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13. ABSTRACT *(Maximum 200 words)*

Research examined the similarity behavior between forced unsteady separated flows illicited by airfoils and delta wings. For the first time, all of the existing unsteady separation data reported in open literature was assembled and contrasted directly. A vortex model which predicted vortex development and shedding characteristics from first principles was developed. Preliminary work was also initiated in using neural network techniques to model and predict these nonlinear unsteady flows.

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Final Report

United States Air Force
Office of Scientific Research
(AFOSR-88-0272)

June 7, 1993

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Table of Contents

Dr. Steve Huyer	Ph.D. awarded Apr 1991
Cpt. Tom McLaughlin	Ph.D. awarded July 1992
Cpt. Eric Stephen -	Ph.D. awarded Dec 1992
Mr. Michael Horner	Ph.D. expected Sep 1993
Cpt. Dave Bunker	Ph.D. expected July 1994

I. Equipment Acquisition and Development

a) Flow Visualization: Collection & Reduction

Image collection and processing equipment has been purchased under the contract to support a variety of our research topic areas. This imaging system currently utilizes standard illumination methods but may be modified to support stroboscopic and pulsed laser visualization techniques. The data reduction system is P.C. based and is capable of reducing data from either the imaging system or standard video tape. Both the imaging and data collection system are portable and have been used to support research activities at the University of Colorado, United States Air Force Academy, the University of Glasgow and Wright-Patterson Air Force Base.

As part of a cooperative effort between the University of Colorado and the Canadian National Research Council, C.U. developed an in-house image processing capability that enabled processing of flow visualization data. Initially, data collection and reduction were separated into a two part process. Our Canadian colleagues first acquired the data using a Kodak imaging system then down load the data to NTH (television) standard video tape. The subsequent processing of the flow visualization data was accomplished at the University of Colorado.

The reduction of video flow visualization data utilized a video "frame grabber", also purchased under this contract. This hardware digitized and stored select portions of the video tape for subsequent reduction. The frame grabber occupies an expansion board on an IBM clone 80386 processor. Software developed at C.U. allows the 80386 to interact with a programmable VCR through an IEEE port. The processor is capable of driving the VCR to selected pre-programmed events (frames). This capability permits cycle and span averaged data collection to be automated for large data runs. The software used to reduce to flow visualization data will be discussed later.

An advanced version of the Kodak EktaPro (model 1000) was also purchased under the grant. This high-speed video collection and analysis system is the corner stone of our flow visualization capability. Consisting of a low-light imager (located in the camera), image processor, and video monitor, the EktaPro is capable of collecting digitized video data from 30 to 1000 frames per second. Individually digitized frames from the video tape can be directly down loaded to the PC, eliminating the need for a digitizing frame grab capability. The Kodak EktaPro has been used to collect data both at the University of Colorado and at the Seiler Research Laboratory.

b) Pressure Distributions Around a Circular Cylinder at Low Reynolds Numbers

Another novel method has been developed to measure the local surface pressure values at low tunnel velocities. This technique was used to examine both the steady and unsteady component of velocity fluctuations around a rotating circular cylinder. Only time averaged pressure and force data had been previously reported. Temporally averaged data fail to capture the induced fluctuations which result from the temporal shedding of boundary layer vorticity into the wake. From these data, the foundation of a large scale vortex shedding model was developed. The pressure results and vortex model will be discussed later.

The test model was made using an oversized cylinder turned down to a 6 in. diameter. The span length was cut to 3 ft. so the model could be mounted in the low speed Seiler tunnel, high speed (Mach 0.6) DFAN tunnel or low turbulence C.U. tunnel. A small pressure port was machined mid span to hold a miniature Endevco pressure transducer.

One of the major difficulties in recording pressure data at low velocities is the very low signal to noise ratios typically induced by the test environment. Running leads carrying milli- or even micro-volt signal levels from a tunnel test section to calibrated differential amplifiers can account for most of this error.

Cpt. Tom McLaughlin designed and constructed a compact battery powered high gain amplifier that could be close coupled to the pressure transducer inside of the cylinder. The design was sufficiently robust to survive the high centripetal acceleration environment created by the cylinder rotation. The resulting high signal to noise ratio allowed pressure data collection at low tunnel velocities.

The same design is currently being considered for modifying the multi-port pressure wings used by the Air Force Academy. If coupled with the appropriate MUX, pressure data collection would be possible at much lower tunnel velocities. Also, such a design change would permit data collection at high velocities (Mach 0.6) without the complex routing of numerous pressure leads through a rotating sting.

II. Software Development

The portable image processing package was developed on a PC compatible 80386 microprocessor operating at 25 MHz. Although the data reduction package was designed specifically for reducing the Canadian delta wing flow visualization data, the basic precepts used for analyzing this data can easily be modified to analyze any vortical flow structure. In fact, the same software and analysis routines are currently being adapted by another research group to reconstruct the three dimensional development patterns of plants grown in microgravity environments.

The rolling delta wing data consisted of laser sheet imaging of smoke released upstream of the model. The laser sheet was visualized from positions both perpendicular and parallel to the free stream velocity. Visualization data from the parallel vantage point clearly shows well defined vortical flows above the delta wing - characteristic of delta wing flow fields. These vortical structures provided the base line for software development.

Typically, visualization data are quantified according to readily observable characteristics: Vortex size, shape, location and coherence. Although such characteristics are easily discerned using the human analog computer, defining specific algorithms which identify these vortex attributes are much more difficult. Given the non uniformity inherent to visualization data including smoke distribution, flow turbulence, smoke artifacts etc., quantifying flow structure in some test circumstances can be impossible.

An inherent problem with most flow visualization techniques are the aberrant inconsistencies derived from flow seed anomalies. To address this issue, the intensity of the digitized data is normalized to a mean and standard deviation value. This enhancement improves both high and low density smoke images.

Analysis of the normalized visualization data was accomplished using a three step process. First, the delta wing position was located in the viewing field. This established the local coordinate system and provided physical limits in which vortical structures had to be identified. Second, vortices were located over the wing and the physical size, shape and location were recorded. Third, if clearly defined vortices could not be identified, burst vortex criteria were used.

It is important to remember that delta wing visualization data is both three-dimensional and temporally dependent. The technique outlined above reduces visualization data at a specific span location and phase angle. Once reduced, three-dimensional effects including vortex burst behavior and three dimensional tracking as a function of cycle oscillation must be done manually.

A novel approach using neural network architecture to recognize and track flow field structures is also being developed. This technique allows tracking of cohesive small structures as well as the large vortical structures described above. The neural network will permit resolving all of the flow structure attributes previously described using significantly reduce computational overhead.

III. Original Reports on Research Findings

a) Pressure Measurements on a Rotating Cylinder

Unsteady pressure measurements around a rotating cylinder were collected at varying velocity ratios and Reynolds numbers. Most of this work was conducted in the 3' x 3' low speed wind tunnel located at the United States Air Force Academy. Initially, data were collected within the high speed facility (Mach 0.6). It was discovered that the 6 in. diameter model created a significant momentum deficit at the tunnel center line. Since the Mach 0.6 tunnel is a closed loop facility, this deficit adversely affected the inlet flow conditions. The test apparatus was relocated to the open return Seiler low speed tunnel and the problem was eliminated.

Instantaneous pressure profiles were recorded for 100 complete revolutions of the circular cylinder. A reference phase pulse was generated at the start of each rotation. Data collection for a single rotation was triggered using this phase pulse and pressure data for one complete rotation was stored as a singe data record. These data records were averaged providing mean and standard deviation distributions around the cylinder.

Lift and drag coefficients were calculated from the mean pressure distributions. The non-rotating pressure distributions were found to be in excellent agreement with previously published static pressure distribution results. The lift and drag coefficients for a rotating cylinder were also in excellent agreement with previous measurements made using a force balance. These comparisons were used to validate the measurement technique.

The pressure standard deviation profiles provided an excellent metric of the flow unsteadiness. The standard deviation distributions were correlated with Karman vortex shedding at low Reynolds numbers and rotation rates. Peaks in the standard deviation profiles provided an excellent measure of the boundary layer separation "region" from both the upper and lower cylinder surfaces.

These results supported previous findings on boundary layer dynamics. The separation point on the upper surface moves aft with increasing velocity ratio, the opposite effect was observed on the lower surface. This effect produces an increase in lift with increasing rotation speed. For low and High Reynolds numbers, the overall pressure distributions are scaled by the velocity tip ratio.

At certain critical Reynolds numbers and velocity ratios, a reversal in this Magnus lift effect had been noted. Increasing the velocity tip ratio (rotation rate) produced a decrease in the integrated lift. It had been postulated that a laminar to turbulent boundary layer transition produced this effect. These results documented, for the first time, that a boundary layer transition on the lower surface is in fact responsible for this lift reversal

Previous flow visualization and hot-wire data had shown that the Karman vortex shedding of coherent vortex structures abated at velocity ratios greater that 1.0. Data collected in these studies suggest that at high velocity ratios, the entire boundary layer is forced to transition. Turbulent flow from the lower surface boundary layer is carried around the cylinder and is interjected into the upper surface boundary layer. The resulting upper surface shear layer, comprised of this now turbulent boundary layer, no longer maintains the expected laminar distribution. The altered shear layer will no longer support the normal Karman vortex street roll-up of vorticity into coherent structure.

From this and other previously collected pressure data, an empirical shedding model has been developed which accurately predicts the Strouhal bluff body shedding frequency from the principals of vortex accumulation. These results are presented in the analysis section. Strong correlation exist between the vorticity shedding observed with bluff bodies and dynamically stalled airfoils. A unified model which ties the effects of vortex shedding to pressure gradient effects and vorticity accumulation from separated shear layers will also be examined later.

b) Pressure Gradient Contributions to Dynamic Stall Vortex Initiation

The development of dynamic stall over a pitching wing is driven by a number of factors. The major contributor to the shed vorticity is, of course, the magnitude of the pressure gradients along both the chord and span. Recent studies involving the diffusion and partial attenuation of these pressure gradients have been initiated to examine the effects of three-dimensional pressure gradients on the dynamic stall process.

A passive porous suction surface was added to a NACA 0015 wing constructed with a semi-aspect ratio of 2.0. Static surface pressure measurements indicated that the adverse pressure gradient along the chord was significantly reduced with the addition of the porous surface. Also, the overall pressure magnitudes were reduced.

Flow visualizations taken during constant rate pitching motions indicated that no clearly discernible dynamic stall vortex was produced over the porous surface at low pitch rates. As the non-dimensional pitch rate was increased, dynamic stall vortices were observed to initiate earlier in the pitch cycle and tended to be less cohesive. A simple model involving fluid motion through the porous surfaces was developed to explain this and other observed phenomena.

c) Three Dimensional Flow Field Kinematics Near the Root of an Oscillating Wing

In order to take full advantage of dynamic and post-stall flight maneuvering capability, it is necessary to understand the flow characteristics at the root/wing interface. Most investigations have focused on the two-dimensional dynamic stall structures generated along the span. And, to a lesser extent, the orthogonal vortex-vortex interaction near the wing tip. Few investigations have examined the root/wing interaction zone.

Preliminary root/wing investigations have been conducted both at the University of Colorado and at the United States Air Force Academy. These studies have used various wing geometry's and motion histories. In addition to flow visualization, hot-wire anemometer and force measurements have also been used to quantify the dynamic stall effects in this area.

Typically, a wing mounted to a circular splitter plate is used to conduct these experiments. From visualization results at various span locations, a leading vortex and a shear layer are observed to form from root to tip during the wing pitch motion. The leading edge vortex initiated parallel to the leading edge along the span. At the splitter plate, the vortex intersected the root perpendicular to the root plate. At the wing tip, the dynamic stall vortex turned upstream toward the leading edge of the tip. A contiguous vortex line can be envisioned which ran from the splitter plate through the dynamic stall vortex around the wing tip and out through the wing tip vortex.

The shear layer vortex was initially comprised of ancillary vortex structures located at mid span. As the leading edge vortex developed, these structures coalesced into the shear layer vortex at mid span.

As the dynamic stall vortex convected over the span, the vortical flow became strongly three dimensional. Mid span, the vortex convected two dimensionally until it reached mid chord. At the tip, the dynamic stall vortex remained pinned to the leading edge of the wing tip. At the splitter plate, vortex convection was also slightly restrained.

When the dynamic stall vortex reaches mid chord, a significant alteration occurs. The dynamic stall vortex lifts from the wing surface forming an inverted U shape vortex over the wing. The center of the U vortex is located approximately mid span and continues to lift from the airfoil surface. This vortex sheds from the surface and pinches closed at the bottom of the U forming a ring shaped vortex.

This behavior is not unique to this wing test geometry. The same effect has been observed for flat plate "wings" and two-dimensional model geometries as well. Preliminary results from the United States Air Force Academy suggests that this effect was observed for both static and dynamic splitter plates used on two and three dimensional test geometries. Obviously, the previously held model of a simple orthogonal interaction at the root is no longer valid.

Data from an instrumented splitter plate suggests that the high velocities associated with the root/wing interaction have a significant effect. The induced low static pressures at the root surface cause the splitter plate to deflect toward the wing tip. Further investigations being conducted at the Air Force Academy will help quantify the vortex/root interaction.

d) Uniform Flow Instability in Unsteady Flow Fields

A thin symmetric airfoil undergoing sinusoidal oscillations in pitch at low Reynolds numbers generates highly repeatable unsteady flow fields comprised of several different kinds of vortical structures. Due to the complex nature of forced unsteady separation, the underlying physical mechanisms driving vortex initiation and organization from bound surface vorticity have yet to be realized.

Often, vortices that appear to be similar in structure are grouped together to simplify analysis. Two common types of vortical structures produced by an airfoil oscillating in pitch at low Reynolds numbers are the leading edge and ancillary vortices.

Previous investigations have documented the effects of pitch oscillation parameter variations on the behavior of the leading edge vortex and ancillary structures. Close examination of the behavior of these structures reveals that a serial flow history or some relatively simple fluid mechanisms exist in the wake.

To examine this phenomenon, flow visualization was used in the 40.6 cm x 40.6 cm low speed wind tunnel at the University of Colorado. A 30.5 cm x 15.2 cm x 0.6 cm flat plate was mounted horizontally and oscillated sinusoidally in pitch about its quarter chord in the center of the wind tunnel test section. For all tests, the free stream velocity as maintained at 5.0 ft/sec. Smoke was used to visualize the flow. The highly repeatable flow patterns allowed for the use of multi-exposure photography (typically 5 to 7 exposures).

The wake structure closely resembled the classic Karman vortex street found in the wake of a static cylinder. Fluids moving beneath the trailing edge of the plate move faster than fluids above the trailing edge, causing a Helmholtz shear flow instability. This shear layer drives the formation of consecutively shedding ancillary structures immediately downstream of the trailing edge. A perturbation in a laminar boundary layer above a critical Reynolds number will generate disturbances downstream in a certain band of frequencies that tend to grow with time.

As indicated above, uniform flow instabilities that have been traditionally associated with static conditions can contribute notably to the organization of an unsteady flow field. Karman vortex shedding, Helmholtz shear flow instability and Tollmien-Schlicting instabilities were observed in the low Reynolds number oscillating flat plate experiment described above. A closer examination of extended dynamic conditions may reveal that these "static" phenomena may provide some of the physical mechanisms driving forced unsteady separation.

e) The Oscillating Delta Wing: Force Data

The development of the Advanced Tactical Fighter has encouraged a great deal of research concerning post-stall maneuvering through control of unsteady flow fields and thrust vectoring. Since the plan form geometry of the ATF is that of a delta wing, developing an understanding of the physical aerodynamic phenomena associated with pitching delta wings is essential to understanding post-stall maneuvering. Present experimental activities have focused on both the vortex kinematics and unsteady aerodynamic loading produced by an oscillating 45-degree delta wing. Leading edge smoke wire flow visualization was documented using both still and high speed video photography. Force balance data recorded unsteady lift and drag coefficient data.

Data were taken across an extended range of reduced frequencies, mean angles of attack and pitch axis locations at a fixed oscillation amplitude to substantiate hypotheses regarding the observed phenomena. Reduced frequencies of 0.1, 0.2, 0.3 0.4, 0.5, and 1.0 were examined at a 20-degree mean angle of attack. Mean angles of 10, 15, 20, 25 and 30 degrees were examined at a K value of 0.2 in order to evaluate the effects of the angle of attack, pitching from pre- to post-stall. Trailing pitch axis location and a 9-degree oscillation amplitude were used in these experiments.

High speed video photography (250 frames/second) permitted a detailed qualitative assessment of the vortex kinematics associated with an oscillating delta wing. In general, there appeared to be three phases of the unsteady delta wing flow development:

1) Development of a series of discrete vortex structures visually similar to initial vortices formed on an oscillating rectangular wing. As many as four discrete vortices were formed during wing pitch-up.

2) Transition of these structures into a conical delta wing near maximum angles of attack.

3) Subsequent global separation or vortex shedding as the wing pitched down.

An increase in mean angle had three effects on flow development. Fewer discrete vortices were elicited and transition to a conical phase was less pronounced with increased mean angle. Qualitatively similar flow fields were seen later in the cycle. Finally, an increase in chaotic vortex structures and global separation were observed with increased mean angle.

Increasing reduced frequency had four flow development effects:

1) A greater number of discrete vortex structures were elicited

2) Transition into conical vortex structures was delayed

3) Enhanced global separation could be delayed or eliminated

4) Vortex cohesiveness increased.

The lift and drag histories produced by an oscillating delta wing were quite complex. Dynamic lift values often exceeded their static counter parts by a factor of two. Unsteady drag was lower for all dynamic tests conducted below the static stall angle. Drag in excess of static values were observed at angles exceeding stall. This drag increase was most likely due to the lift enhancement achieved at the same angles.

Hysteresis loops in the lift and drag data were seen in all test cases. The hysteresis characteristics differed depending on motion history. For low mean angles, counterclockwise lift hysteresis was observed. Moderate reduced frequencies and low mean angles showed little hysteresis. Increasing mean angle resulted in clockwise hysteresis. At high reduced frequencies and large mean angles, counterclockwise hysteresis was resulted.

The hysteresis loops indicate a persistence in circulation. These loops also relate the temporal delays associated with different wing motion histories. High K values and low mean angles eliminate the onset of global separation. Low K and high mean angles produce global separation prior to reaching maximum angle of attack. High K and low mean angle yield lift enhancement, while low K and high mean angle show periods of lift deterioration.

Modest speculations can be made about the bounded vorticity dependence upon reduced frequency and mean angle of attack. As K was increased, the total dynamic lift decreased as 1/K. This reduction indicates decreased bound vorticity. Increasing mean angle increases total dynamic lift up to a mean angle of 25 degrees. Apparently, the additional vorticity produced can only be bound to a certain point. After K and mean angle exceed threshold values the additional vorticity produced can not be bound.

It is clear the unsteady flows produced by an oscillating delta wing produced substantial effects in terms of aerodynamic loading. Future work should concentrate on specific vortex kinematics and hysteresis effects generated across an even wider range of motion histories. These and the present studies will provide information and understanding that will be crucial to the eventual exploitation and application of these unsteady flow fields.

f) The Rolling Delta Wing

The Canadian NRC conducted a comprehensive test program to evaluate the effects of rolling motions on the aerodynamic loading on a 65 degree delta wing. This program involved the collection of force balance, surface pressure and flow visualization data. As discussed earlier, flow visualization data was collected by the NRC and analyzed by the University of Colorado. Force data was reduced by the NRC and was used for comparison with visualization data.

The flow visualization provided two dimensional cuts of the conical delta wing vortices over the suction surface of the wing. The cuts were provided by laser sheet illumination normal to the surface. Smoke was injected forward of the wing and entrained in the flow on the upper surface to stain the vortices.

The wing was oscillated in roll about center body while the center body maintained a 30 degrees angle of attack. To examine the effects of variations in oscillation parameters, a range of mean roll angles, oscillation amplitudes and oscillation frequencies. The mean roll angles ranged from 0 to 40 degrees, the oscillation amplitudes from 0 to 42 degrees, and the reduced frequency, K, from 0.02 to 1.0.

Vortical flow behavior could be explained by the effective incidence and sweep back angles and the persistence of the flow structures. The combination of the 30 degree angle of attack with a roll angle provides reduced effective incidence angle and an effective sideslip angle. The sweep back angle of the wing is therefore reduced on the windward side of the wing and increased on the leeward side due to the sideslip angle. With this combination the windward wing passes in and out of stalled region while passing through the range of test roll angles. At low roll angles the sweep back angle is near 65 degrees and the incidence angle is near 30 degrees.

From the delta wing geometry it can be shown that the sweep back angle decreases more rapidly than the incidence angle. With roll angles greater than 14 degrees the decrease in sweep back causes the windward wing to effectively stall. With increased roll the incidence angle decreases more rapidly and the windward wing enters an unstalled region.

The persistence of the flow structures is exhibited by the delays in the dynamic flow field behavior when compared to the static flow field for similar instantaneous geometries. The flow structures were quantified by span wise position of the vortex as well as the chord wise burst point position. During the oscillation cycle, passage from a staticaly unstalled geometry the a stalled geometry did not instantaneously invoke the related flow field changes. Rather the vortex position and burst point changes depended on the amount of time the wing spent under stalled or unstalled conditions described in previous paragraph.

Increases in the K value provided less time for the flow field to adjust to differing geometries. Therefore as the reduced frequency increased, the vortex and burst point exhibited less motion. At a K value of 1.0, the vortex structure exhibited little change during the oscillation cycle. The vortex position above the wing varied slightly due to a pulling away effect with rapid oscillations.

The rolling moment data from the NRC shows stable, non zero roll angles corresponding to the passage of the windward wing through the stalled. The anomalous roll moment data for oscillations around a zero mean roll angle attest to the flow persistence alluded to above.

g) Unsteady Separation from Conical Forebodies

Our most recent research initiative examines the forced unsteady separated flow derived from a rotating forebody. Under steady flow conditions, the separated boundary layer remains well behaved through large angle of attack variations. Two vortices are formed from the separated vorticity on the lee ward side of the body as it is rotated from approximately 0 to 10 degrees. These vortices grow in size as the angle of attack is increased. At angles in excess of 20 degrees, variations in the vortex position and structure create large normal force components. These loads can result in serious control problems with aircraft attempting to fly at high angles of attack. Virtually no loads data exist for aircraft maneuvering dynamically through these large angle excursions, the same maneuvers envisioned for super-maneuverable aircraft.

Under forced conditions, little is known about the resulting vortex dynamics. Some preliminary flow visualization work by Gad-el-Hak and Ho (1987) suggests a strong hysteresis in the vortex position with sinusoidal pitching motions. Currently, only a limited amount of unsteady force data has been collected (Smith and Nunn 1976). These data focused on the unsteady lift and drag components, side force loading was not reported.

Based upon the work by Huyer (1991), strong similarities exist between the flow structures observe from oscillating delta wings and pitching forebodies. Separation from conical forebodies lack the distinct separation point defined by the leading edge geometry of a delta wing. The separation criteria will most likely be dependent upon the same boundary layer behaviors observed with cylinders (Stephen 1992). The longitudinal vortex wake formation will depend upon the shaded wake behind the forebody and the rate of the applied pitch forcing function.

Cpt. Dave Bunker will address many of these issues with his Ph.D. dissertation work. Using a three phase experimental approach including; flow visualization, hot-wire anemometer and surface pressure data, the unsteady boundary layer separation process will be defined. These data will permit the vortex genesis to be determined from boundary layer vorticity separation through vortex formation. Hopefully, from these data, an analytical model can be derived which predicts vortex development in a manner similar to that derived for the delta wing.

IV. Summary Analysis of Forced Unsteady Separation

a) Two- and Three-Dimensional Unsteady Separation Prediction

Cpt. Tom McLaughlin's dissertation work examined the similarity behavior between forced unsteady separated flows illicited by airfoils and delta wings. For the first time, all of the existing unsteady separation data reported in open literature was assembled and contrasted directly. From the resultant data base, descriptive algorithms were derived which described the unsteady separated flow behavior. Across an extensive range of test geometries, forcing parameters, flow conditions, test facilities, experimenters and test methods, these predictive algorithms suggest that most, if not all, of the separation behavior can be fully described with rather simple descriptive models.

Differences between separation behaviors are dependent primarily on the type of forcing function and not on the test geometry. This is true even when the separation behavior is expanded to include three-dimensional test geometries. The most dominant effect is the forcing rate.

The unsteady separated flows produced by pitching airfoils and wings have in common three events which occur in sequence: 1) the initiation of the dynamic stall vortex, 2) achieve maximum lift and 3) separation of the dynamic stall vortex from the body surface. The resulting load history reflects these flow developments and can be idealized by a ramp up to peak C_L followed by a ramp down at the same rate post dynamic stall. The resulting load behavior is predicted by:

Non-dimensional time to peak lift

T^* to C_{Lmax}	$0.838\,(\alpha^+)^{-0.815}$	$\alpha^+ < 0.2$
	$\alpha = 50^\circ$	$\alpha^+ > 0.2$

Peak lift magnitude (0015 wind tunnel data only)

C_{Lmax}	$4.8\,(\alpha^+)^{+0.185}$	all α

Force data collected produced by sinusoidal oscillations collapsed in similar manner to the pitch data. There were, however, anomalies in the vortex genesis described above. For most test conditions the vortex initiates and develops before the airfoil achieves maximum angle and reverses direction. Under certain combinations of α_ω and K, vortex initiation is forced to occur at the maximum angle. This is a premature separation condition clearly evident in the data. The corresponding force history shows a rapid increase and decrease along the lift curve slope without hysteresis. The resulting load behaviors for sinusoidal motions were predicted by:

<u>Non-dimensional time to peak lift</u>

T* to C_{Lmax}	$(K^+)^{-0.81}\alpha_m^{-0.45}$	$\alpha_m + \alpha_\omega \le \alpha_{ss} + 40\,(K-0.05)$
	$\alpha = \alpha_{max}$	$\alpha_m + \alpha_\omega \ge \alpha_{ss} + 40\,(K-0.05)$

One of the more interesting results of this relationship is the dependence of the non-dimensional time (T*) to peak load (C_{Lmax}) on α_m and <u>not</u> α_ω. The ramp motion data suggests that only the pitch motion drives the peak force initiation time and magnitude. In contrast, the sinusoidal case is affected by both rate and mean angle. *The magnitude of the oscillation angle* (α_ω) establishes the criteria for hysteresis - if sufficiently large, dynamic stall is initiated prematurely and hysteresis in the transient load history can be eliminated.

Another interesting relationship is the dependence of C_{Lmax} on $\alpha_{C_{Lmax}}$. When C_{Lmax} was plotted as a function of $K \cdot \alpha_m$ a poor correlation was obtained. However, when C_{Lmax} for all of the sinusoidal data for a particular airfoil was plotted as a function of $\alpha_{C_{Lmax}}$, a linear relation was obtained. The magnitude of the linear regression, when the y intercept is forced to zero, matches almost exactly the value of static lift curve slope for that airfoil.

Surprisingly, the addition of three-dimensional geometries had only minor effects on the relationships described above. The effects of wing sweep and delta wing angle are similar. In general, the addition of three dimensionally delayed the onset of peak force and reduced the magnitude of the lift curve slope. Both changes were systematic, the onset of peak force was represented by a simple shift in the linear regressions. However, the magnitude of the shift was dependent upon the airfoil geometry.

b)Vortex Model for Unsteady Separation

Cpt. Eric Stephen's dissertation work used many of the temporal scales defined by Cpt McLaughlin and developed working models which predicted vortex development and shedding characteristics from first principles. The overall driving mechanism for vortex development relies on the pressure distribution over the body and the wake structure aft of the body. The pressure gradients derived from the pressure distributions set vorticity production by diffusion and establish the available vorticity flux rate for large scale vortex development. The organization of this vorticity is a function of the separated shear layer characteristics and the size of the shadowed wake volume which contains the shed vorticity.

The premise of the generic vortex development model is quite simple. The peak pressure distributions around a body establish the pressure gradients for vorticity diffusion. The peak magnitude of these gradients are established by the temporal relations set by the dynamic motion parameters. For dynamically pitching airfoils, Stephen derived a fluid element model which accounted for the accumulated vorticity as the element passed over the airfoil surface. The amount of vorticity contained in the element is proportional to the local gradient which feeds the element.

With the onset of pitch, vorticity aft of the suction peak decreases rapidly and changes sign at the trailing edge. As the pitch motion continues, the point where the vorticity changes sign moves forward over the surface. The maximum excursion upstream of the "cross-over" point is dependent upon the pitching rate. Similar to McLaughlin's results, the temporal sequence of these events are set by: 1) forward movement of the cross-over point in vorticity sign, 2) break down in the leading edge suction peak and 3) C_{Lmax}. The reverse flow rate could not be obtained by the vorticity tagging method but the results suggest vortex initiation occurs when the reverse flow reaches the peak pressure location. These three temporal events are nearly collinear with the temporal scale provided earlier by McLaughlin.

After vortex initiation, vortex convection was shown to be a function of the vorticity feed rate and the shadowed wake volume. For test conditions where the leading edge vortex developed and shed during a shadowed wake, the vortex diameter was established by the airfoil angle of attack. The amount of additional vorticity (flux rate) shed into the shadowed region after vortex initiation is set by the separated shear layer. Assuming a solid body rankine vortex formation, the convection rate is set the diameter change necessary to accommodate the vorticity inflow. Calculating a convection speed based on this model produced values within 15% of measured convection rates.

The most encouraging aspect of this generic approach is the applicability to other test geometries. In fact, using the same approach produced excellent results for predicting vortex development and bluff body shedding from cylinders, pitching airfoils, rotating plates and pitching delta wings.

V. Research Interactions

a) United States Air Force Academy

The interaction with both the Frank J. Seiler Research Laboratory and the Department of Aeronautics has produced a strong research program in unsteady aerodynamics. The coordination of research activities permits significant cost savings in equipment and personnel. For example, most of the pressure data is collected at the Seiler facility. Force data, flow visualization and reduction capabilities using the new data acquisition system are located in Boulder. Sharing equipment and personnel has created both a personal and academic bond to the mutual benefit of both programs.

Many of the research findings presented are co-authored with Academy personnel or students visiting the Seiler lab as summer interns. Most of the research activities are coordinated to help eliminate duplicative efforts. Also, regular meetings between the principles help share both data and experimental techniques.

This interaction has been enhanced with the recent addition of two former C.U. students. Dr. Will Faller is currently serving a one year appointment at the FJSRL facility. Will's work has shown the predictive capability of neural networks in determining unsteady separated flow behaviors. In addition, Cpt. Eric Stephen has returned to FJSRL after successfully completing his Ph.D. program at the University of Colorado. Eric is actively publishing much of his dissertation work while developing new research initiatives in unsteady aerodynamics. Some of these activities reflect a continuation of his work in predictive modeling for delta wings.

b) Wright Patterson AFB

An informal interaction with Jerry Jenkins at Wright Patterson, based upon mutual interests in unsteady flows, has been in existence for several years. Greg Addington, a Palace Knights recipient and graduate from our program, has now joined Jerry's staff. Greg will be examining the effects of vortex burst location on delta wing control. To help support this initiative, C.U. has transferred its flow visualization reduction capability to Greg at Wright Patterson. Hopefully, a better understanding of the burst characteristics will provide more insight into the underlying vortex development phenomena on delta wings.

c) University of Glasgow

Dr. Galbraith at the University of Glasgow was been active in unsteady aerodynamics research for several years. His research efforts have produced a significant amount of unsteady pressure and force data. These data have been used to investigate the unsteady aerodynamics associated with helicopter rotors.

Michael Horner, a graduate student in our program, will complete his doctoral degree this year while working with Dr. Galbraith. Mike has recently returned from Glasgow and is in the final stages of data reduction. Mike's dissertation work focuses on the unsteady aerodynamic effects of longitudinal vortex impingement on rotational blades.

e) National Renewable Energy Laboratory

One of the more exciting prospects for technology transfer from AFOSR funded research to industry will occur through NREL, a Department of Energy National Research Laboratory. NREL is actively conducting wind turbine research for industry. Wind turbines have demonstrated strong three-dimensional forced unsteady separated flow behaviors. Our recent collaborative interactions with NREL have documented the existence of dynamic stall phenomena and have provided guidance to their data acquisition and reduction program. Most of the flow geometry insight and test parameter standardization is based upon the long standing results obtained through the AFOSR program.

The results of our preliminary interactions have clearly defined distinct regions of turbine performance. These regions include the benign two-dimensional behavior normally considered in wind turbine design. However, both dynamic stall and strong three-dimensional flow effects have also been documented. Now that a performance baseline has been achieved, the parameters which drive off-nominal performance can be established. The information derived from this interaction will continue to be shared with AFOSR through our joint interaction with FJSRL.

V. Bibliography

Addington, G. A., "Comparisons of the Unsteady Flow Fields Elicited by Constant Rate and Sinusoidal Pitching Motions of an Airfoil," Final Report USAF-AES GSRP, Sep 1990.

Addington, G. A., Schreck, S. J., Luttges, M. W., "Static and Dynamic Flow Field Development about a Porous Suction Surface Wing," unpublished work in progress, Dec 1991.

Horner, M. B., Addington, G. A., Young, J. W., III, Luttges, M. W., " Controlled Three-Dimensionality in Unsteady Separated Flows About a Sinusoidally Oscillating Flat Plate," AIAA Paper No. AIAA-90-0689, Jan 1990.

Huyer, S.A., Robinson, M.C., Luttges, M.W., "Unsteady Aerodynamic Loading Produced by a Sinusoidally Oscillating Delta Wing." AIAA Paper AIAA-90-1536, Accepted for publication in Journal of Aircraft.

Huyer, S.A., Butterfield, C.P., Simms, D., Robinson, M.C., Luttges, M.W., "Examination Of Forced Unsteady Flow Fields On A Rotating Wind Turbine Blade." In preparation for submittal to AIAA Journal 1992.

Huyer, S.A., "Forced Unsteady Separated Flows on a 45o Delta Wing", Ph.D. Dissertation, University of Colorado 1991.

Huyer, S. A., Luttges, M. W., "The Vortex Kinematics Associated with an Oscillating Delta Wing," AIAA Paper No. AIAA-91-1797, June 1991.

Huyer, S., Robinson, M., Luttges, M., "Unsteady Aerodynamic Loading Produced by a Sinusoidally Oscillating Delta Wing," AIAA Paper No. AIAA-90-1536, June 1990.

Huyer, S. A., Luttges, M. W., Unsteady Flow Interactions Between the Wake of an Oscillating Airfoil and a Stationary Trailing Airfoil," AIAA Paper No. AIAA-88-2581, June 1988.

Huyer, S. A., Reavis, M. A., Luttges, M. W., "A Comparative Study of Differing Vortex Structures Arising in Unsteady Separated Flows," AIAA Paper No. AIAA-88-2582-CP, June 1988.

Klinge, J., Schreck, S., Robinson, M., Luttges, M., "Three- Dimensional Flow Field Kinematics near the Root of an Oscillating Wing," AIAA Paper No. AIAA-91-3264, Sep 1991.

Klinge, J. D., "The Effect of Wall Dynamics on the Flow Field near the Root of an Oscillating Wing," Final Report USAF-UES GSRP, Sep 1990.

Klinge, J. D., Schreck, S. J., Luttges M. W., "Dynamic Effects on High Frequency Unsteady Flow Structures," AIAA Paper No. AIAA-90-0690, Jan 1990.

McLaughlin, T.E., Robinson, M.C., and Luttges, M.W., "Aerodynamic Foundations For Use Of Unsteady Aerodynamic Effects In Flight Control.", AIAA Paper 93-0188.

McLaughlin, T.E., "Aerodynamic Foundations for use of Unsteady Aerodynamic Effects in Flight Control", Ph.D. Dissertation, University of Colorado 1992.

McLaughlin, T.E., Stephen, E.J., Robinson, M.C., "Pressure Measurements On A Rotating Circular Cylinder." AIAA Paper AIAA-91-3265, Sep 1991.

Roache, J. W., DeAndrea J., "Three Dimensional Flow Fields Elicited by Pitching a Canard and Forward Swept Wing Configuration," AIAA Student Paper, Jan 1991.

Schreck, S. J., Addington, G. A., Luttges, M. W., "Flow Field Structure and Development Near the Root of a Straight Wing Pitching at Constant Rate," AIAA Paper No. AIAA-91-1793, June 1991.

Stephen, E. J., "Similarity in Separated Flow Fields Producing Large Scale Vortices", Ph.D. Dissertation, University of Colorado 1992.

Stephen, E. J., McLaughlin, T. E., Luttges, M. W., "Flow Visualization Image Analysis of High-Rate Roll Experiments on a Delta Wing," AIAA Paper No. AIAA-92-0317, Jan 1992.

Stephen, E. J., McLaughlin, T. E., "Preliminary Flow Visualization Results for Oscillating Delta Wing," Progress report for Canadian NRC interaction, July 1991.