Modelling the Unsteady Loads of Plunging Airfoils in Attached, Light and Deep Stall Conditions

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Introduction

- Aims and scope
- Models of aerodynamic loads

Experimental Setup

Results

- Mean lift
- Unsteady lift amplitude
- Mean pitching moment
- Unsteady pitching moment amplitude
- Phase-averaged loads and flow field

Conclusions
**Aims and scope**

**AIMS** of the project:
- Create database of loads and flow field measurements for validation of models and CFD methods
- Test existing reduced order models for high reduced frequency and high angle of attack
- Development of flow control devices to reduce extreme loads

**Scope** of this presentation:
- Quasi-2D wing (airfoil) flow
- Unsteady lift and pitching moment for reduced frequency up to $k \approx 1.1$
- Compare loads measurements with predictions from Theodorsen, Leishman-Beddoes, Goman-Khrabrov and LDVM
A vertically plunging airfoil is characterized by a periodic oscillation of the effective angle of attack.

Wing vertical position:

\[ h(t) = \frac{A}{2} \cos 2\pi f t \]

Effective angle of attack:

\[ \alpha_{eff}(t) = \alpha + \tan^{-1}\left(\frac{U_{pl}(t)}{U_\infty}\right) \]
In this presentation the following reduced-order models are considered:

- Theodorsen
- Leishman-Beddoes (LB)
- Goman-Khrabrov (GK)
- LESP-based discrete vortex method (LDVM)
Modelling: Theodorsen Model

- Theodorsen theory assumed incompressible, attached, irrotational flow and planar wake.

- Unsteady lift includes period variation of circulation (effective angle of attack, wake), and “added mass” effect

\[ C_l = \left[ 2\pi k j C(k) - \pi k^2 \right] A_c e^{j\omega t} + 2\pi \alpha \]

- Pitching moment at \( \frac{1}{4} \) of the chord depends only on the added mass effect, no effect from circulation

\[ C_{m,\frac{1}{4}} = \left[ \frac{\pi}{4} k^2 \right] A_c e^{j\omega t} \]
Modelling: semi-empirical models

\( \alpha_{eff}, \) (forcing)

Unsteady attached flow

Trailing edge separation

Leading edge separation

Vortex shedding

Circulation

Added-mass: function of \( \alpha_{eff} \)

Semi-empirical models have been developed to account for the higher complexity of the flow field around the stall angle

• Leishman-Beddoes (LB), indicial response
• Goman-Khrabrov (GK), state-space representation
Modelling: semi-empirical models

\[ C_L^f = C_N(\alpha(M)) \left( \frac{1 + \sqrt{f}}{2} \right)^2 \alpha \]

\( \alpha_{eff}, \) (forcing)

Unsteady attached flow

Trailing edge separation

Leading edge separation

Vortex shedding

Static separation

\( \alpha_1 \) stall angle
\( S_1, S_2 \) empirical constants

\( f \): position of trailing edge separation
(0: attached flow, 1: full separation)
Modelling: semi-empirical models

\[ \alpha_{eff}, \text{ (forcing)} \]

Unsteady attached flow

Trailing edge separation

Leading edge separation

Vortex shedding

Loads

Dynamic stall

Leishman-Beddoes (LB)

Delay in separation calculated with indicial method

\[ f''_i = f'_i - D_{f_i} \]

\[ D_{f_i} = D_{f_{i-1}} e^{\left(\frac{\Delta s}{T_f}\right)} - (f'_i - f'_{i-1}) e^{\left(\frac{\Delta s}{2T_f}\right)} \]

Where \( \Delta s \) is time step, \( T_f \) empirical constant

Goman-Khrabrov (GK)

State-space representation

\[ \tau_1 \frac{df}{dt} + f = f_0 (\alpha - \tau_2 \frac{d\alpha}{dt}) \]

\( f_0 \) static separation parameter

\( \tau_1 \) delay in angle of attack

\( \tau_2 \) delay in separation

\( f \) load parameter

Separation

Leading edge vortex

Delayed separation

Re-attachment
Modelling: semi-empirical models

\( \alpha_{\text{eff}}, \) (forcing)

- Unsteady attached flow
- Trailing edge separation
- Leading edge separation
- Vortex shedding

\( \text{Loads} \)

Dynamic stall

- Separation
- Leading edge vortex
- Delayed separation
- Re-attachment

Instantaneous vortex contribution equal to the difference between theoretical linear lift and static lift for a given effective angle of attack
Modelling: Discrete Vortex Method

- **LDVM**: Discrete vortex method based on leading edge separation parameter (LESP)

- Extension of unsteady airfoil theory for large and high frequency oscillation, and non-planer wake. Instantaneous chord-wise bound vorticity described as a Fourier series.

\[
\gamma(\theta, t) = 2U(t) \left[ A_0(t) \frac{1 + \cos \theta}{\sin \theta} + \sum_{n=1}^{\infty} A_n(t) \sin(n\theta) \right]
\]

\[
A_0(t) = -\frac{1}{\pi} \int_{0}^{\pi} \frac{W(x, t)}{U(t)} d\theta
\]

\[
A_n(t) = \frac{2}{\pi} \int_{0}^{\pi} \frac{W(x, t)}{U(t)} \cos(n\theta) d\theta
\]

- Separation at the leading edge starts as a consequence of the strong adverse pressure gradient just downstream of the suction peak. A Leading edge separation parameter (LESP) is defined as the normalized leading edge velocity:
- \( \text{LESP} = A_0 \). Leading edge separation starts when \( \text{LESP} > \text{LESP}_{\text{crit}} = 0.25 \)
## Modelling: Summary

<table>
<thead>
<tr>
<th>Method</th>
<th>Advantages</th>
<th>Shortcomings</th>
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<tbody>
<tr>
<td>Theodorsen</td>
<td>• Exact solution</td>
<td>• Only valid for small oscillation</td>
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<td></td>
<td>• No numerical integration</td>
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<tr>
<td>Semi-empirical models (LB, GK)</td>
<td>• Account for dynamic stall</td>
<td>• Requires a number of empirical constants</td>
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<td></td>
<td>• Faster than other numerical methods</td>
<td>• Not validated for high frequency plunging motion</td>
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<td>LDVM</td>
<td>• Better representation of the LEV</td>
<td>• Assumption of attached flow</td>
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<td>• Slower than semi-empirical model</td>
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Experimental Facility

- **Water Tunnel:** $Re=20,000$
- **Water Tunnel: Rig:** lightweight, frictionless air bearing carriage, linear motor, accelerometer and optical encoder.
- **Wing:** NACA0012 profile, chord $c=62.71\text{mm}$, aspect ratio $AR=5$
PIV Measurements

• **Flow Field:** 2D-PIV. Laser applied in the mid-span of the wing. Images acquired with a 4MP camera installed underneath the water tunnel. Spatial resolution of the velocity field is about 1% of the chord.

• **Glass plate:** 2 mm from the wing tip, enable quasi-2D flow and optical access for the camera
Load Measurements

Lift Measurements
• Load Cell
• Non-dimensional lift: \( C_l = \frac{F_y}{0.5 \rho U_{\infty}^2 c L} \)

Pitching moment:
• measured at \( \frac{1}{4} \) of the chord
• Torque sensor: \( C_{Mz} = \frac{M_z}{0.5 \rho U_{\infty}^2 c L c} \)

• Data reduction through Fourier approximation:
\( C_l(t) \approx a0 + a1 \cos(2\pi ft + \phi) \)
• Accelerometer is used to remove inertial force of moving structures from the measured signal
• Measurements validated with literature (Chiereghin et al, 2017)
Experiments: Parameters definition

- **Experimental text matrix:**
  - Angles of attack $\alpha = 0, 5, 9, 15, 20^\circ$
  - Chord-based reduced frequency, $k = \pi Sr_c = 0$ to 1.1, alternatively: Strouhal number, $Sr_c = \frac{fc}{U_\infty} = 0$ to 0.35
  - Peak to peak amplitude: $A/c = 0.05$ to 0.5
  - This produces a peak effective angle of attack up to $\approx 45^\circ$
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Conclusions
**Time-averaged Lift, Theodorsen, LDVM**

- Strong mean lift enhancement, in particular in post-stall conditions
- For sufficiently high $k$ and $A/c$, the linear lift $2\pi\alpha$ is also exceeded
- Good predictions of mean lift from LDVM up to stall angle $\alpha=9^\circ$
- Poor agreement between exp. and LDVM in post stall $\alpha=15^\circ$ or higher
Time-averaged Lift, semi-empirical models

- The methods do not match the experimental data
- Reasonable prediction of the trend only for $k<0.5$
Effect of vortical structures

$k=0.94 \ A/c=0.5$

- Mean lift offset determined by coherent vortical strictures
Lift enhancement, data trend

- Some trend observed between the lift enhancement and the maximum effective angle of attack during a plunging cycle.

\[ C_{l,\text{mean}} - C_{l,\text{static}} \]

\[ \max(\alpha_{\text{eff}}) \ [^\circ] \]
Lift amplitude, Theodorsen, LDVM

- Reasonable agreement with Theodorsen even at high k
- However, experimental amplitude exceeds Theodorsen prediction at some point for $\alpha \geq 15^\circ$
- Better agreement with LESP
Lift amplitude, semi-empirical models

- Reasonable prediction from LB
- Good prediction from GK only at low k (<0.4)
• Plunging produces a “nose-down” pitching moment

• Good prediction from LESP only for A/c=0.5
Pitching Moment Amplitude, Semi-empirical Models

- Experimental data follows Theodorsen trend only for $\alpha=0^\circ$
- For $\alpha\geq9^\circ$ the trend is not monotonic, with local minimum and local maximum
- LESP predicts the trend but not the frequency of the local minimum/maximum and their magnitude
Effect of the Reduced Frequency

α=15°, A/c=0.5, t/T=0.5

- Vortical structures produce a departure from Theodorsen prediction.
- This difference is more evident for the pitching moment where the suction effect at the downstroke of the motion produces a nose-down moment opposite to the nose-up moment of the added-mass.
Effect of the Geometric Angle of Attack

- Position and intensity of the vortex at the downstroke depends on both the frequency and the geometric angle of attack
- Evident effect on the pitching moment loop
- Modelling more complicated
1. Mean lift is poorly estimated by all methods.
   • Good prediction from LDVM only at high plunging frequency and amplitude
   • Semi-empirical models good only at low frequency
   • Approximate linear correlation with maximum effective angle of attack

2. Theodorsen provides good predictions of lift amplitude and phase lag even in post-stall conditions. However, poor predictions of unsteady pitching moment
   • Some improvement provided by LDVM

3. Non-monotonic variation of pitching moment amplitude caused by convection of LEV