Experimental Elastic Deformation Characterization of a Flapping-Wing MAV using Visual Image Correlation

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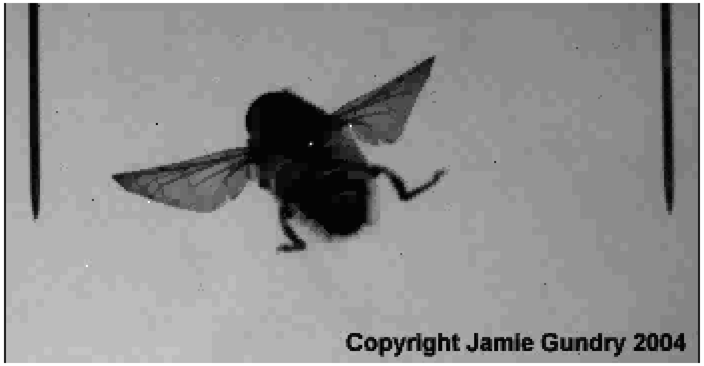
Overview

- Introduction / Motivation
- Methodology
- Validation
- Dynamic Tests
  - Setup
  - Post-processing
- Results
  - Wing Motion
  - Uncertainty in Rotation Angle
  - Wing Deformation
- Conclusion / Future Work

Introduction

- Interest in research community to further develop MAV technology for performance in tightly confined environments at varying flight conditions
- Biological Inspiration
  - Flexible wings
    - Can readily adopt to changing flight conditions
    - Fixed-wing MAVs whose wing structures are fabricated from aeroelastic material show improvement over rigid counterparts
  - Flapping wings
    - Flexible, fixed-wings show an advantage, but still do not meet all of the agility and versatility requirements
    - Natural fliers (bats, birds, insects) use flapping motion at low speed



Motivation

- Worth investigating kinematics and dynamics of flapping motion
- Kinematics and dynamics must be decoupled when applying biologically-inspired technologies
  – Only rigid-body-motion is needed for IMU and system identification
  – However, combining wing mechanics of flexible wings with feedback control requires knowing elastic deformation
- Dynamic visual image correlation (VIC) enables simultaneous measurement of rigid-body-motion and deformation

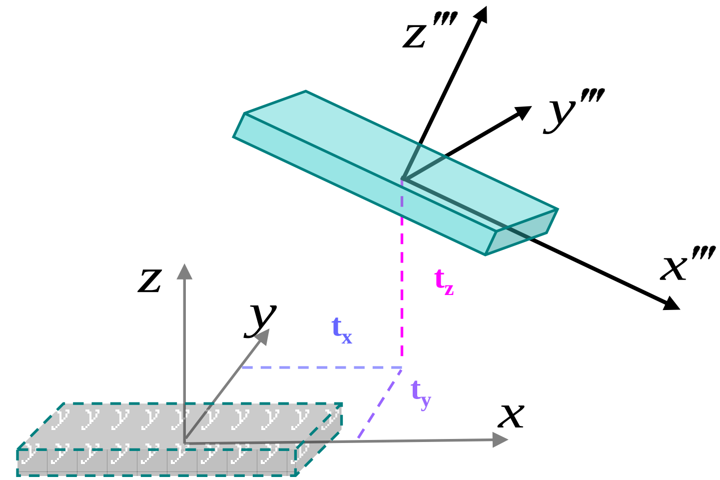
Methodology

- **VIC measures full-field displacements through stereo triangulation**
  - **Provides reference points (X, Y, Z)**
  - **Provides displacement measurements (u, v, w)**
  - **Displacement is result of both kinematics and deformation**
- **Deformation is difference between total displacement and rigid body displacement**

$$\begin{bmatrix} u_{Elastic} \\ v_{Elastic} \\ w_{Elastic} \\ 1 \end{bmatrix}_i^{\hat{x},\hat{y},\hat{z}} = \begin{bmatrix} X+u \\ Y+v \\ Z+w \\ 1 \end{bmatrix}_i^{\hat{x},\hat{y},\hat{z}} - [HTM] \begin{bmatrix} X \\ Y \\ Z \\ 1 \end{bmatrix}_i^{\hat{x},\hat{y},\hat{z}}$$

- **Acquire rigid body displacement by deriving homogeneous transformation matrix (HTM)**

Rigid-body-motion from HTM



- **Motion based on AOI frame of reference**
  - **Rotation**
    - **Flapping angle, $\Gamma \rightarrow R_y$**
    - **Sweep angle, $\Psi \rightarrow R_{z'}$**
    - **Feather angle, $\Theta \rightarrow R_{x''}$**
  - **Translation (t_x, t_y, t_z)**
- **Homogeneous Transformation Matrix**

$$HTM = \begin{bmatrix} c\Gamma c\Psi & -s\Psi & s\Gamma c\Psi & t_x \\ c\Gamma s\Psi c\Theta + s\Gamma s\Theta & c\Psi c\Theta & s\Gamma s\Psi c\Theta - c\Gamma s\Theta & t_y \\ c\Gamma s\Psi s\Theta - s\Gamma c\Theta & c\Psi s\Theta & s\Gamma s\Psi s\Theta + c\Gamma c\Theta & t_z \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

$$\left[\bar{Z} + \bar{W}\right]_{N\,x\,1} = \left[\bar{X} \quad \bar{Y} \quad \bar{Z} \quad \bar{1}\right]_{N\,x\,4} \begin{bmatrix} HTM_{31} \\ HTM_{32} \\ HTM_{33} \\ HTM_{34} \end{bmatrix}_{4\,x\,1}$$

$$\Theta = \tan^{-1}\left(\frac{HTM_{23}}{HTM_{22}}\right)$$

$$\Psi = \tan^{-1}\left(\frac{-HTM_{12}}{c\Gamma \cdot HTM_{22} + s\Gamma \cdot HTM_{32}}\right)$$

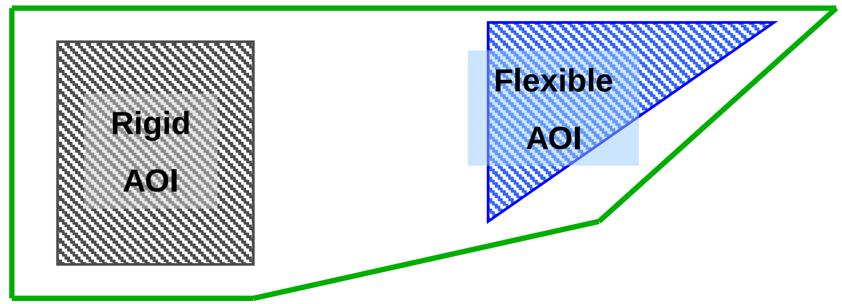
$$\Gamma = \tan^{-1}\left(\frac{-c\Theta \cdot HTM_{31} + s\Theta \cdot HTM_{21}}{HTM_{11} / c\Psi}\right)$$

  - **Setup problem in form [b] = [A] [x] and solve for [x]**
    - **[b] = VIC measurements**
    - **[A] = known reference points (X,Y,Z)**
    - **[x] = coefficients of the transformation matrix**

Deformation Estimate

- **Project rigid-body-motion to flexible area-of-interest**

$$\begin{bmatrix} X+u \\ Y+v \\ Z+w \\ 1 \end{bmatrix}_i^{\hat{x},\hat{y},\hat{z}} = \underbrace{HTM \begin{bmatrix} X \\ Y \\ Z \\ 1 \end{bmatrix}_i^{\hat{x},\hat{y},\hat{z}}}_{Rigid\ Body\ Motion} + \underbrace{\begin{bmatrix} u_E \\ v_E \\ w_E \\ 1 \end{bmatrix}_i^{\hat{x},\hat{y},\hat{z}}}_{Elastic\ Deformation}$$

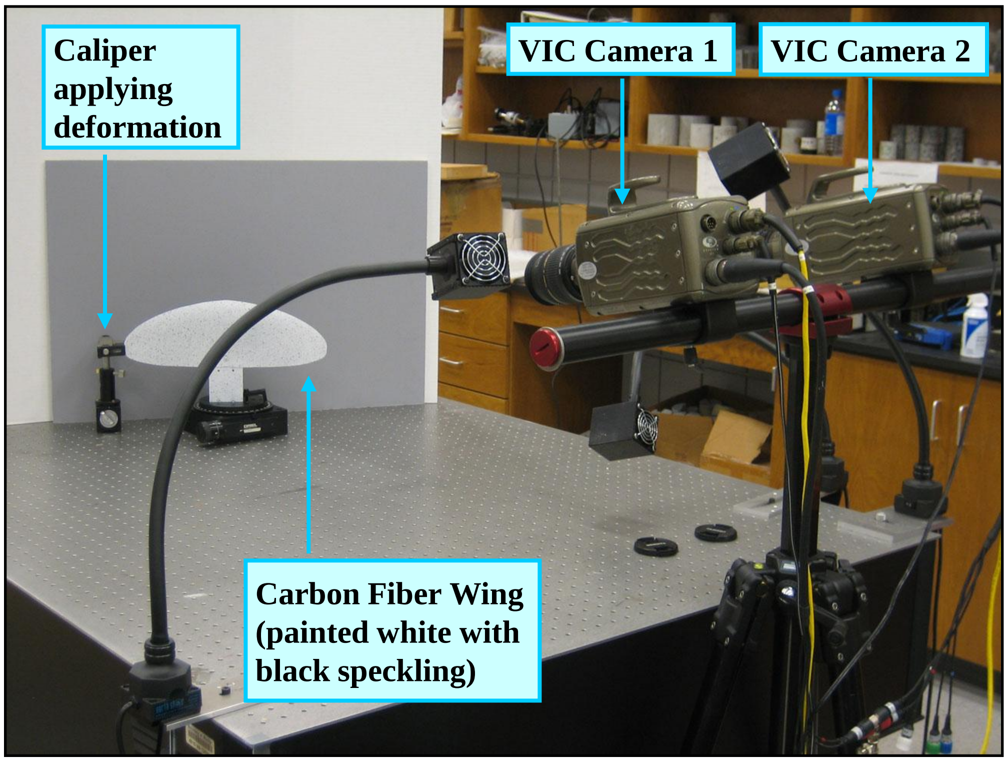


- **Simple subtraction to get deformation**

$$\begin{bmatrix} u_E \\ v_E \\ w_E \\ 1 \end{bmatrix}_i^{\hat{x},\hat{y},\hat{z}} = \underbrace{\begin{bmatrix} X+u \\ Y+v \\ Z+w \\ 1 \end{bmatrix}_i^{\hat{x},\hat{y},\hat{z}}}_{Complete\ Motion} - \underbrace{HTM \begin{bmatrix} X \\ Y \\ Z \\ 1 \end{bmatrix}_i^{\hat{x},\hat{y},\hat{z}}}_{Rigid\ Body\ Motion}$$

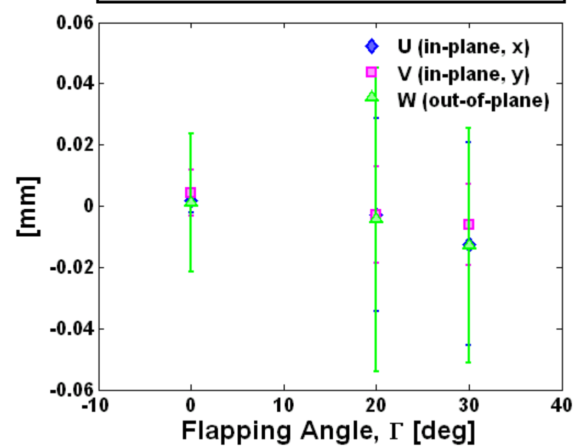
Validation Tests

- Subjected carbon fiber wing to known rotations and deformations
- Repetition tests at 0 with no deformation → acquire measurement uncertainties



Estimate Errors	
Rotation, Γ(°)	Deformation (mm)*
0.2	0.3 – 0.9
** Note: AOI did not extend completely to wing tip*	

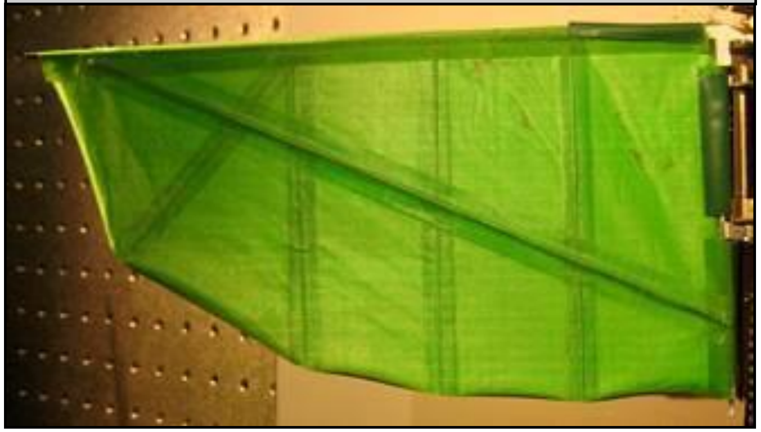
Measurement Errors



Dynamic Tests

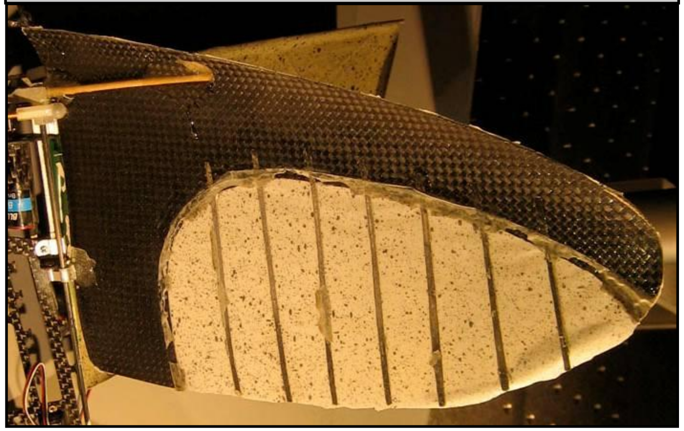
- **Two wings of different material subjected to flapping motion**

Kite Wing



- Acquired from commercial vehicle capable of flapping flight
- Kite-like material does not stretch
- Carbon fiber rods

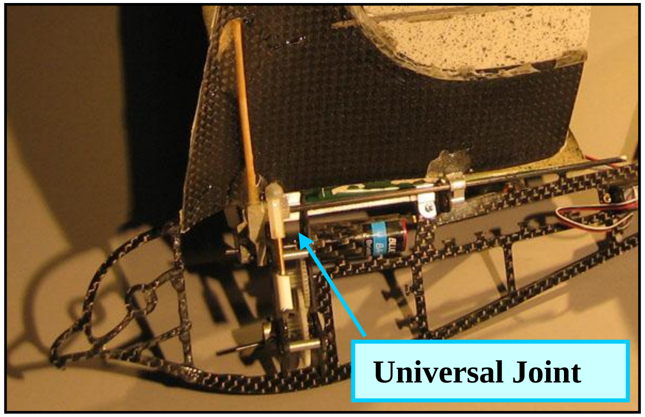
Latex Wing



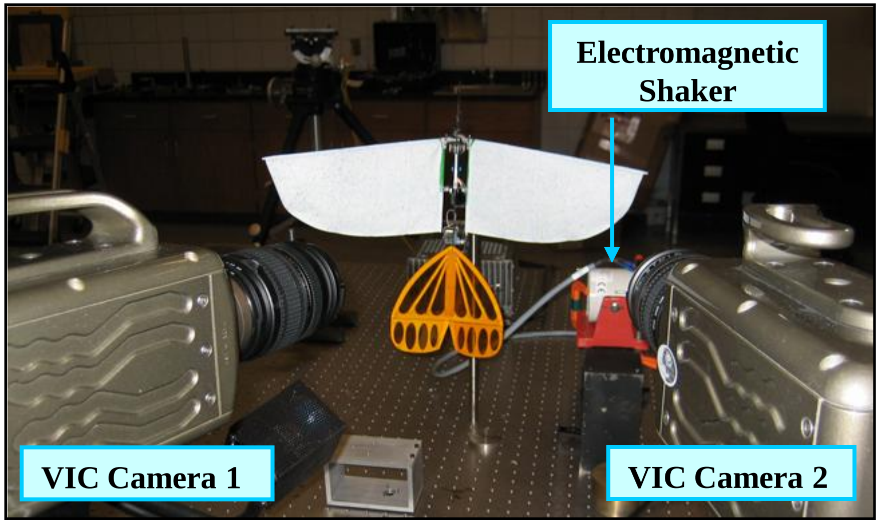
- Fabricated at the UF MAV Lab
- Thin latex (0.33 mm thick) stretches significantly
- Wing perimeter is bidirectional carbon fiber
- Battens are unidirectional carbon fiber

Test Setup

- Rigid plate affixed to inboard section of wing
- Wing attached to linear actuator via a rigid rod and universal joint with low friction
- Sinusoidal signal fed to linear actuator at 5 Hz and 10 Hz
- Load cell placed between the wing and the linear actuator
- Data recorded for 1 sec at 100 fps



Electromagnetic Shaker (Linear Actuator)	Load Cell
Ling Dynamic Systems V201/3-PA 25E	Bruel & Kier 8230
Frequencies up to 13,000 Hz	Sensitivity of 110 mV/N



Data Post-Processing

MATLAB

Read VIC Data

- Rigid AOI Files
- Flexible AOI Files

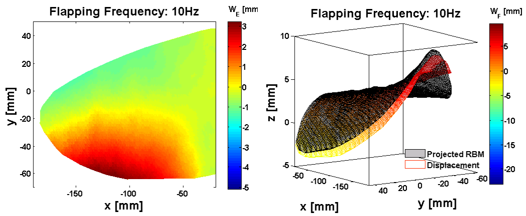
HTM Algorithm

- HTM from Rigid AOI
- Sensitivity Matrix
- Uncertainty Estimates

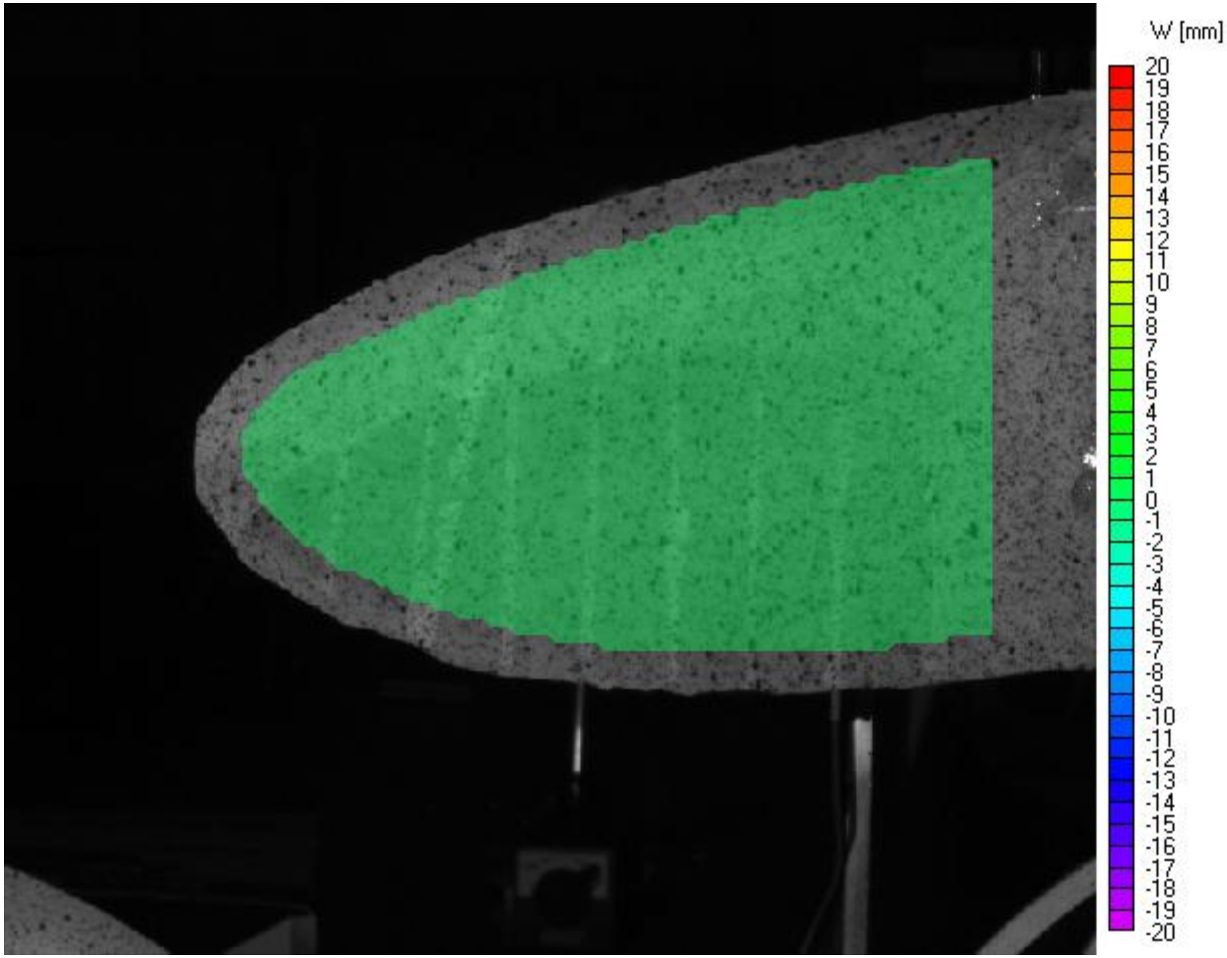
Decouple Motion

- Project RBM to Flexible AOI
- Acquire Deformation

Plots



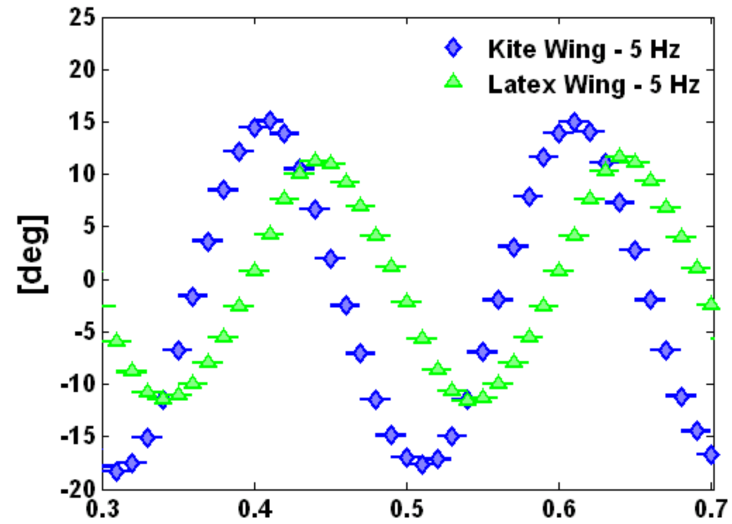
Correlation from VIC Software

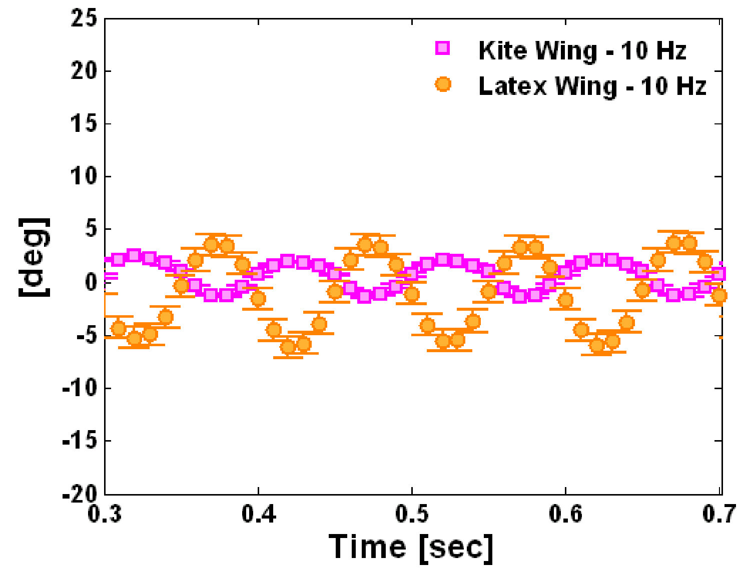


Results – Wing Motion

- **Acquired time history of flapping angle**
  - **2 cycles worth of data displayed**
  - **Amplitude was adjusted by load cell to stay within acceleration limits**
- **Kite wing**
  - **Amplitude: 16.5° at 5 Hz**
    2.0° at 10 Hz
- **Latex wing**
  - **Amplitude: 12.0° at 5 Hz**
    4.5° at 10 Hz
  - **Estimates at 10 Hz have largest uncertainty of all tests**

	5 Hz	*10 Hz*
Kite Wing	*1.06e-02°*	*8.94e-03°*
Latex Wing	*1.68e-03°*	*1.01°*





Results – Uncertainty in Estimates

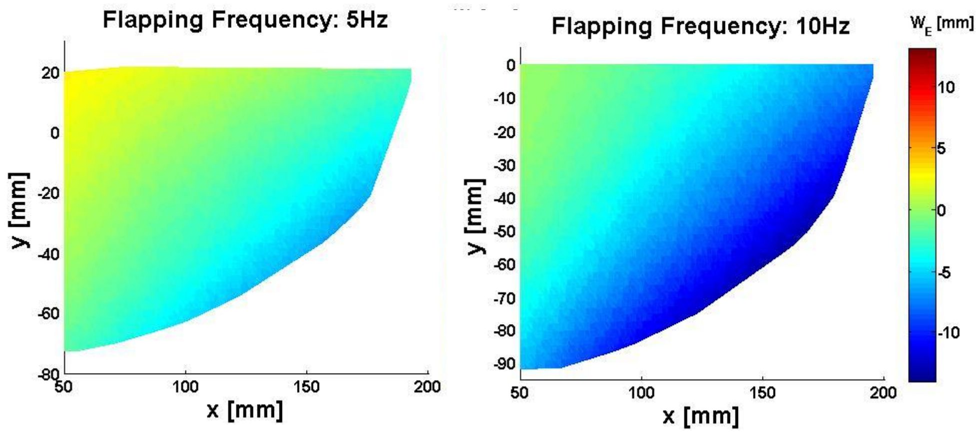
- **Coefficients pertaining to very small X, Y, or Z values will have a larger uncertainty**
  - **Result of model used in linear regression**
  - **Algorithm initially assumed Z would be small compared to X, Y**
    - **Performs inverse trigonometry with the first two columns of the HTM**
    - **Uncertainty in flapping angle is a function of $u_{HTM,11}$, $u_{HTM,21}$, $u_{HTM,31}$, $u_{HTM,\Theta}$, $u_{HTM,\Psi}$**
  - **Correlated rigid AOI for latex wing at 10 Hz, however, had small values for X as well**

$$u_{HTM} = \begin{bmatrix} u_U/X & u_U/Y & u_U/Z & u_U \\ u_V/X & u_V/Y & u_V/Z & u_V \\ u_W/X & u_W/Y & u_W/Z & u_W \\ - & - & - & - \end{bmatrix}$$

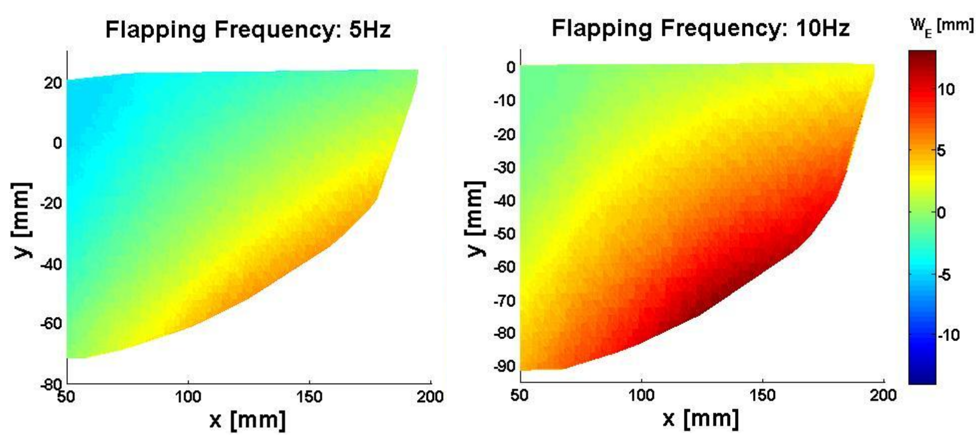
$$u_{HTM,L10} = \begin{bmatrix} 1.68e-02 & -1.71e-05 & 7.94e-03 & 2.75e-03 \\ -2.26e-03 & 2.30e-06 & -1.07e-03 & -3.70e-04 \\ -1.77e-02 & 1.08e-05 & -8.36e-03 & -2.89e-03 \\ -- & -- & -- & -- \end{bmatrix}$$

Results – Kite Wing Deformation

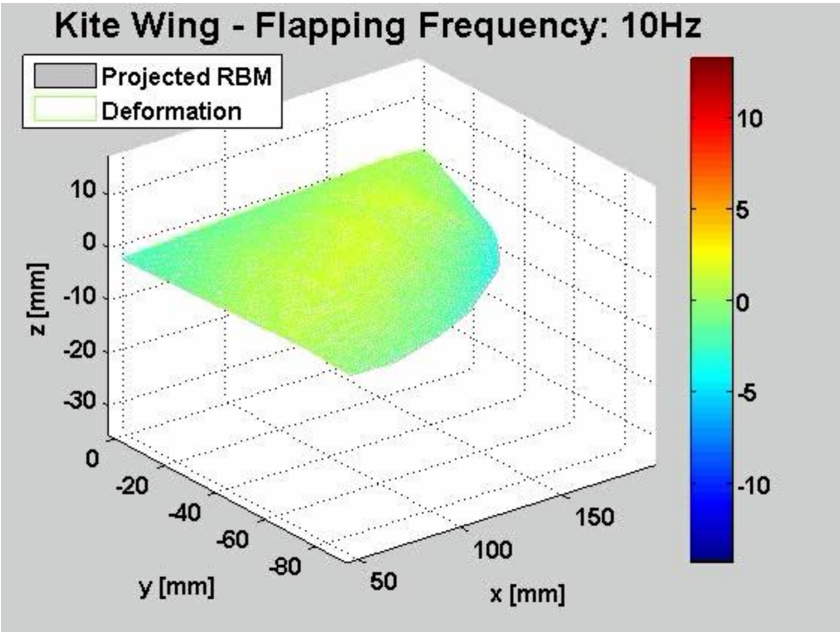
Start of Upstroke



Start of Downstroke

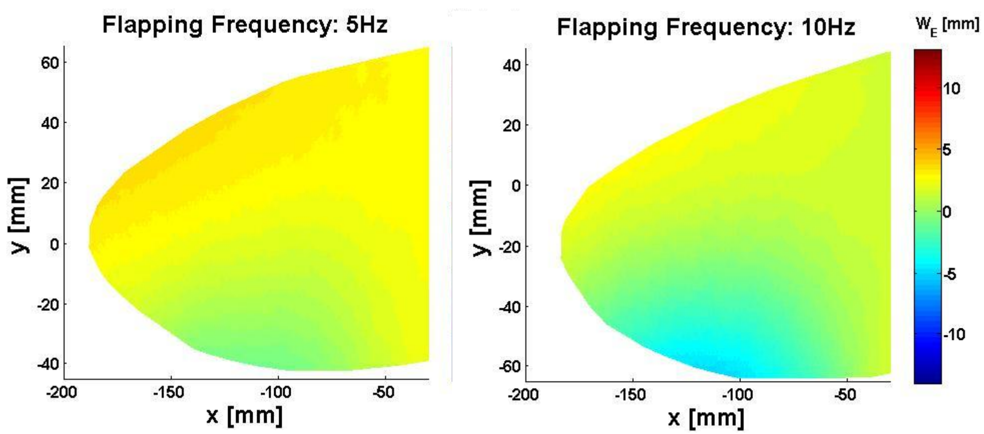


- Out-of-plane
  - Unidirectional contour bands
  - Small amount of wing twist
- Maximum Deformation
  - ± 5 mm at 5 Hz
  - 12 mm at 10Hz

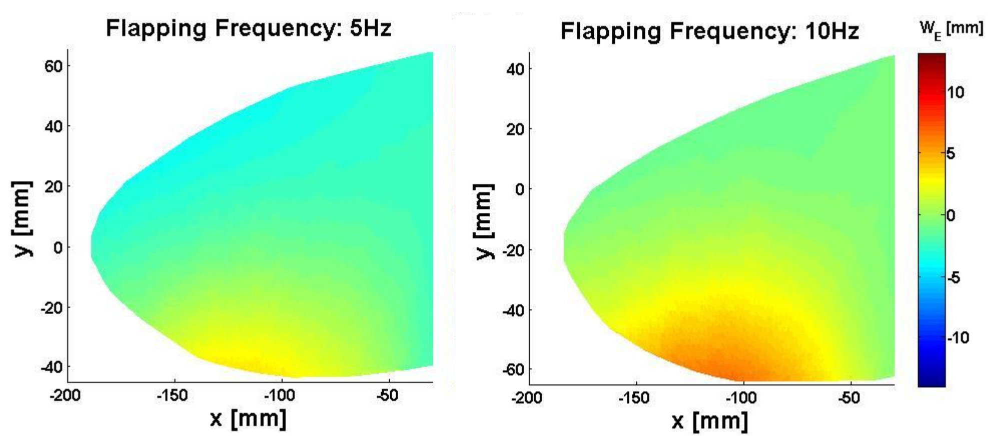


Results – Latex Wing Deformation

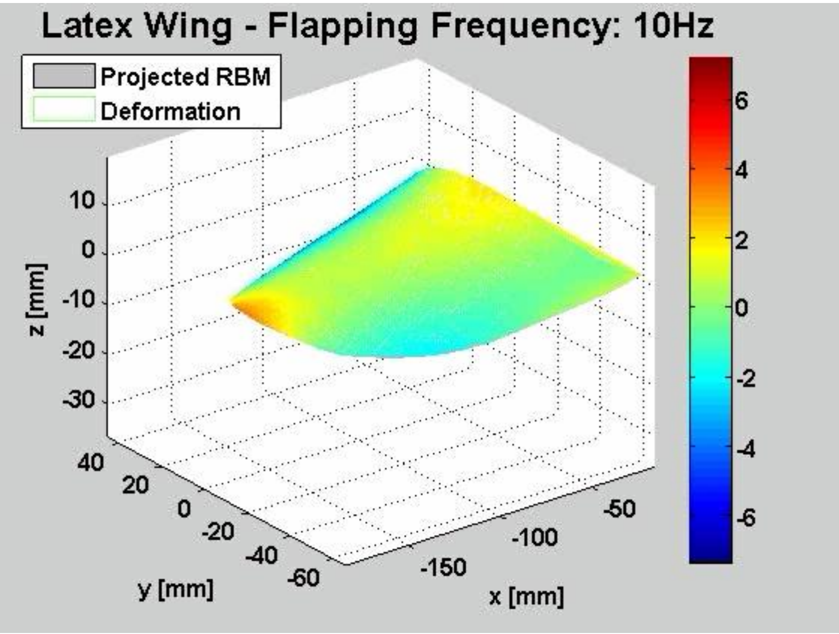
Start of Upstroke



Start of Downstroke



- In-plane and out-of-plane
  - Circular contour bands
  - Small amount of wing twist
- Maximum Deformation
  - ± 3 mm at 5 Hz
  - 5 mm at 10Hz



Conclusion

- **Method for decoupling the wing kinematics from the deformation of a flapping-wing using VIC data**
  - **Constructed HTM from rigid-body-motion and projected to flexible AOI → subtracted to get deformation**
  - **Provided time history of flapping angle and contour plots**
  - **Observed that a careful check of HTM uncertainties should be carried out prior to projecting RBM**
- **Future work**
  - **Dynamic VIC in conjunction with wind tunnel testing**
    - **Can the corresponding change in aerodynamics with wing shape be quantified?**
  - **Study of wing deformation in vacuum**
    - **How much of the deformation is related to inertial forces versus aerodynamic loads?**

Thank you for your attention