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14.  ABSTRACT

The overall project goal was to investigate low Reynolds number (10,000-100,000) flapping flight for MAV applications. Large-Eddy Simulations (LES) is used for unsteady aerodynamic analysis. The dominant force producing mechanism is the formation of a spiral leading-edge-vortex (LEV). Effect of wind gusts and stroke deviation is investigated followed by the aerodynamics of a flapping fruit bat wing. Finally, very high Reynolds number dynamic stall on a pitching NACA-012 airfoil is studied. The work resulted in 3 archived journal publications numerous conference proceedings 1 Ph.D. and 1 M.S. thesis. Two additional journal papers are under

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Unsteady Aerodynamics of Flapping Wings at Re=10.000 - 100,000 for Micro-Air Vehicles-Final Report

**ABSTRACT**

The overall project goal was to investigate low Reynolds number (10,000-100,000) flapping flight for MAV applications. Large-Eddy Simulations (LES) is used for unsteady aerodynamic analysis. The dominant force producing mechanism is the formation of a spiral leading-edge-vortex (LEV). Effect of wind gusts and stroke deviation is investigated followed by the aerodynamics of a flapping fruit bat wing. Finally, very high Reynolds number dynamic stall on a pitching NACA-012 airfoil is studied. The work resulted in 3 archived journal publications,numerous conference proceedings,1 Ph.D. and 1 M.S. thesis. Two additional journal papers are under preparation.

**Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing.  List the papers, including journal references, in the following categories:**

**(a) Papers published in peer-reviewed journals (N/A for none)**

| Received | | Paper |
|---|---|---|
| 08/23/2013 | 7.00 | Kamal Viswanath, Tafti D. K.. Effect of Stroke Deviation on Forward Flapping Flight, AIAA Journal,  (01 2013): 145. doi: |
| 08/29/2011 | 1.00 | Kamal Viswanath, Danesh K. Tafti. Effect of Frontal Gusts on Forward Flapping Flight, AIAA Journal,  (9  2010): 0. doi: 10.2514/1.J050263 |
| **TOTAL:** | **2** | |

**Number of Papers published in peer-reviewed journals:**

**(b) Papers published in non-peer-reviewed journals (N/A for none)**

| Received | Paper |
|---|---|
| **TOTAL:** | |

**Number of Papers published in non peer-reviewed journals:**

**(c) Presentations**

Tafti, D. K., Viswanath, K. and K. Nagendra, Deconstructing the Essential Elements of Bat Flight, APS 66th Annual Meeting, Division of Fluid Dynamics, 24-26 November 2013, Pittsburgh, PA.

## Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

| Received | | Paper |
|---|---|---|
| 08/23/2013 | 8.00 | K. Viswanath, K. Nagendra, D. K. Tafti. Climbing Flight of a Fruit Bat Deconstructed, AIAA Science and Technology Forum and Exposition 2014. 13-JAN-14, . : , |
| 08/29/2011 | 2.00 | Danesh Tafti. UNSTEADY AERODYNAMICS OF A FLAPPING WING FOR MICO AIR VEHICLE (MAV) APPLICATIONS , Proceedings of the 37th National & 4th International Conference on Fluid Mechanics and Fluid Power, IIT Madras, Chennai, India. 16-DEC-10, . : , |
| **TOTAL:** | **2** | |

**Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):**

## Peer-Reviewed Conference Proceeding publications (other than abstracts):

| Received | | Paper |
|---|---|---|
| 02/11/2014 | 11.00 | K. Viswanath, K. Nagendra, D. Tafti. Climbing Flight of a Fruit Bat Deconstructed, AIAA SCITECH 2014. 13-JAN-14, . : , |
| 08/29/2011 | 3.00 | Kamal Viswathan, Danesh Tafti. Effect of Stroke Deviation on Forward Flapping Flight , 50th AIAA Aerospace Sciences Meeting. 09-JAN-12, . : , |
| **TOTAL:** | **2** | |

**Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):**

## (d) Manuscripts

| Received | Paper |
|---|---|
| 08/23/2013 9.00 | K. Viswanath, K. Nagendra, J. Cotter, M. Frauenthal, D.K. Tafti. Straight-Line Climbing Flight Aerodynamics of a Fruit Bat, <br> Physics of Fluids (05 2013) |
| 08/27/2012 4.00 | Kamal Viswanath, Danesh K. Tafti. Effect of Stroke Deviation on Forward Flapping Flight, <br> AIAA Journal (10 2011) |
| **TOTAL:** | **2** |

**Number of Manuscripts:**

## Books

| Received | Paper |
|---|---|
| **TOTAL:** | |

## Patents Submitted

## Patents Awarded

## Awards

D. Tafti awarded William S. Cross Professorship, 2009.
D. Tafti awarded College of Engineering Deans Research Award, 2012

## Graduate Students

| NAME | PERCENT_SUPPORTED | Discipline |
|---|---|---|
| Kamal Viswanath | 0.75 | |
| Venkata Ravi Kasibhotla | 0.08 | |
| **FTE Equivalent:** | **0.83** | |
| **Total Number:** | **2** | |

## Names of Post Doctorates

| NAME | PERCENT_SUPPORTED |
| --- | --- |
| **FTE Equivalent:** | |
| **Total Number:** | |

## Names of Faculty Supported

| NAME | PERCENT_SUPPORTED | National Academy Member |
| --- | --- | --- |
| Danesh Tafti | 0.06 | |
| **FTE Equivalent:** | **0.06** | |
| **Total Number:** | **1** | |

## Names of Under Graduate students supported

| NAME | PERCENT_SUPPORTED | Discipline |
| --- | --- | --- |
| Jeffrey Cotter | 0.00 | |
| Mathew Fruenthal | 0.00 | |
| **FTE Equivalent:** | **0.00** | |
| **Total Number:** | **2** | |

## Student Metrics
This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: ...... 0.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:...... 0.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale):...... 0.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense ...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields:...... 0.00

## Names of Personnel receiving masters degrees

| NAME |
| --- |
| Venkata Ravi Kasibhotla |
| **Total Number:** 1 |

## Names of personnel receiving PHDs

| NAME |
| --- |
| Kamal Viswanath |
| **Total Number:** 1 |

## Names of other research staff

| NAME | PERCENT_SUPPORTED |
|------|-------------------|
| **FTE Equivalent:** | |
| **Total Number:** | |

## Sub Contractors (DD882)

## Inventions (DD882)

## Names of other research staff

| NAME | PERCENT_SUPPORTED |
|------|-------------------|
| **FTE Equivalent:** | |
| **Total Number:** | |

Considerable scientific progress was made during the course of this project. Our initial focus was on flat plate (stiff and flexible) flapping wing kinematics. In this geometry we investigated the effect of large gusts engulfing the wing and the effect of stroke deviations on the aerodynamic forces. Then we used the knowledge gathered in this domain to attack the complex measured kinematics of a bat wing. The experiments were done at Brown University. We used the point traces on the wing to construct a space-time mesh of the wing surface which was then immersed in a background grid. One surprising conclusion from this work was that in spite of the apparent complexity of wing motion, the motion could be decomposed into 2-3 modes which reproduced the force signature of the wing. Finally, we investigated the challenging problem of dynamic stall at very high Reynolds numbers on a pitching NACA0012 airfoil. We found that the upstroke behaved quite benignly but the downstroke produced very complex flow structures and the lift was very dependent on the shedding and formation of LEVs and TEVs. Fair comparisons were obtained with experiments considering that the experimental tunnel cross-section is much smaller than the computational domain and could potentially interfere with the vorticity dynamics on the airfoil.

Effect of Frontal Gusts on Forward Flapping Flight:

The response of a rigid flapping wing in forward flight, at Re=10,000, subjected to frontal gusts has been investigated. The phasing and duration of the gusts and their impact on the various unsteady mechanisms are analyzed within a single flapping cycle. The gust is characterized by a step function with integral length scale much larger than that of the physical dimension of the MAV and with time scale much smaller than the flapping time period. The instantaneous lift and thrust profiles were observed to be influenced by a combination of the effective angle of attack, wing rotation and the Leading Edge Vortex (LEV) structures existing in the flow at any given time, with the LEVs themselves being influenced by the duration and magnitude of the change in effective angle of attack. Frontal gusts applied during the downstroke accelerated the development of the flow resulting in the formation and detachment of multiple LEVs on the wing surface which increased the lift and thrust illustrating the importance of the LEV dynamics to force production. The effect of the gust is observed to be diminished when it occurs during rapid supination of the wing. The lift and thrust profiles are found to react in a similar fashion for gusts applied during the downstroke while they experienced opposite effects during the upstroke. During the upstroke, force characteristics are seen to primarily react to effective AOA changes more than changes in flow structures.

Effect of Frontal Gusts on Flexible Wings in Forward Flapping Flight:

The response of a flexible wing and a rigid wing in flapping forward flight, at Re=10,000, subjected to frontal gusts is investigated. The impact of a gust of chosen phasing and duration on the various unsteady mechanisms are analyzed within a single flapping cycle. The gust is characterized by a step function with integral length scale much larger than that of the physical dimension of the MAV and with time scale much smaller than the flapping time period. The instantaneous lift and thrust were observed to be influenced by a combination of the effective angle of attack, chosen kinematics, transient Leading Edge Vortex (LEV) structures, and the dynamic cambering in the case of the membrane wing. The effect of the gust on the lift profile is observed to have opposite effects for the rigid vs. flexible case while the thrust behaves in a similar profile.

Effect of Stroke Deviation on Forward Flapping Flight:

The performance of a rigid thin surface flat-plate flapping wing in forward flight, at Re=10,000, using different stroke deviation trajectories has been investigated to assess the different capabilities that such kinematics might offer. The instantaneous lift and thrust profiles were observed to be influenced by a combination of the Leading Edge Vortex (LEV) and the Trailing Edge Vortex (TEV) structures existing in the flow at any given time. Unlike regular no deviation flapping cycles, the TEV is shown to be significant for out-of-plane trajectories. Both clockwise and anticlockwise variations for trajectory choice are analyzed for their efficacy as an improved kinematic choice over a no-deviation base case. The power requirements for the different cases, based on the fluid torques, are used as an index of the cost of performance across all cases. The anti-clockwise 8-cycle deviation is shown to be very complex with high power costs albeit having better performance. The clockwise O-cycle holds promise in being utilized as a viable stroke deviation trajectory for forward flight over the base case.

Straight-Line Climbing Flight Aerodynamics of a Fruit Bat:

From flight data obtained on a fruit bat, Cynopterus brachyotis, a kinematic model for straight-line flapping motion is extracted and analyzed in a CFD framework to gain insight into the complexity of bat ¿ight. The intricate functional mechanics and architecture of the bat wings set it apart from other vertebrate flight. The extracted kinematic model is simulated for a range of Reynolds numbers, to observe the effect these phenomena have on the unsteady transient mechanisms of the flow produced by the flapping wings. The Strouhal number calculated from the data is high indicating that the oscillatory motion dominates the flow physics. From the obtained data, the bat exhibits fine control of its mechanics by actively varying wing camber, wing area, torsional rotation of the wing, forward and backward translational sweep of the wing, and wing conformation to dictate the fluid dynamics. As is common in flapping flight, the primary force generation is through the attached unsteady vortices on the wing surface. This force output is modulated by the bat through varying the wing camber and the wing area. The power requirement

for the kinematics is analyzed and correlated with the aerodynamic performance. Understanding the physics of these robust fliers will help devise prescribed kinematics for mechanical flappers as well as improve upon them from nature.

3D Dynamic Stall Simulation of NACA0012 Airfoil:

The work investigates the physics behind the dynamic stall process by simulating the flow past pitching NACA-0012 airfoil at 100,000 and 1,000,000 Reynolds number based on the chord length of the airfoil and at different reduced frequencies of 0.188 and 0.25, respectively in a three dimensional flow field. The mean angles of attack are 12 and 15 degrees and the amplitudes of pitching are 6 and 10 degrees, respectively. The turbulence in the flow field is resolved using large eddy simulations with dynamic Smagorinsky model at the sub grid scale. The lift hysteresis plots of this simulation for both the configurations are compared with the corresponding experiments. The development of dynamic stall vortex, vortex shedding and reattachment as predicted by the present study are discussed in detail. There is a fairly good match between the predicted and experimentally measured lift coefficient during the upstroke for both cases. The net lift coefficient for the Re=100,000 case during downstroke matches with the corresponding experimental data, the present study under-predicts the lift coefficient as compared to the experimental values at the start of downstroke and over-estimates for the remaining part of the downstroke. The trend of the lift coefficient hysteresis plot with the experimental data for
the Re=1,000,000 case is also similar. This present simulations have shown that the downstroke phase of the pitching motion is strongly three dimensional and is highly complex, whereas the flow is practically two dimensional during the upstroke.

# Technology Transfer