence for variations in vorticity accumulation is quite pronounced. For example, deployment of the spoiler produces added vorticity at that site and produces a volume of shadowed flow simultaneously. A small stagnation site is produced ahead of the spoiler, as well. As the spoiler is fully deployed and as it begins the retraction process, a vortex forms immediately downstream. But, the flow upstream accelerates over the leading edge to yield additional vorticity. At sufficiently high angles of attack, this leading edge vorticity forms into a minor vortex that has the same sense as the vortex that had formed behind the spoiler. Thus, the boundary layer characteristics defined by airfoil angle of attack determine both the site of vorticity production and the site of accumulation. Thereafter, the deployed spoiler provides a shadowed volume for additional vorticity produced by the spoiler, itself. And, the spoiler disrupts the shedding/production balance of the vorticity along the airfoil chord. In many ways, the delivery of an air pulse from the airfoil leading edge achieves the same results. The boundary layer is disrupted, vorticity is added and the freestream influences are forced away from the airfoil surface. Suction, somewhat paradoxically, generated the opposite effects yet aids in maintaining flow attachments at angles of attack beyond static stall angles.

In an attempt to force a modest degree of vortex entrapment, pulsed air delivery was coupled with sinusoidal pitching which was sufficient to produce a characteristic unsteady flow field. The air pulse, when delivered immediately prior to the formation of a leading edge vortex or simultaneously with the formation, hastened the growth and apparent strength of the vortex. The subsequent convection of the vortex was slowed such that the total dwell time over the airfoil was increased. this resulted in flow attachments that persisted at angles of attack well beyond those using air pulses or sinusoidal pitching, alone. The duration of low attachment was enhanced.

From the point of view of future applications, these experiments demonstrated control of boundary layer growths and separations in ways not requiring large amounts of energy or extensive amounts of lifting surface motion relative to the incident flows. These demonstrations indicate a number of enabling technologies may be used to generate and control unsteady flows. However, it is critical to note that the aerodynamic forces realized via unsteady flows remain transient and spatially localized. Various control strategies for unsteady flows must be consistent with these characteristics.

Three-Dimensionality. Three-dimensional effects yielded by a pitching wing were first described by our research group. Using a simple straight wing planform constructed using an NACA 0015 blank, the sinusoidal pitching yielded two very different areas of flow/wing interaction as well as zone of interfacing between these two flow regimes. At distances of 1 chord or more inboard of the wing tip, the unsteady flow initiation and development was quite similar to that reported for airfoils and flat plates extending to the walls of the wind tunnel. At the wing tip unsteady flow separations were absent. In fact, along the span of the wing near the wing tip the characteristic leading edge vortex was much diminished in size and persisted for only brief periods during each oscillation cycle. The wing tip flow was both well behaved and a reflection of the flow dynamics along the inboard span. Simple plots of the angularity of the wing tip vortex showed that an inboard vortex enhanced the flow around the tip from pressure to suction side of the wing. When the inboard leading edge vortex shed from the wing the tip flow relaxed indicating an instantaneous reduction in the pressure difference from pressure to suction side of the wing. Plots of the rotational characteristics of the tip flow versus periods during the pitching cycle show complete hysteresis loops indicative of considerable overall lift enhancement.

Additional three-dimensional tests have been completed using both forward and rearward swept wing configurations. The rational characteristics of the wing tip circulations revealed quite different hysteresis loops. The spanwise distribution of leading edge vortex flows also differed from that seen using the straight wing. In brief, the forward swept wing showed evidence for enhanced flow attachment that was very pronounced but was followed by episodes of cataclysmic stall. The rearward swept wing showed much core modest attachment (and enhanced lift) effects but showed little evidence for cataclysmic stall. From these examinations we have determined that wing configuration has a profound effect on both the type of unsteady flow field produced and the dwell times of the vortices associated with the flow field. The underlying physical mechanisms are thought to be related to vorticity production, accumulation and shedding. These concepts are consistent with a model of unsteady separated flows that we presented at the U.S. Air Force Academy Workshop.

The three-dimensional work has been extended to rather complex evaluations. Using a reflection model of the X-29 the canard has been instrumented to perform rapid pitching motions having a variety of mean angles of attack and oscillation or pitching magnitudes. Also, the oscillation rates could be varied. The whole model was mounted in the wind tunnel such that it and the forward swept wing would have an angle of attack to the incident flow. The flows elicited in these tests were exceeding complex. Angles of attack of the whole model induced flow downwash that altered the convection path of the canard vortices. Canard tip vortices passed upward and over the trailing forward swept wing. Dynamically, these flow conditions produced a variety of transitional flow structures highly repeatable from one oscillation cycle of the canard to the next. Detailed hotwire anemometric measurements corroborated the flow visualization studies. For these examinations, it has become feasible to design novel flight tests for the X-29 aircraft. Being planned at this time, these tests will take advantage of experiments done in the C.U. wind tunnels examining the effects of low values; these can be achieved on present canard controls of the X-29.

<u>Acceleration.</u> A broad range of studies have been completed using flow accelerations: graded and instanteous. Many of these studies have employed three-dimensional test surfaces: rectangular, delta, sail and circular wings. Detailed visualizations indicate a wide range of interactions between starting vortex systems and a variety of circular, horseshoe and tip vortices. A prominent set of observations provide the details of leading edge and tip vortex interactions as well as trailing edge vortex interactions. The "anchoring"

of vortices to the effective leading edges of the planform tips persists throughout all of the observations. Even in instances of pitching these characteristics of the vortex flows are retained, with varying degrees of turbulence.

Based upon the above observations, experiments were extended to cover the effects of pure pitching and plunging. These experiments revealed propulsive vortex signatures. Thus, the typical lift enhancement familiar to studies of unsteady separated flows can be construed to include general aerodynamic force enhancements, definitely including propulsion. Combinations of pitching and plunging have been simultaneously described in our ongoing insect work (summarized below) and can be readily recognized as the basis for both lift and thrust components in insect flight. The propulsive demonstration using an NACA 0015 airfoil emphasized the role of both pitching and plunging amplitudes. Again, this will be discussed later in regard to dragonfly flight kinematics.

Overall, the experiments show that acceleration histories contribute substantially to the unsteady flow fields observe. Depending on the flow interactions with the test surface resulting vorticity production is either very localized spatially or distributed. Areas of the chord that show considerable reverse flow experience more modest build up of vorticity. These areas are most often disparate in respective positions alone both the chord and span (three-dimensional test surfaces).

<u>Quantification.</u> Throughout the above cited efforts considerable work has been done to quantify flow velocities and pressure profiles. In the insect work, force balance measurements have been achieved, as well. Interestingly, there have been no instances in which carefully analyzed flow visualizations have differed substantially from interpretations gleaned from quantitative measurements. Flow history effects have made some flow visualizations difficult but the highly energetic nature of unsteady separated flows prevents flow histories from having a major impact on interpretations. Also, transitions to turbulence prevent attempts to "interpret" flows having excessive history effects.

Across several sinusoidal pitching tests and constant pitching tests anemometric measurements typically show velocities having upwards to three times free stream velocities. These velocities are inevitably associated with the formation and passage of the leading edge vortex. The velocity peaks are achieved for very brief, factional portions of the oscillatory pitching cycle. They are often accompanied by ancillary velocity peaks indicative of the convection of a vortex through the plane sampled by the hotwire. These velocity maxima are often coupled with a turbulence (variance) level that is quite modest. On the other hand, turbulence maxima are inevitably found in adjacent flow only slightly more distal from the pitching test surface. The movement of velocity maxima and turbulence maxima away from the test surface differ. Whereas the velocity maxima move outward slowly, the turbulence maxima move to the boundary of the freestream quite quickly. The physical meaning of these observations remains to be clarified.

A somewhat enigmatic observation in anemometric measurements is the behavior of the boundary layer in regard to reverse flow. Despite evidence for reverse flow occurring in flow visualizations of low K experiments and high constant rate pitch experiments, high K tests show little evidence for reverse flow except for regions immediately beneath the nacent leading edge vortex. Our most recent anemometric data, gathered with tandem hot wire elements, suggests that the boundary layer shows only brief episodes of reverse flow for high K test conditions. Within 0.0010" of the airfoil surface the flows appear to achieve velocities of 30-40% freestream velocities. Clearly these observations require additional elucidation and, in fact, work continues in this area.

In cooperation with F.J. Seiler Research Lab personnel we have been able to conduct a variety of pressure profiles for a sinusoidally pitching airfoil. As expected, lift coefficients were enhanced. The shape of the pressure profiles minimized what we presume to be the vorticity distributions on an airfoil driven through sinusoidal pitching. In closely related experiments we have also evaluated the pressure profiles produced over an air foil positioned in the immediate wake of a pitching airfoil. These observations were somewhat more difficult to interpret. When the leading edge vortex of the upstream airfoil passed over the trailing airfoil, a pressure minimum was induced. But, when passage was directed too far above the trailing airfoil little lift was produced. Often, the pressure history on the trailing edge airfoil was very complex revealing a splitting of the oncoming vortex or even the passage of the vortex beneath the airfoil. The observations clearly suggest that applications needs be satisfied by some method through which leading and trailing airfoils can remain in geometrically stable relation of one to the other. Or, the area between the airfoils can simply be closed to reflect a single deformable surface.

<u>Insect Flight.</u> Studies of dragonfly flight have been quite extensive. Detailed wing kinematic observations have been achieved in the field, in a zero-flow apparatus and in the wind tunnel. Biomechanics studies have included detailed analysis of wing box, thoracic exoskeleton and muscle attachment characteristics. Put together, the observed kinematics can be related to wing muscle activation and to thoracic skeletal deformation. Elements of sculling, pitching and plunging have been described. And, the limits of fore/aft wing phase angles have been traced to the underlying biomechanics.

With the detailed kinematics at hand, a physical model has been produced and subjected to extensive wind tunnel testing. Model corrugated wings have been used, as well. At K values of about 0.2 the model has been observed to produce flow field structures exactly like those produced by live dragonfly specimens evaluated under the same conditions. By evaluating kinematic elements individually in the mechanical model, the effects of pitching, plunging and sculling have been assessed separately. In addition, various pairings of these kinematics have been studied. Not surprisingly, pitching must be superimposed on plunging such that it occurs at the top and bottom of the plunging cycle. This pairing tolerates some "spreading" of the pitching kinematics across as much as 10-12% of the plunging cycle before cohesive flow structures are lost. Higher K values result in more turbulence arising from disruptive interference between starting vortices. Variations in the phase angles between fore and aft wings result in the aft wing intercepting fore wing vortices at different points in the plunging cycle. This, as noted below, changes the amount of aerodynamic force vectored as lift as opposed to thrust.

Evaluations of dragonfly force production began several years ago with our demonstration that periodic lift peaks were sometimes 20 fold greater than dragonfly body weight. Even lift forces averaged throughout a flight episode showed 2-3 times the body weights of the dragonflies tested. We reported that these values occurred with what appeared to be "normal" flight kinematics despite the tethering required for the tests. Some researchers argued that the flight episodes may not be "normal". The crucial point, however, is that exceedingly high lift values were produced--and observation worth serious attention. Also, we showed that these values could not have been obtained using steady state aerodynamics. Thus, the dragonfly has become the first documented case of insects using unsteady separated flows. This had been postulated by previous workers bu not directly corroborated.

It required almost two additional years to devise a sensitive, non-resonant force balance to measure lift, thrust and side forces to prepare direct correlations between wing kinematics and aerodynamic force generation. While flight episodes are visualized by high speed camera in the wind tunnel, a kymographic camera records the continuous force outputs from the three-dimensional force balance, The results show that moderate variations in wing kinematics result in significant variations of aerodynamic force. Correlations of force and kinematic elements revealed an important role of plunging amplitude in overall force production. Early and rapid pitching also yielded higher total forces. Finally, the phase relation between fore and aft wings determined how much force would be realized as lift and how much would be thrust. Interestingly, the total force generation varied less than the distribution of force between lift and thrust. This, of course, might simply reflect the effects of restraining the dragonflies to the force balance.

The three-dimensionality of flow about the dragonfly wings is rather modest largely because the plunging yields propulsive vortices that move outward from the wing tips. The result is that most effective (determined by correlations with force generation) flow structure behave as two-dimensional entities. This result is not unexpected since researchers both at the U.S.A.F. Academy and C.U. have shown that three-dimensional effects on wings rarely influence flow for distances of more than one chord length inboard of the wing tip. For these observations, pressure measurements corroborate the qualitative impressions of flow visualization. It seems desirable to extend these pressure measurements to the plunging typical of the dragonfly kinematics.

What we have learned from these studies is that unsteady separated flows are readily used to support rather elaborate flight. The dragonfly achieves all of this with modest amounts of nervous system control and with modest amounts of feedback. The fluid/wing interactions are based largely upon corporal motions that are highly stereotyped. Maneuvering and agility are achieved by small, but important modifications of these corporal motions. It seems feasible that engineering flight systems may be designed to take advantage of unsteady flows in a similar fashion. Thus, some of the flight mechanics used by the dragonfly should be unraveled for simulation purposes.

Computational Efforts

Vortex entrapment. Using inviscid techniques it has been possible to show that vortices are readily trapped over deformable airfoils at sites both near the leading and trailing edges. In addition, the application of suction (of blowing) and the use of oscillation can serve as entrapment forcing functions. In several instances, the trapped vortices may move upstream prior to being convected downstream and shedding.

Periodic placement of vortices in the flow resulted in high integrated lift values. But, when the number of vortices over the lifting surface is allowed to increase a point of diminishing return is experienced. There appears to be an optimal relation between vortices released into the flow over the lifting surface and the amount of effectiveness of those vortices. This observation was corroborated by using vortices having different magnitudes of circulation.

Although these studies provide considerable insight into the nature of vortex/lifting surface interactions, some questions have been raised regarding the source of the vortices. Whether the conditions needed to yield actual vortices are consistent with numerical studies remains to be seen. As clearly evident in the experimental work, however, effective vortices can be produced in a broad range of ways. Thus, the initial conditions may be allowed to vary considerably for numerical calculations. Of course, a more realistic approach depended upon use of viscous computational codes.

Simulations. Considerable effort has been exhausted in simulating the unsteady flows generated about an airfoil starting at rest. Having created a special grid with high density near the airfoil surface, small time step iterations were performed with a Navier-Stokes solver. Reynolds numbers up to 5000 could be accommodated. The results of the simulation were plotted out in the form of streakline flow visualizations collected under identical circumstances. The resulting match was extremely good. Only the details of boundary layer thickening and vorticity tongue formation were lost in the simulation models. Yet, the overall vortex formation and some of the ornamentation were clearly evident. Unfortunately, additional flow velocities and the inclusion of pitching could not be accommodated with the computer power available. Follow up studies are being pursued to develop code for pitching airfoil.

Significantly, we have shown a rather accurate simulation of unsteady separated flow development. Added test cases are being pursued. With the demand for many combinations of test parameters intrinsic to the unsteady flow investigations, these simulations have the potential for rapidly assessing addition test parameters and for doing so in a manner that will aid in the development of requisite flight mechanics considerations. This could be a crucial step to using unsteady flow control in flight vehicles or demonstrator, experimental aircraft such as the DARPA/Navy X-31.

Natural Flight Simulations. Generic work on vortex-lifting surface interactions has been extended to considerations of dragonfly flight. Detailed interactions, however, have not been possible. The kinematics of each dragonfly wing and the phase relations between fore and aft wings defy facile simulations. The tandem wing arrangement has been considered. And, as suggested by previous work the shed vortex incidence on the following airfoil is critical to the vortex-airfoil interaction that emerges. The incidence, of course, is determined by the flow conditions of shedding and the angle of attack of the following airfoil.

From the computational work on vortex placement and strength as well as repetitive release rates, it is possible to scale the K value used by the dragonfly. Some conclusions that emerge are that increased flight velocities are somewhat asymptotic and that the maximum total force generation is similarly asymtotic. Both conclusions are consistent with observations gathered in the experimental work.

With the detailed kinematics and lift histories just completed experimentally, it should be possible to re-evaluate the possibility of direct simulations of natural flight mechanisms.

Professional Personnel

(1) Principal Investigators

Marvin W. Luttges, Professor, Aerospace Engineering Sciences

C.Y. Chow, Professor, Aerospace Engineering Sciences

Peter Freymuth, Professor, Aerospace Engineering Sciences

(2) Faculty Colleagues

Donald A. Kennedy, Assoc. Professor, Aerospace Engineering Sciences

A. Richard Seebass, Professor, Aerospace Engineering Sciences

(3) Students Receiving Ph.D. Degrees (Date, Dissertation Titles)

Dana Billings, 1984 "The Unsteady Boundary Layer of an Elliptic Cylinder Following the Impulsive Onset of Transitional and Rotational Motion."

Chyn-shan Chin, 1985 "Vortex Flow About Oscillating Airfoil With Surface Suction".

Michael C. Robinson, 1985 "Development of Vorticity and Vortices from Forced Unsteady Separated Flows".

Louis Stodieck, 1985 "Diagnostically Important Relationships Between Electrical and Mechanical Events of the Heart Measured In Vivo and In Vitro."

Ismail Hindash, 1985 "Theoretical Investigation of Laminar and Turbulent Unsteady Boundary Layers Along a Flat Plate."

John H. Russell, 1985 "A Study of the Unsteady Aerodynamic Forces Generated by a Deforming Jonkowski Airfoil."

Rodney Lee Cusic, 1985 "An Asymptotic Theory of Supersonic Turbulent Interactions in a Compression Corner."

Chung-Lung Chen, 1986 "Computation of Transonic Flow Over Porous Airfoils."

Robert R. Leben, 1986 "Multigrid Calculations of Boundary-Fitted Orthogonal Coordinates with Applications to Unsteady Flows."

Muh-Sheng Chen, 1986 "Numerical Optimization Design of Transonic Airfoils."

Hank Helin, 1986 "Experimental Studies on the Dynamic Development and Control of Unsteady Separated Flows."

Quen-Yaw Sheen, 1986 "Potential Flow Analysis of Unsteady Jonkowski: Aerofoil in Presence of Discrete Vortices."

Jeffrey C. Ashworth, 1987 "Three-Dimensional Unsteady Flow Elicited by Finite Wings and Complex Configurations.

Fathi Finaish, 1988 "Unsteady Flow Analysis Based Upon Flows With Impulsive Starts."

(4) Students Receiving M.S. Degrees (Date, Thesis Area)

Mark D. Palmer, 1984 "Quantified Vortex Initiation in Flows Beginning From Rest."

Christopher Somps, 1984 "Dragonfly Flight Analyses."

Fathi Finaish, 1984 "Experimental Studies of Vortex Formation on Airfoils in Accelerating Flows."

Neal Mosbarger, 1984 "Boundary Layer Perturbations Related to Unsteady Flow Genesis."

Jon Adler, 1985 "Three-dimensional Flow About A Straight NACA 0015 Wing."

Roxana Behbehani, 1985 "Numerical Analyses of Discrete Vortex Interactions on Rotating Airfoils."

Cheryl A. Morroni, 1985 "Experimental Studies of Unsteady Flows in Microbursts."

Mark A. Waltrip, 1985 "Three-Dimensional Flows About Forward Swept Wings."

Kalpana Chawla, 1986 "Numerical Production and Release of Discrete Vortices."

Kai-Hsiung Kao, 1986 "Computational Models of Aerofoils in Unsteady Flows."

Steve Huyer, 1988 "Analysis of Experimentally-Produced Vorticity in Unsteady Flow."

John McGlinchey, 1988 "Force Balance Measurements of Unsteady Flows Produced by Insects."

Mark Reavis, 1988 "Correlations of Wing Kinematics and Force Generation in Wind Tunnel Tested Dragonflies."

Bruce Pulford, 1988 "Analyses of Interactive Flight Kinematics in the Dragonfly."

(5) Additional Ph.D. Students (Anticipated Degree Date, Area)

Jeff Beel, 1988 "Analyses of Motor System Innervation."

Daniel Saharon, 1988 "Dragonfly Model Kinematics and Flow Perturbations."

Chris Somps, 1989 "*In vitro* Analysis of Dragonfly Flight Systems."

Scott Schreck, 1990 "Boundary Layer Vorticity and Unsteady Flows."

Mark Kliss, 1989 "*In vivo* Analysis of Dragonfly Thoracic Ganglia.

Mike Horner, 1990 "Nacent Unsteady Vortex Analyses Using Anemometry."

Kalpana Chawla, 1989 "Numerical Analyses Using Multigrid Approaches."

(6) Undergraduate Involvements

Experiments dealing with unsteady separated flows have been the focal point of the Department Senior Design Laboratory for the duration of the project. Of the 80-100 students enrolled for the full academic year teams of 3-5 students designed and carried out experimental studies related to unsteady separated flows. During each of these periods, as average of 2-3 papers were prepared for the Annual AIAA Student Paper Competition. Numerous prizes were won in the undergraduate and graduate (M.S.) divisions.

(7) U.S. Air Force Academy Interactions. Our research group has continued to work closely with DFAN and FJSRL personnel. Cooperation on projects, exchange of expertise and timely loans of equipment have been important for both research groups. We aided in wing tunnel design and specifications. And, we have had a number of exchange research seminars. Both Workshop of Unsteady Separated Flow efforts have arisen from Academy and C.U. interactions. We have been pleases to work with several Air Force personnel in their respective Ph.D. programs and we look forward to future opportunities to work with that high level of student. In each instance, to date, U.S. Air Force students have received their Ph.D.'s in timely fashion and with records of distinguished achievements.

Interactions

As described above, the present project has involved C.U. and the U.S.A.F.A. in a variety of mutually beneficial interactions. Research efforts have been completed conjointly, papers have been coauthored, equipment use has been shared, students have participated in research at both sites, wind tunnel availability has been afforded Air Force personnel during tunnel moves and construction, and new research initiatives have been undertaken. The details of these continuing interactions have been too numerous to cite in discrete detail. However, this cooperation has "spilled over" to such things as a model, powered aircraft competition between C.U. and the U.S.A.F.A. and to student practice sessions for research papers presented at AIAA Student Paper Competitions. Also, several C.U. faculty have participated directly in research and teaching elements as "in residence" academicians.

The most recent interaction between C.U. and the U.S.A.F.A. is a science support effort related to the X-31. Organized by Hank Helin at Air Force Office of Scientific Research, this effort will use DARPA/OSR support to study the applications implications of a broad range of interdisciplinary issues related to X-31 operations and tests.

It is notable that the insect flight research on unsteady separated flows has been interfaced with and ONR grant focused on dragonfly nervous system and musculature. This latter work has been managed by Frank Hempel at ONR. Through this work we are prepared to better understand the control problems and solutions associated with the use of unsteady separated flows.

Patents

None

UNSTEADY SEPARATED FLOWS: STRUCTURES AND PROCESSES

Publications supported by AFOSR

Unsteady forces on an elliptical cylinder undergoing time dependent geometrical changes," Russell, J.H. and Chow, C.-Y., Aeronautics Digest, USAFA-TR-84-7, pp. 2-12, Sept. 1984.

"First experimental evidence of vortex splitting," Freymuth, P.; Bank, W.; and Palmer, M., Phys. Fluids, 27(5), May 1984, pp. 1045-1046.

Unsteady Separated Flows, Francis, M. and Luttges, M.W. (eds.), University of Colorado, Aerospace Engineering Sciences, Boulder, Colorado (1984), 187 pp.

"Vortices around airfoils," Freymuth, P.; Bank, W.; and Palmer, M., American Scientist, Vol. 72, May-June 1984, pp. 242-248.

"Analysis of vortex development from visualizations of accelerating flow around an airfoil, starting from rest," Freymnuth, P. and Palmer, M., AIAA 17th Fluid Dynamics, Plasma Dynamics and Lasers Conference, Snowmass, Colorado, June 25-27, 1984, AIAA Paper 84-1568.

"Comparative visualization of accelerating flow around various bodies, starting from rest," Freymuth, P.; Palmer, M.; and Bank, W., Workshop on Unsteady Flow, USAF Colorado Springs, Francis and Luttges, eds., 1984, pp. 52-57.

"A parametric analysis of vortex patterns visualized over airfoils in accelerating flows," Freymuth, P.; Finaish, F.; and Palmer, M., Proceedings of the 8th Symposium on Turbulence, Rolla, published 1984, pp. 135-144. (Also to appear in Experiments in Fluids).

"Trapping of free vortex by airfoils with surface suction," Chow, C.-Y.; Chen, C.L.; and Huang, M.K., AIAA Paper No. 85-0446, Jan. 1985.

"Use of titanium tetrachloride for visualization of accelerating flow around airfoils," Freymuth, P.; Bank, W.; and Palmer, M., Flow Visualization III, W. J. Yang, Editor, Hemisphere Publishing Corp., 1985, 99-105.

"Dragonfly flight: Novel uses of unsteady separated flows," Luttges, M.W. and Somps, C., Science 228, 1326-1329 (1985).

"Reply by authors to P.R. Payne," Huang, M.K. and Chow, C.-Y., Journal of Aircraft, Vol. 22, 351, 1985.

"The vortex patterns of dynamic separation: A parametric and comparative study," Freymuth, P., A review article published in Progress of Aerospace Science, Vol. 22, pp. 161-208, 1985, Pergamon Press.

"Three-dimensionality in unsteady flow about a wing," Luttges, M.W. and Adler, J., AIAA-85-0132, AIAA 23rd Aerospace Sciences Meeting, Jan. 14-17, 1985, Reno, Nevada.

"Unsteady flow about a Joukowski airfoil in the presence of moving vortices," Chow, C.-Y.; Huang, M.K.; and Yan, C.Z., AIAA Journal, Vol. 21, 657-658, 1985.

"Visualization of spanwise vortex structure in the starting flow behind an airfoil," Freymuth, P.; Bank, W.; and Finaish, F., AIAA 23rd Aerospace Sciences Meeting, Jan. 14-17, 1985, Reno, Nevada. Paper AIAA-85-0447, pp. 1-9, 1985.

"Control of unsteady separated flow structures on airfoils," Luttges, M.W.; Robinson, M.; and Kennedy, D., AIAA-85-0531, AIAA Shear Flow Conference, March 12-14, 1985.

"Parallel methods for heterogeneous fluid structures," Leben, R. and Gustafson, K., presented in the National Workshop on Parallel Processing using the HEP, Norman, OK, March 1985.

"Further experimental evidence of vortex splitting," Freymuth, P.; Bank, W.; and Palmer, M., J. Fluid Mech., Vol. 152, pp. 289-299, 1985.

"Numerical simulation of streaklines in unsteady flows," Leben, R., AIAA Student Conference, Wichita, KS, April 1985.

"Reynolds number dependence of vortex patterns in accelerated flow around airfoils," Freymuth, P.; Bank, W.; and Palmer, M., Experiments in Fluids, Vol. 3, pp. 109-112, 1985.

"Numerical Study of Porous Airfoils in Transonic Flow," Chen, C.L.; Chow, C.Y.; Holst, T.L.; and Van Dalsen, W.R., NASA TM-86713, May 1985.

"Surveying unsteady flows by means of movie sequences - A case study," Freymuth, P.; Bank, W.; and Finaish, F., Proceedings of Int. Symp. on Physical and Numerical Flow Visualization, ASME FED, Vol. 22, pp. 27-37, 1985.

"Unsteady forces acting on a flat plate airfoil undergoing chord deformations," Russell, J.H. and Chow, C.-Y., Aeronautics Digest, USAFA TR-85-11, pp. 1-27, Sept. 1985.

"Streamwise and spanwise vortical patterns visualized over airfoils in unsteady flow," Freymuth, P.; Finaish, F.; and Bank, W., Proceedings of the Conference on Low Reynolds Number Airfoil Aerodynamics, T.J. Mueller, Editor, Vol. UNDAS-CP-77B123, June 1985, University of Notre Dame, pp. 269-280.

"Dragonfly Flight," Luttges, M.W.; Somps, C.; and Fisher, L., Annual Meeting of Society for Neuroscience, Luttges, M.W.; Somps, C.; and Fisher, L., No. 512, 1985, Dallas, Texas.

"Complementary flow visualization," Freymuth, P. and Bank, W., Phys. Fluids, Vol. 28, p. 2633, 1985.

"Three-dimensional vortex patterns in a starting flow," Freymuth, P.; Finaish, F.; and Bank, W., J. Fluid Mech., Vol. 161, pp. 239-248, 1985.

"Vortices produced by air pulse injection from the surface of an oscillating airfoil," Luttges, M.W., and Robinson, M., AIAA 24th Aerospace Sciences Meeting, Jan. 6-9, 1986, Reno, Nevada, AIAA-86-0118.

"Unsteady forces acting on a deforming Joukowski airfoil," Chow, C.-Y. and Russell, J.H., AIAA 24th Aerospace Sciences Meeting, Jan. 6-9, 1986, Reno, Nevada, AIAA-86-0118.

"Visualization of the vortex street behind a circular cylinder at low Reynolds numbers," Freymuth, P.; Finaish, F.; and Bank, W., Phys. Fluids, 29, 1986, pp. 1321-1323.

"Three-dimensional unsteady flow fields elicited by a pitching forward swept wing," Luttges, M.W.; Ashworth, J.; and Waltrip, M., AIAA-86-1104, AIAA/ASME Fluid Mechanics, Plasma Dynamics and Lasers Conference, May 12-14, 1986, Atlanta, Georgia.

"Multigrid calculation of subvortices," Gustafson, K. and Leben, R., Applied Mathematics and Computation, Vol. 19, 89-102, 1986.

"The wing tip vortex system in a starting flow," Freymuth, P.; Finaish, F.; and Bank, W., Z. Flugiwiss.u.Weltraumforsch, 10, 1986, pp. 116-118.

"Generation of discrete tones from airfoils at low Reynolds Numbers," Luttges, M.W.; Robinson, M.C.; and Helin, H.E., AIAA-86-1917, AIAA 10th Aeroacoustics Conference, July 9-11, 1986, Seattle, Washington.

"Parametric exploration of unsteady wing tip vortices," Flow Visualization IV, Proceedings of the Fourth International Symposium on Flow Visualization, August 26-29, 1986, Ecole Nationale Superieure de Techniques Avancees, Paris, France, pp. 419-424.

"Trapping of free vortex by airfoils with surface suction," Chow, C.-Y.; Chen, C.L.; and Huang, M.K., AIAA Journal, Vol. 24, 1217-1218, August 1986.

"Visualizing the combined system of wing tip and starting vortices," Freymuth, P., TSI Flow Lines, 1st Issue, May 1986, 4 pages.

"Comparison in three-dimensionality in the unsteady flows elicited by straight and swept wings," Luttges, M.W. and Ashworth, J., AIAA Atmospheric Flight Mechanics Conference, AIAA 86-2280, August 18-20, 1986, Williamsburg, Va.

"Unsteady loading on airfoil due to vortices released intermittently from its surface," Journal of Aircraft, Vol. 23, No. 10, October 1986, pp. 750-755.

"Art and science in the visualization of vortex dynamics," CU Engineering No. 3, 1986, pp. 33-35.

"Visualization of dynamic stall controlled by large amplitude interrupted pitching motions," Luttges, M.W.; Helin, H.E.; and Robinson, M.C., AIAA-86-2281, AIAA Atmospheric Flight Mechanics Conference, Aug. 18-20, 1986, Williamsburg, Va.

"Visualization of wing tip vortices in unsteady and steady wing," Freymuth, P.; Finaish, F.; and Bank, W., AIAA-86-1096, 1986.

"Control of wake structure behind an oscillating airfoil," Luttges, M.W.; Robinson, M.C.; and Helin, H.E.; AIAA-86-2282, AIAA Atmospheric Flight Mechanics Conf., Aug. 18-20, 1986, Williamsburg, Va.

"Visualization of three-dimensional unsteady separated flow elicited by a pitching dragonfly wing model with a plunging tip," Luttges, M.W. and Saharon, D., AIAA Fluid Dynamics Conf., Jan. 12-15, 1987, AIAA-   , Reno, Nevada.

"Unsteady loading on airfoil due to vortices released intermittently from its surface," Chow, C.-Y. and Chiu, C.-S., Journal of Aircraft, Vol. 23, No. 10, October 1986, pp. 750-755.

"A parametric analysis of vortex patterns visualized over airfoils in accelerating flow," Freymuth, P.; Palmer, M.; and Finaish, F., Experiments in Fluids, 5 (1987), pp. 284-288.

"Further visualization of combined wing tip and starting vortex systems," Freymuth, P.; Finaish, F.; and Bank, W. AIAA Journal, Volume 25, No. 9, September 1987, pp. 1153-1159.

"Unsteady vortical flows around an airfoil," Chow, C.-Y. and Sheen, Quen-Yaw, Presented at Workshop II on Unsteady Separated Flow, July 28-30, 1987, 7 pages.

"Propulsive vortical signatures of plunging and pitching airfoils," Freymuth, P., AIAA Paper 88-0323, AIAA 26th Aerospace Sciences Meeting, January 11-14, 1988, Reno, Nevada, 11 pages.

Turbomachinery Calendar and Course Catalog, Freymuth, P., 1988, page 5.

"Three-Dimensional Flow Produced By a Pitching-Plunging Model Dragonfly Wing." M. Luttges and D. Saharon, "AIAA 25th Aerospace Sciences Meeting." Reno, NV Jan. 12-15, 1987.

"Comparisons of Unsteady Flow Fields About Straight and Swept Wings Using Flow Visualization and Hot Wire Anemometry." M. Luttges, J. Ashworth and S. Huyer, "AIAA 25th Aerospace Sciences Meeting." Reno, NV, Jan. 12-15, 1987.

"Unsteady Separated Flows Driven By Periodic Leading Edge Deformation." M. Luttges and S. Huyer, "AIAA 19th Fluid Dynamics, Plasma Dynamics and Laser Conference.", Honolulu, HW, June 8-10, 1987.

"Unsteady Flow Separation Between Two Stacked Airflows in Accelerated Flow." L. Luttges, M. Harvanek, F. Finaish, and H. Helin, "AIAA 19th Fluid Dynamics, Plasma Dynamics and Lasers Conference." Honolulu, HW, Junw 8-10, 1987.

"Aerodynamic Forces Produced By a Dragonfly", M. Luttges and M.A. Reavis, AIAA 26th Aerospace Sciences Meeting." AIAA-88-0330, Reno, NV, Jan. 14, 1988.

"Application of Forced Unsteady Aerodynamics to a Forward Swept Wing X-29 Model", M. Luttges, J. Ashworth and T. Mouch. "AIAA 26th Aerospace Sciences Meeting." Reno, NV, Jan. 11-14, 1988.

"Visualization of Unsteady Separated Flow Produced by Mechanically Driven Dragonfly Wind Kinematics Model", M. Luttges and D. Saharon. "AIAA 26th Aerospace Sciences Meeting." AIAA-88-0569, Reno, NV, Jan. 11-14, 1988.

"Unsteady Separated Flow Structure: Extended K Range and Oscillations Through Zero Pitch Angle." M. Luttges and S. J. Schreck. "AIAA 26th Aerospace Sciences Meeting." AIAA-88-0325, Reno, NV, Jan. 11-14, 1988.

"Unsteady Flow Interactions Between the Wake of an Oscillating Airfoil and a Stationary Trailing Airfoil." Huyer, S. and Luttges, M. AIAA Paper 88-2581. AIAA 6th Applied Aerodynamics Conference. Williamsburg, Virginia, June 6-8, 1988.

"Visualization and Anemometric Analyses of Forceds Unsteady Flows About an X-29 Model." Ashworth, J., Mouch, T. and Luttges, M. AIAA Paper 88-2570. AIAA 6th Applied Aerodynamics Conference. Williamsburg, Virginia, June 6-8, 1988.

"A Comparative Study of Differing Vortex Structures." Huyer, S., Reavis, M. and Luttges, M. AIAA Paper 88-2582. AIAA 6th Applied Aerodynamics Conference. Williamsburg, Virginia, June 6-8, 1988.