Closed-loop control of leading-edge and tip vortices for small UAV

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Summary

We present plans and preliminary results for a recently initiated multidisciplinary research effort aimed at closed-loop control of three-dimensional leading edge and tip vortices on low aspect ratio wings relevant to micro and small unmanned air vehicles. The goal of control is to extend the parameter space for which steady lift can be maintained at high angles of attack and to regulate leading edge and tip vortex formation to improve maneuverability and gust response. Initial efforts toward model-based control design and sensor-actuator configuration are presented. Dynamically dominant modes will be identified by integrating proper orthogonal decomposition (POD) and balanced truncation, and tunable empirical models will be based on energy exchange between the mean flow and POD modes and the addition of shift modes to track structures along natural and controlled transients. Plans for experimental and computational cross-validations of closed-loop control strategies are discussed, and preliminary results assessing actuator authority are presented. The differing stability characteristics of a leading-edge vortex in two-dimensional computations and finite-aspect ratio three-dimensional experiments are also highlighted.

1 Introduction

Recently, much attention has been focused on the development of closed-loop control strategies for diverse problems in fluid mechanics. Compared to open-loop control, feedback is typically required to modify the inherent dynamics of the flow (e.g. stabilize an instability), to improve performance
robustness or to lower the required control authority, such as the energy of actuation. The principal difficulty is the inherent complexity of the flow. In the context of model-based design, it is manifested by the difficulty in obtaining sufficiently low-order models of the flow so that simple but effective controllers may be designed. Successful examples include the control of shedding from bluff bodies [22, 9, 7], elimination of combustion instabilities [8, 3], and suppression of cavity oscillations [21, 6]. Modeling approaches used in these studies include physics-based models, for example based on transfer/describing functions (together with system identification), or Proper Orthogonal Decomposition/Galerkin projection (and extensions). A key to the success of some recent closed-loop control efforts [27] is the recognition that good control design must respect the limits of validity of the model, and the implications of any modeling limitations on the control architecture (e.g. actuator/sensor placement) and the limits of achievable performance (see, for example [3, 21]). A corollary is that interdisciplinary collaboration between modern control experts and fluid mechanicians is crucial to the development of these models.

In this spirit, we have recently embarked on a five-year multidisciplinary research effort aimed at closed-loop control of three-dimensional leading edge and tip vortices (LEV/TV) on low aspect ratio (AR) wings relevant to micro and small unmanned air vehicles (MAV/SUAV). Birds, insects, and bats offer enticing benchmarks for MAV and UAV performance including low cruising speed, agility, and propulsive efficiency, and sensor-based control. Some unique properties of bio-fliers stem from the role of a stable LEV that allows high lift at extremely high angles of attack, $\alpha$. The stability is partly due to the low Reynolds number (Re), but more strongly affected by three-dimensionality due to the low-aspect ratio (wing span to chord length, AR) typical of biological wings. Studies indicate that stability of the LEV is related to the spanwise transport of vorticity through an axial flow toward the tip vortex (TV). Even during purely translational motion (as opposed to flapping), strong three-dimensionality leads to a stabilizing interplay between flow separation LEV and TV at low Re ($10^2$ to $10^3$) [5]. Recent studies of 3D wings of swift birds using PIV indicate that these birds create stable LEV up to Re $\sim 10^5$, provided the wings have sufficient tip sweep [25]. Moreover, lift maximization [26] and rapid maneuvering in bio-fliers are achieved through careful synchronization of vortex shedding as regulated by asymmetry and timing of wing-strokes.

Unfortunately, similar mechanisms cannot presently be applied to fixed wing aircraft, except through control surfaces that cannot respond (due to
mechanical bandwidth constraints, stress limitations, and aircraft inertia) to the fast timescales required for agility. Fixed wing designs typically use high AR to obtain better efficiency (induced drag scales with the inverse of AR), higher minimum flight speed, and higher payload capacity. However, high AR severely limits the maximum \( \alpha \), increasing minimum cruising speed and decreasing agility. If flow control can be used to broaden the envelope (in both AR and Re) of high-lift aerodynamics, then decreased stall speed and enhanced agility can be obtained without sacrificing efficiency. The objective of closed-loop actuation near the leading edge and tip is to enable benefits associated with low AR and low Re aerodynamics to be achieved with fixed wings at higher AR and Re. We argue that closed-loop control can stabilize the LEV/TV system, preventing or delaying shedding/stall at high \( \alpha \), and, when desirable for maneuvering, synchronize vortex shedding to produce controlled roll, yaw, and pitching moments. The actuation strategy (see below) will be capable of producing spanwise non-uniform forcing that may also render conventional control surfaces redundant.

The feasibility and benefits of open-loop forcing of the LEV were previously demonstrated in a two-dimensional airfoil study [1], where detailed measurements on an NACA0012 airfoil undergoing pitching maneuvers identified a highly localized \((0.004 < x/c < 0.005)\) primary source of vorticity feeding into the LEV. This implies the feasibility of LEV control with a spatially localized actuator. In fact, [1] used phase-conditioned, open-loop control with suction to delay the development of the LEV by 40\% of the pitch maneuver time. Using the same open-loop actuation [2] demonstrated an increase in \( C_{L,\text{max}} \) from 1.0 to 2.4, and the stall \( \alpha \) was increased from 12\( ^\circ \) to 30\( ^\circ \) during pitching maneuvers. It is also well established, especially on 2D airfoils, that open-loop unsteady mass injection near a separation point can reduce the detrimental effects of separation (e.g., in [10]) with very low actuation authority.

With high-bandwidth instrumentation it will be possible for a closed-loop controller to react on the short time scale of the shear layer feeding the LEV and we postulate that such feedback will enable (i) attenuation and / or regulation of LEV shedding, (ii) robust performance in the presence of disturbances that would otherwise desynchronize and diminish the beneficial effects of actuation, and (iii) coordination with flight control to enhance maneuverability and extend the operating envelope of MAV/SUAV. Commercially available micro-valves (previously implemented at IIT) will provide pulsed and harmonic blowing and suction up to 200 Hz \((F^+ > 2.0\) for largest models\) and amplitude up to 100 m/s \((C_\mu > 0.04)\) for LEV/TV con-
trol. By embedding the actuators inside the wing, it will be possible to excite the flow very close to the leading edge separation location (approximately $x/c < 0.01$.) We will consider actuator configurations depicted in Figure 1, which shows actuator modules that will be tiled along the (rounded) leading edge and tip of a NACA 0012 airfoil. In order to demonstrate closed-loop control of maneuvers, the water tunnel and oil tank experiments will involve active control of pitch, yaw, and roll angles via an array of radio-controlled servo motors capable of providing sufficient bandwidth and torque. Unsteady wind tunnel experiments will involve active control of pitch and the airfoil will be mounted on a plunge mechanism to control landing/perch maneuvers.

![Figure 1](image)  
**Figure 1**  Schematic showing actuator modules tiled along leading edge and tip of a NACA 0012 airfoil

To summarize, the overall objectives of the research are to:

- Extend the parameter space for which steady lift can be maintained at high angles of attack by using closed-loop control to stabilize and regulate leading edge vortex formation.
- Use control to synchronize vortex shedding and improve maneuverability and gust response, and produce unsteady pitch, yaw, and rolling moments (and ultimately eliminate conventional control surfaces made redundant by flow control actuators).
- Introduce model-based control design early in the system design process in order to deliver optimal performance and minimize intrinsic performance limitations.
- Develop a set of widely applicable model-based flow control algorithms and architectures.
Demonstrate closed-loop control in simulations and laboratory experiments in order to assess the advantages of closed-loop control over open-loop forcing.

This project is intended to investigate a flow phenomenon that is the subject of current research using techniques that integrate fluid mechanics, feedback control and nonlinear dynamics, which in and of themselves are novel. This paper presents our vision and preliminary results at an early stage of our collaborative effort. We discuss the methodology and some preliminary results for a combined experimental, computational, and modeling studied aimed at achieving our objectives.

2 Methodology

2.1 Experimental facilities

Modeling and control will be closely integrated with experiments and state-of-the-art flow diagnostics in two separate experimental facilities: an unsteady wind tunnel (IIT) and a fixed-speed oil tunnel (Caltech). The success of closed-loop flow control depends critically on developing control strategies that account for hardware and performance limitations of the real systems. This means that experiments must, to the extent possible, provide a rich operating envelope that can mimic actual flight conditions so that what is learned in the laboratory can be transitioned to design of actual aircraft. At the same time, state-of-the-art diagnostic techniques are needed to provide accurate and complete data for modeling, and to ensure that performance gains from closed-loop control are accurately measured. The choice of these three facilities thoroughly covers the Re range appropriate for the scales of target MAV and UAVs, from about $10^2$ to $10^6$. Furthermore, the three facilities possess complimentary experimental advantages for developing both general control strategies and specific strategies that may be more effective at different scales.

For the higher Re, leading edge and tip vortex interaction studies will be conducted under steady and dynamic flight conditions in the Andrew Fejer Unsteady Flow Wind Tunnel. A computer-controlled shutter allows the freestream speed to be modulated at frequencies up to 1 Hz. Airfoil models will be installed on a pitch/plunge traverse mechanism, consisting of independently controlled pitch angle and Y-axis traverse. The pitch angle, vertical position and freestream speed are controlled by a dSPACE system to study complex maneuvers and gusts. Micro-valve actuators (200 Hz bandwidth)
are distributed around the leading edge and tip of the airfoil (Figure 1 (currently 6 are installed over half the span of the full span model). The valves will be independently controlled and phase-coupled with a feedback during closed loop control. Appropriately positioned Kulite pressure sensors will be used as a feedback signal allowing the synchronization of vortex shedding and stabilization of the LEV. The feedback signal for the latter will be a differential surface pressure. Detailed experiments using DPIV feedback in oil and numerical simulations will be used in conjunction with modeling to determine optimal sensor locations. Figure 2 shows the impact of steady mass injection from the first and second (most upstream) of the airfoil tip actuators on the sectional pressure coefficients at 82.5% of the half-span. In the present configuration, the mass injection is tangent to the rounded tip and coanda effect wraps the jets 180° from the suction to pressure side. Increase in sectional lift coefficient is roughly linear in actuation effort (as measured by $C'_{\mu} = \frac{\dot{m}_j V_j}{2 \rho U_\infty^2 c}$) increasing by as much as 50%. The flow visualization shows an accompanying change in the tip vortex structure.

**Figure 2**  Sectional pressure coefficients for steady mass injection through upstream tip actuator (top left) and mid-chord tip actuator (bottom left) for various actuation effort and corresponding natural (top right) and actuated (bottom right) smoke-wire visualizations. The angle of attack is 10° and Re=68000.
Future studies at IIT will focus on transient response to unforced and open-loop forcing. We will include "basic maneuvers" such as pure pitch and pure vertical displacement (plunge) motion. After documenting the LEV/TV system behavior under baseline and basic maneuvering, closed-loop control forcing experiments will be conducted using basic maneuvers to assess performance enhancements over open loop control in regulating LEV/TV system. Real-time performance of the overall control strategies will be tested using a Captive Trajectory System (CTS) to simulate free flight conditions. A CTS system senses the instantaneous load on the airfoil model, then incrementally moves the model to a new position based on its mass and inertia. Climb and descent vertical motion coupled with the precisely variable wind tunnel speed will allow takeoff and landing maneuvers to be simulated in two dimensions, which will play a critical role in the assessment of the real-time control strategies developed by the other members of the team.

For the lower Reynolds numbers, Digital Particle Image Velocimetry (DPIV) and Defocused-DPIV (DDPIV) measurements in a recirculating oil facility (currently under fabrication) will complement the wind tunnel experiments under conditions up to Re of $10^4$. A half-scale model with similar actuators to those used in the wind-tunnel tests will be extensively documented with DDPIV in critical regions near the tip where the flow is strongly three-dimensional. The much lower timescale of vortex shedding in water ($\approx 1$ Hz) will enable the use of DPIV as a sensor for real-time closed-loop control. This strategy will provide a sensor rich feedback environment that we will use to identify critical vortical structures by thresholding or eigenvalue analysis [13]. Information about circulation and vortex stretching will then be used directly in a feedback loop to probe the "upper bounds" of the controller performance. Finally, detailed three-dimensional data from DDPIV will be used to validate the numerical simulations discussed below.

2.2 Modeling and Control Design

Tractable mathematical models will play an important role in understanding the dynamical features of separation problems, guiding the design of sensor-actuator configurations, and designing feedback laws for controlling these flows. The goal is to develop approximate models that are as simple as possible, capturing just enough of the physics to describe the phenomena of interest and how they are affected by actuator inputs. Leading edge vortices are coherent structures whose qualitative dynamical behavior can be described by low-dimensional dynamical systems. For instance, at low Reynolds numbers and/or aspect ratios, a leading edge vortex is stable, and
remains attached to the upper surface of a wing. As the Reynolds number, angle of attack or aspect ratio increases, a transition to a periodic vortex shedding takes place. Phenomenological models of similar phenomena have been used to control dynamic stall vortices in rotorcraft [15], but the precise nature of the transition is not well understood from a dynamical systems point of view (e.g., whether the transition is the result of a supercritical or subcritical Hopf bifurcation, or a co-dimension-2 bifurcation), and one of the initial goals of this work is to develop mathematical models that capture this behavior, including the influence of air injection or similar actuation.

Several techniques for obtaining low-dimensional models are being developed, and while only initial steps have been made on the leading-edge vortex problem, here we describe some of these techniques that we have recently applied to related problems, such as channel flows, cylinder wakes, and the flow past a backward facing step.

Identification of dynamically dominant modes: Integrating POD and model reduction. A popular approach for low-dimensional modeling is projection of high-dimensional governing equations onto a lower-dimensional subspace determined by Proper Orthogonal Decomposition (POD) of a set of data obtained from simulations or experiments [11]. One of the shortcomings of conventional POD/Galerkin models is that while POD modes retain the most energetic structures (in the sense of a user-defined energy norm), low-energy structures may be critically important to the dynamics. Other model reduction tools such as balanced truncation do effectively identify dynamically important modes (identified by the observability Gramian), and have extensions to nonlinear models, but are computationally intractable for very large systems, such as discretizations of the Navier-Stokes equations. Recent developments have made approximate balanced truncation feasible for very large systems, by using a few energetically dominant modes as the measured output, and subsequently using adjoint simulations to extract dynamically dominant modes [20]. These methods rely on high-order simulations to provide both Navier-Stokes and adjoint solutions. For linear problems, the new method has error bounds that improve as the number of modes increases (unlike conventional POD), and performs much better than conventional POD in examples such as linearized channel flow. We will apply these methods to LEV stabilization, and in the process extend them to address transient envelopes, including time-varying linearizations derived from multiple transient reference orbits.
Identification of dynamically dominant modes: Physics and empirically based tuned models. Model reduction represents a mathematical, “top-down” approach, selecting a dynamically dominant low order basis from a high dimensional state space. A complementary, “bottom-up” approach uses a very low order POD model as a starting point and exploits a-priori and empirical observations concerning the physics of the system to augment it. One key aspect of (natural or controlled) attractor dynamics is the energy exchange and balance with the mean flow. This mechanism can often be captured (at least locally) by a single em shift or global mode. The inclusion of a shift mode has been established as an enabler for the robustness of very low order dynamic models for vortex shedding behind a 2D circular cylinder [17], capturing the bifurcation into instability and convergence to the attractor. We shall adapt this approach to the 3D, low aspect ratio airfoil.

Yet another limiting aspect of very low order POD models in flow control is the fact that the shape and key properties, such as temporal and spatial frequencies of dominant flow structures tend to change along transients. For example, models of the actuated cylinder wake may require dozens of modes [4], casting in doubt the utility of such models for practical feedback design and implementation. A recent development of tuned models [14] exploit the continuity of dominant structure deformations along natural and carefully controlled transients. In such cases the system can be modeled by a single parameter family of very low dimensional, mutually similar local models. The tuning parameter is a measurable quantity, derived e.g. from the frequency and amplitude of an oscillatory sensor signal. In the cylinder wake example, third order local models, capturing the local first vortex shedding harmonic and the shift mode are ample. This approach is promising as a means to maintain feasible dimensionality also under varying operating conditions, including flight velocity, transient maneuvers, etc.

Auxiliary models for sensor arrays. An array of distributed sensors, such as surface mounted pressure gages, is a natural and practical candidate to obtain real time flow information for feedback implementation. In the context of low order model based design, the information extracted from these sensors would be limited to few dynamic variables, such as location and intensity of the leading edge vortex, meaningful concepts of the phase and amplitude of a periodic instability, and in the context of tuned models, the value of the tuning parameter(s). Low dimensionality of targeted dynamic manifolds means that the combined signal of the sensor array would be a spatio-temporal (traveling) waveform, ideally characterized by few, slowly varying parameters (e.g., harmonic coefficients). Exploiting the parameter-
ized spatio-temporal pattern as a low dimensional auxiliary model, dynamic estimation (e.g., and with an extended Kalman filter or an FIR filter bank) can be used to efficiently determine useful sensor information. An advantage of the focus on the slowly varying parametrization is the simultaneous filtering of spatial and temporal noise and un-modeled stochastic/chaotic effects that will otherwise mask the needed data in low signal to noise environment. This approach has been verified experimentally as a means to manipulate shear layer instability in the flow over a backward facing step [18]. Similarly, when the desired repertoire of coordinated actuation patterns of a set of actuators, such as air jets, is restricted to a low dimensional parameterized family of spatio-temporal patterns, such patterns will be used as auxiliary models for actuator dynamics, reducing the actuation command to a more implementation-friendly lower dimensional, narrow band signal.

2.3 Computations

Direct Numerical Simulations of unsteady vortex-dominated flows will be used to provide data and cross-validation with the modeling, experimental and control design efforts described previously. Two and three-dimensional simulations of the NACA 0012 geometry (with and without actuation) are modeled via an immersed boundary (IB) method (see [19, 16]) and focused on chord Re $\sim 1000$ such that turbulence models are not required. The IB method allows for surfaces with arbitrarily specified motion, and actuation can be (approximately) accommodated by specifying a time varying non-zero penetration and/or slip velocity along the surface. In the IB method, the no-slip boundary condition is enforced by adding a set of regularized forces on the surface of the body. We have developed a new implementation of the immersed boundary method that eliminates the need for constitutive relations for the forces, instead treating them as Lagrange multipliers that allow a regularized no-slip boundary condition to be enforced on the surface. The new method fits neatly into the classical Fractional-Step (Projection) method that uses a 2nd-order-accurate discretization via a staggered-mesh finite-volume formulation. The method uses second-order implicit and explicit time marching for the viscous and advection terms, respectively. The Poisson equation that determines the pressure is modified to find both pressure and surface forces, and both the intermediate momentum equation and modified Poisson matrix equations are symmetric and positive definite, allowing efficient iterative solution via the conjugate gradient method. Further details and two-dimensional validations are reported elsewhere [23].
2.4 Preliminary computational and modeling results

Comparison of 2D and 3D simulations and experiments. Results are presented here for an impulsively started flat plate with Re = 100. Two-dimensional simulations are compared to three-dimensional simulations for a plate with AR = 2. Companion experiments for the 3D plate were performed in an oil tow-tank facility at Caltech. In figure 3, the coefficient of lift, $c_L$, is plotted versus $\alpha$. For the 2D simulations, the flow reaches a steady state up to $\alpha \approx 22^\circ$, where a Hopf bifurcation occurs and for $\alpha > 22^\circ$, unsteady (periodic) vortex shedding is observed. The maximum and minimum lifts occurring during the shedding cycle are indicated on the plot. The 3D results with AR=2 (experimental and computational) reach steady state regardless of $\alpha$, an indication of the strong stabilizing influence of three-dimensionality. Induced drag in 3D causes $c_L$ to fall markedly from the 2D case. Flow visualization (figure 3) shows the strong interplay between tip vortices (depicted with iso-contours of streamwise vorticity) and a mid-span separated region (shown with streamlines colored by velocity magnitude). The measured lift coefficient from computations and experiments are in excellent agreement, providing further validation of the numerical model. It is important to note that the steady 3D separated flow field is not associated with a lift-enhancing leading-edge vortex structure, as would be obtained on a rotating or highly swept wing at this Reynolds number. Further computations and experiments are underway to use fluidic actuators to induce and stabilize the LEV flow structure.

Figure 3 Left: Comparison of 2D and 3D (AR=2) lift coefficient versus $\alpha$ for an impulsively started flat plate with Re=100. Right: flow visualization for $\alpha = 30^\circ$. 
**Balanced truncation and unstable steady states** A critical enabler to the success of POD/Galerkin models is the inclusion of modes based on dynamical importance, rather than energy. These dynamically important modes are identified using adjoint simulations, and reduced-order models are formed using Balanced Proper Orthogonal Decomposition (Balanced POD), an approximate version of balanced truncation that is computationally tractable for very large systems [20]. The resulting reduced-order models have recently been shown to be much more accurate than standard POD/Galerkin models in a 3D linearized channel flow [12]. The required adjoint simulations may be readily obtained at the discrete level from the original Navier-Stokes code developed at Caltech, and is currently being implemented.

A first step is to identify possibly-unstable natural steady states, such as a leading-edge vortex, that one may wish to stabilize with feedback. While stable steady states may be found by integrating forward in time, unstable steady states are more difficult to compute. We find these using the immersed-boundary Navier-Stokes code discussed above coupled to an approximate Newton iteration, a Newton-Krylov solver that uses GMRES to iteratively solve for the next Newton step $^1$. Using this tool, we have explored the bifurcation behavior near $\alpha = 22^\circ$ discussed in the previous section.

Unstable steady states have been identified for $\alpha > 22^\circ$. Figure 4 shows $c_L$ for the continued unstable steady state, as well as streamlines and vorticity at several values of $\alpha$. The unstable equilibrium for larger angles of attack has a surprisingly low lift, close to the minimum lift observed over the shedding cycle of the natural unsteady flow. A near-term goal is to stabilize the unstable steady state for $\alpha > 22$. While this represents a lower-lift solution, it allows us to develop the tools and models that will be adapted to the three-dimensional flow where stabilization of LEV is the goal of control.

**Reduced-order models.** A 3rd-order Galerkin model has been developed for unsteady shedding of a NACA 0012 airfoil at $\alpha = 30^\circ$, projecting the dynamics onto the first two POD modes of the unactuated flow, and one shift mode that captures the change in the mean flow $^2$. Figure 5 shows favorable agreement between transients predicted by the reduced-order model and the full CFD. In order to capture the actuated flow, more modes are needed, and our approach is to use interpolated modes, or shift modes for which the modes themselves vary in time (akin to a changing coordinate system). Re-

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$^1$ We wish to thank Prof. Y. Kevrikidis, Princeton University, for help in implementing the Newton-GMRES continuation.

$^2$ These preliminary results for Galerkin models were obtained using a CFD code provided to us by Prof. M. Morzynski, Poznan University of Technology.
sults for the present flow indicate that a 3-dimensional space of shift modes (the principal components of the set of all local shift modes, or a "POD of PODs") accurately captures the transients.

Figure 4  Lift vs. $\alpha$ for a 2D flat plate at $Re=100$, with insets showing vorticity and instantaneous streamlines. The gray shaded region indicates the range of instantaneous lift for the unsteady flow, and the red curve indicates the lift of the (stable or unstable) steady state.

Figure 5  Flow resolution by a Galerkin system in terms of POD modes capturing the 1st vortex shedding harmonic and the shift mode. Left: The oscillation amplitude. Center: The shift mode coefficient. Right: The oscillation phase.

Acknowledgments

This research is supported by a Multidisciplinary University Research Initiative (MURI) from the United States Air Force Office of Scientific Research.
(FA9550-05-1-0369) with Program Manager Dr. Fariba Fahroo. We thank Dr. Will Dickson for supplying us with the two-tank data in section 2.4. We wish to acknowledge our MURI collaborators Drs. Michele Milano, Mingjun Wei, Doug MacMynowski, and graduate students Sunil Ahuja, Donatella Centuori, Jesse Collins, Sudeep Doshi, Sean Damien Gates, Melissa Green, Won Tae Joe, Juan Melli, Matthew Munson.

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