Analytical Model for Leading-Edge Vortex Lift on Rotating Samara Seeds

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Abstract

Samara seeds is the name given to a type of seed that has wings which allow them to rotate to reduce their fall speed (figure 1). These seeds have been known to have very high lift coefficients due to the development of a LEV (Leading-Edge Vortex) over the wing.

Figure 1: Rotating samara seed.

This article focuses on the development of a simple analytical aerodynamic model capable of describing the effect of LEVs on the lift of samara wings. This was based on an adaptation of Polhamus’ method into a rotor blade element steady aerodynamic model, which was tested against previous research to check the consistency of the analysis. Furthermore, wind tunnel experiments were conducted to validate the numerical blade element rotor model. Furthermore, wind tunnel experiments were also conducted to validate the numerical blade element rotor model.

The application of this research is the prediction of the performance of rotary micro air vehicles for design purposes.

The LEV is a phenomenon whereby a vortex is being developed along the wing from its leading edge. This LEV seems to be an example of convergent evolution found to occur on natural wings such as in birds [1] [2], insects [3], bats [4], and samara seeds [5] [6] [7], and also on artificial delta wings [8].

Previous aerodynamic models for insect-like flapping [9] included techniques capable of modelling LEVs for insect flight and delta wings, which suggested the potential for development of similar models for the case of samara wings. One method that seemed especially promising was that of Polhamus’ leading-edge suction analogy for vortex lift calculation [10]. This was originally developed for delta wings, but was successfully adapted in models for insect flight [11] [12] and lift generation of avian tails [13], among others.

The analysis presented in this article is composed of three elements:

1- Analytical development of an expression for lift coefficient of a rotating aerofoil with LEV.
2- Performance analysis of rotating samara wing in autorotation in vertical flight conditions using blade element method.
3- Wind tunnel testing of rotating samara seed and flow visualisations with the purpose of validation of the numerical analysis.
1. **Analytical model description**

Polhamus’ model [10] is based on an analysis of the wing using lifting surface methods to extract constants capable of describing the effect of the LEV on the total lift. It assumes that if the LEV remains attached over the upper surface of the wing the total lift will be obtained as the sum of the potential lift and a vortex lift.

This vortex lift will be related to the suction force on the leading edge, translated as a normal force on the upper surface of the aerofoil by imposing a Kutta flow condition at the leading edge (figure 2). The magnitude of the normal force will be the suction created by the centrifugal force of the vortex lift. This can be seen expressed in the following formulae, derived in Polhamus’ paper:

- **Potential flow lift component:**
  
  \[ C_{L,p} = K_p \sin \alpha \cos^2 \alpha \]  

  This potential flow lift coefficient \( C_{L,p} \) will be reduced to:

  \[ C_{L,p} \approx K_p \alpha \]  

  for small angles of attack, and therefore \( K_p \) will be given by the \( C_L \) over \( \alpha \) curve of small-angle theory, and will be derived from any adequate lifting-surface theory.

- **Vortex lift component:**

  The suction force will be rotated into the direction normal to the wing chord plane, and after the leading-edge thrust coefficient is determined, the vortex lift will be calculated:

  \[ C_{L,v} = K_v \cos \alpha \cos \Lambda \sin^2 \alpha \]  

  Where \( K_v \) is given by:

  \[ K_v = (K_p - K_p^2 K_i) \]  

  And \( K_i \) will be equal to:

  \[ K_i = \frac{\delta C_{D_i}}{\delta C_L} \]  

  It can then be seen that \( K_i \) can also be obtained from any reliable lifting-surface theory.

The total lift will be calculated as the combination of the potential flow lift and the vortex lift:

\[ C_L = C_{L,p} + C_{L,v} \]

\[ C_L = K_p \sin \alpha \cos^2 \alpha + (K_p - K_p^2 K_i) \cos \alpha \cos \Lambda \sin^2 \alpha \]
2. Performance validation using Blade element methods

Data for the simplified samara wing was obtained from the lifting-surface method VLM (Vortex Lattice Method) Tornado [14] and checked against the analysis of the aerofoil in XFLR5. The data was then used to obtain the required constants (see previous section).

The final analysis for lift on samara seeds was obtained when the results from Polhamus’ method were included in the Blade-Element Model, a numerical rotor model using strip theory and steady aerodynamics to define the blade(s), tuned to fit Azuma’s [15] experimental results for samara seeds.

The model using the analytical lift curve was compared against results with the empirical lift coefficient curves [15] (figure 3). It can be seen that the results obtained from the analytical LEV model are sensible, falling between the range of the minimal and maximal experimental values [15].

![Figure 3: Vd (vertical flow speed) VS Disk Loading (N/m²) curves, comparing the use of the maximal and minimal Cl curve values from experimental data [15] and the Cl curve from the LEV model (using AR of 4.38 in all cases)](image)

3. Wind tunnel experiment:

To independently validate the results of the model experiments in a vertical low speed wind tunnel are being performed (figure 4), namely PIV measurements and observation of the structure of the flow with a high speed camera on a rotating samara seed for several vertical speeds.

![Figure 4: Low-speed vertical wind tunnel.](image)

This will allow for model validation and the assessment of the stability of the LEV for different vertical speeds, permitting to know when the analytical model would be applicable.
Conclusions:
An analytical model capable of predicting the lift on samara seeds with an active LEV has been developed, using an adaptation of Polhamus’ method and a numerical blade-element model. It has been validated against previous experimental results.

Measurements on a low-speed vertical wind-tunnel are currently being carried out to better understand LEV stability and thus further the applicability of the analytical model.

Word count: 957 words

REFERENCES: