Trends in Early Vortex Formation on a Wall-to-Wall plate in a Pure Plunge

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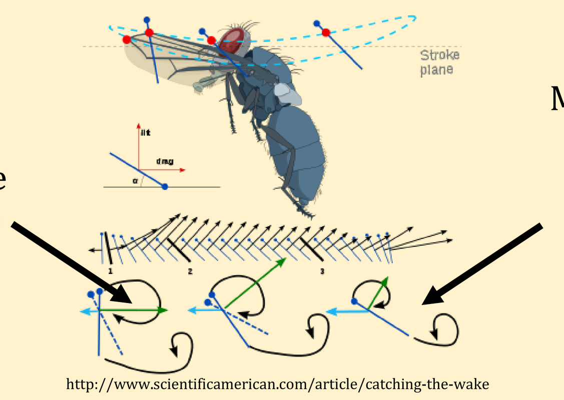
INTRODUCTION

- Aerodynamics of birds and insects have complex vortex structures which are responsible for significant percentage of lift generated.



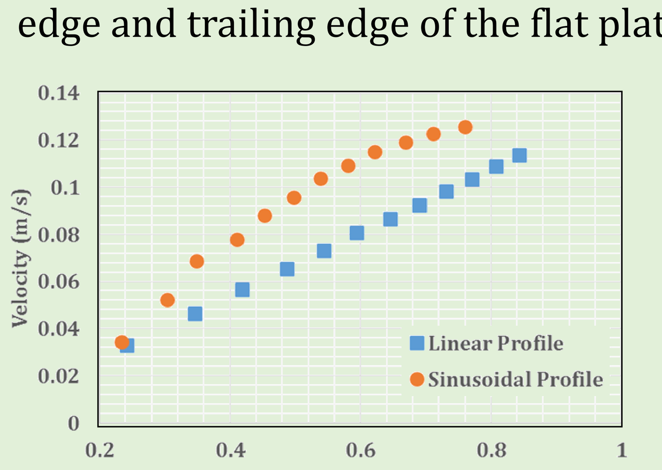
- These complex structures are also seen in helicopter rotor blades which pitch at higher velocities.
- The Leading Edge Vortex (LEV) plays a very important role in generating lift, yet it has not been quantified so far.
- Very little is known about the formation and growth of the LEV on a pitching and plunging wings.
- The lift generated due to LEV is a strong function of circulation contained in the LEV.
- The majority of the mathematical models available in the literature can predict circulation only in free vortex such as the Wingtip vortices.
- The proximity of flat plate to the LEV makes it difficult to predict circulation and velocity in LEV using available models.

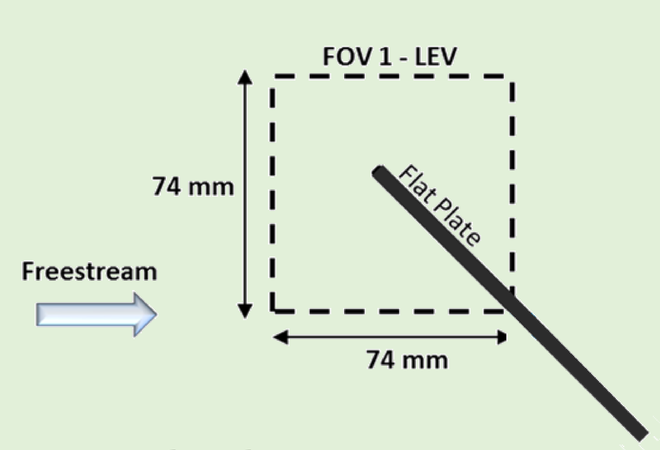
PROBLEM STATEMENT

- Study and analyze the growth and formation of the LEV in different accelerative profiles.
- Analyze the velocity variation and circulation distribution in the LEV and compare with different accelerative profiles.
- Existing algebraic models could not predict azimuthal velocity distribution in the LEV therefore develop a simple model which can predict azimuthal velocity variation in the LEV.

EXPERIMENTAL METHODS

- Experiments were conducted at Horizontal Free Surface Water Tunnel (HFWT) in the Air Force Research Labs (AFRL) on a wall to wall flat plate in a pure plunge.
- Linear and sinusoidal accelerative plunge profiles were considered.
- Particle Image Velocimetry (PIV) was used to determine velocity around the leading edge and trailing edge of the flat plate.





Linear Plunge → $x(t) = kt$

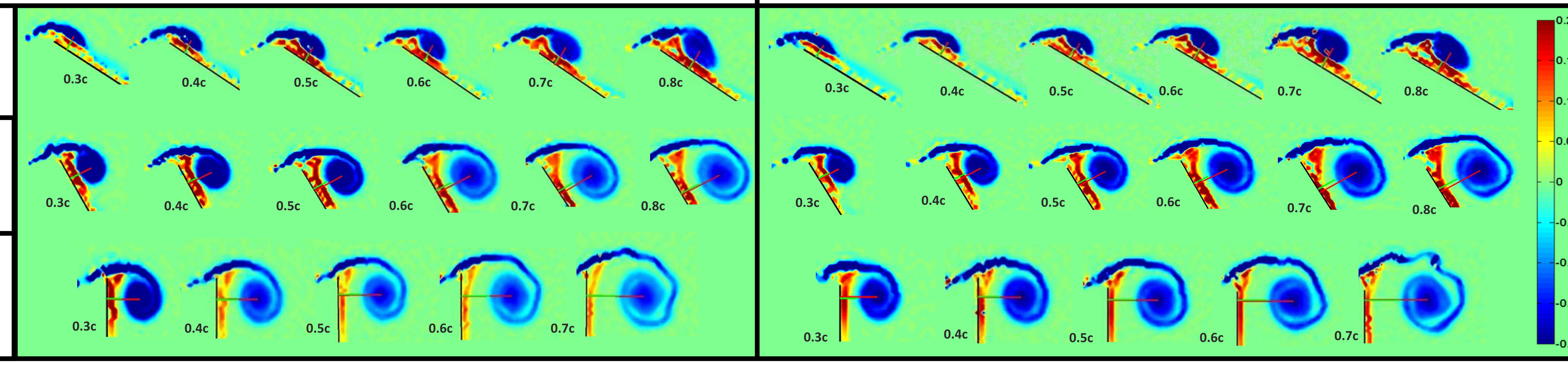
Sinusoidal Plunge → $x(t) = \cos(2\pi f t + \pi)$

Cases considered:

- Angle of attack → 30°, 45°, 60°, 75°, 85° and 90°
- Downstream distance → 0.2c, 0.3c, 0.4c, 0.5c, 0.6c, 0.7c and 0.8c

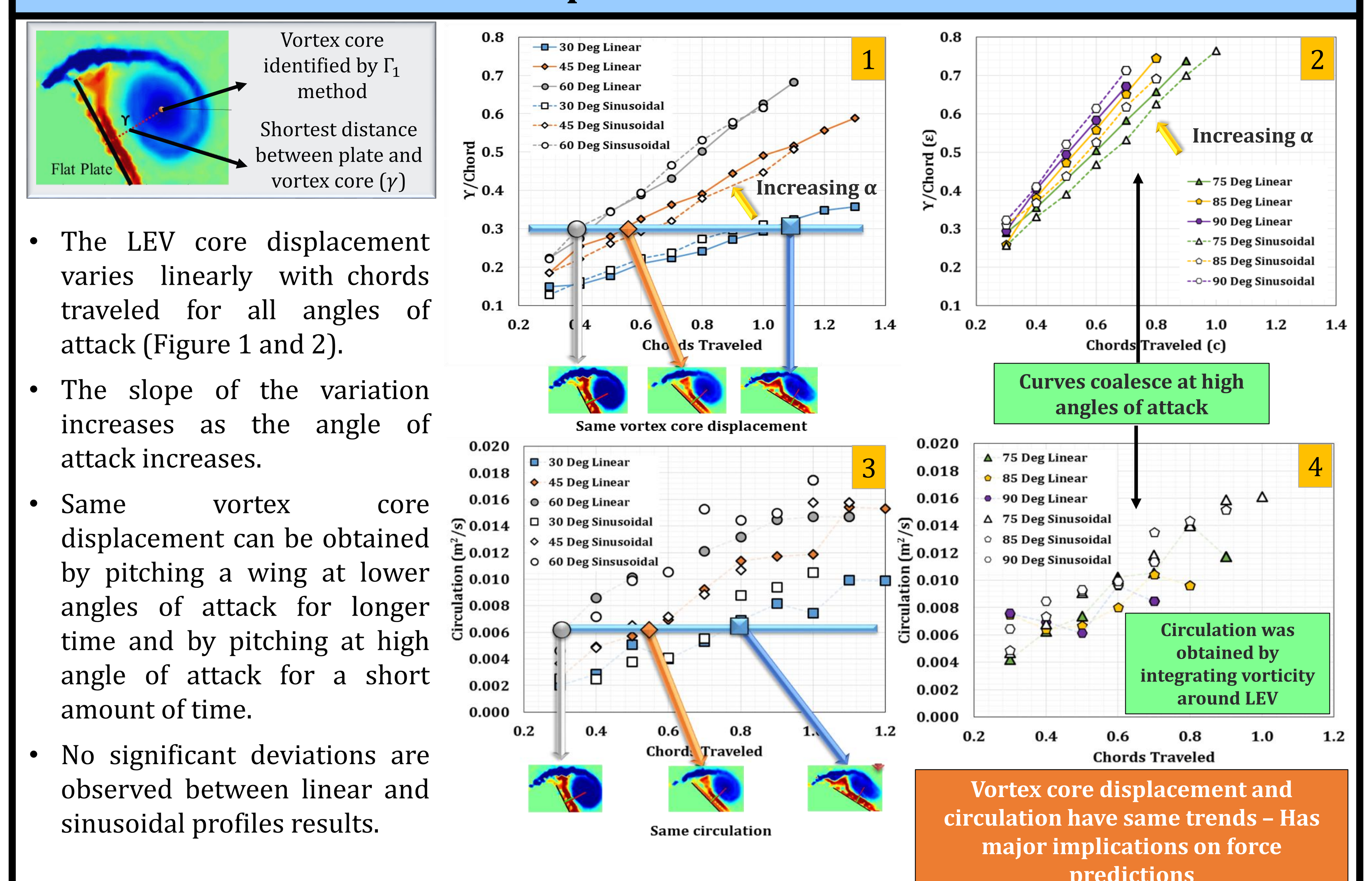
VORTICITY IN THE LEV (RESULTS FROM PIV)

α	Linear Accelerative Profile	Sinusoidal Accelerative Profile
30°		
60°		
90°		



RESULTS

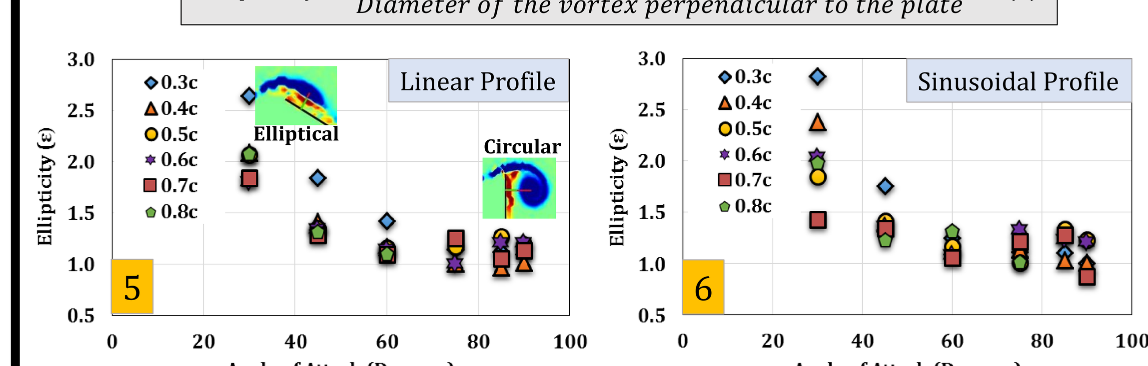
LEV Core Displacement and Circulation

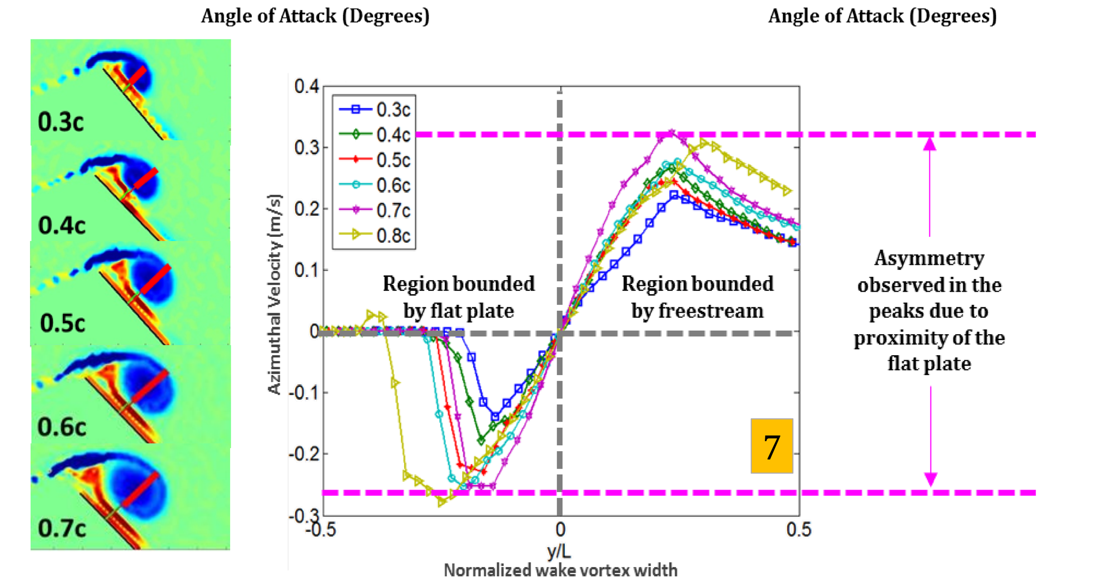


- The LEV core displacement varies linearly with chords traveled for all angles of attack (Figure 1 and 2).
- The slope of the variation increases as the angle of attack increases.
- Same vortex core displacement can be obtained by pitching a wing at lower angles of attack for longer time and by pitching at high angle of attack for a short amount of time.
- No significant deviations are observed between linear and sinusoidal profiles results.

Ellipticity and Velocity Profile of the LEV

$$Ellipticity = \frac{\text{Diameter of the vortex parallel to the plate}}{\text{Diameter of the vortex perpendicular to the plate}} \quad (1)$$





- Proximity to the plate makes the LEV asymmetric/elliptic.
- Circulation in the LEV could not be predicted using existing mathematical models due to ellipticity of the LEV.
- Ellipticity decreases quadraticaly as angle of attack is increased.
- The LEV becomes circular as angle of attack increases (Figure 5 and 6).
- Ellipticity of the LEV results in asymmetric azimuthal velocity profiles (Figure 7)

ALGEBRAIC MODELS

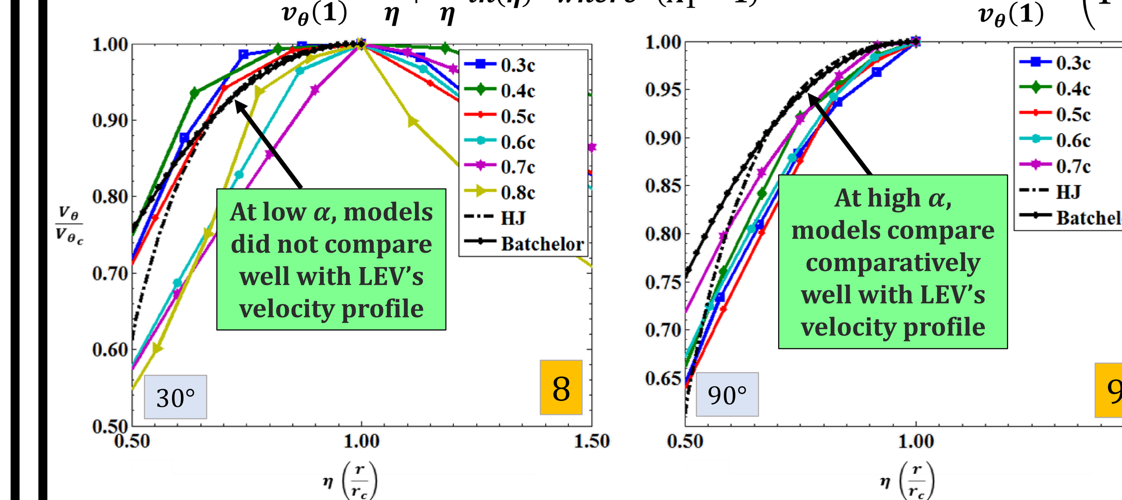
Comparing LEV Sectional Velocity profiles with existing models

- **Hoffmann Joubert (HJ) model:**
  - Predicts the normalized azimuthal velocity profile $(v_\theta/v_{\theta_{max}})$ of a turbulent free-vortex.

$$\frac{v_\theta(\eta)}{v_\theta(1)} = \frac{1}{\eta} + \frac{A_1}{\eta}\ln(\eta) \quad where \quad (A_1 = 1)$$

- **The Batchelor model:**
  - Predicts the azimuthal velocity profile of a laminar free-vortex.

$$\frac{v_\theta(\eta)}{v_\theta(1)} = \left(1 + \frac{1}{2A_1}\right)\frac{1}{\eta}\left(1 - exp(-A_1\eta^2)\right) \quad (A_1 = 1.25643)$$



- Hoffmann Joubert (HJ) model and Batchelor model are used to predict velocity profile in a free-vortices such as Wingtip vortices.
- Neither model compares well with experimental results due to ellipticity of the LEV (Figure 8 and 9)

Proposed algebraic model

- Linear, quadratic and cubic regression of the normalized azimuthal velocity profiles were modeled.
- Based on the errors observed, it was found that a minimum of third order polynomial is required to match LEV's velocity profile.

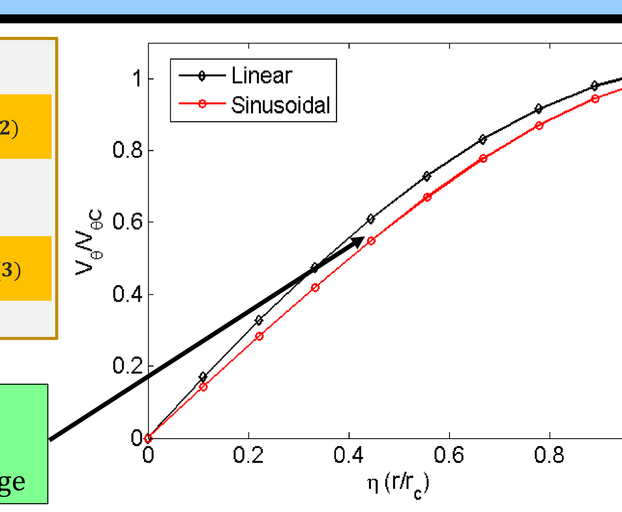
Proposed model for linear profile:

$$\frac{v_\theta(\eta)}{v_\theta(1)} = -0.2122(\eta)^3 - 0.3245(\eta)^2 + 1.5572(\eta) \quad (2)$$

Proposed model for sinusoidal profile:

$$\frac{v_\theta(\eta)}{v_\theta(1)} = -0.3420(\eta)^3 + 0.0628(\eta)^2 + 1.2765(\eta) \quad (3)$$

The coefficients in the models vary significantly for linear and sinusoidal profiles yet they render very little change



CONCLUSIONS

- Minimal variation seen in circulation and azimuthal velocity distributions results between Linear and Sinusoidal profile cases.
- Circulation follows the same trend as vortex core displacement.
- Velocity distributions from experiment did not compare well with existing models.
- A minimum 3rd order polynomial is necessary to predict the azimuthal velocity variations in LEV.
- A new 3rd order polynomial model is proposed based on experimental data.
- This model includes the effect of the vortex proximity to the flat plate which the other models were not conceived to account for.