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Terminology and data presentation for aerodynamic studies on flapping wings

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Technical Note
DRDC Valcartier TN 2013-413
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Work done under TIF project 2006-05-04 "Aero-NAV"

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Abstract

The Aero-NAV TIF project at DRDC Valcartier investigated flapping wing aerodynamics for NAV applications. Tools and capabilities were developed by combining high-accuracy predictions and experimentations with engineering modelling. This Technical Note describes the data presentation considered and used for the Aero-NAV project. Because of the complex flapping wing motion, there are many ways of presenting the results. Therefore, throughout the project, it was important to have a consistent method in the presentation of the results.

Résumé

Le projet FIT Aero-NAV à RDDC Valcartier a étudié l'aérodynamique du battement d'aile pour des applications aux nano-drones. On a développé des outils et des capacités en combinant des prédictions et des expérimentations de haute précision avec la modélisation d'ingénierie. Cette note technique décrit la présentation des données qui a été considérée et utilisée pendant le projet Aero-NAV. À cause du mouvement complexe du battement d'aile, il y a plusieurs façons de présenter les résultats. Ainsi, pendant le projet, il est important d'avoir une méthode consistante pour la présentation des résultats.

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1 Introduction

The development and acquisition of a new class of military systems known as Nano Air Vehicle (NAV) (smaller than 7.5 cm and less than 10 grams) is possible in the not too distant future as a result of technological progress in a number of areas such as aerodynamics, micro-electronics, sensors, micro-electromechanical systems and micro-manufacturing. The potential of nano air vehicles, with their small size and hover capability, opens up new possibilities in the formulation of military strategies with respect to information superiority in urban operations.

The Aero-NAV TIF project at DRDC Valcartier [1][2] investigated flapping wing aerodynamics for NAV applications. Tools and capabilities were developed by combining high-accuracy predictions and experimentations with engineering modelling. The detailed flow physics were captured using a highly accurate unsteady CFD solution at low Reynolds number. A tailored experimental facility (water tunnel at the Institute for Aerospace Research of NRC) was developed for flapping wings operating at high frequency with a complex 3-dimensional pattern. A less computationally-intensive engineering-type method (Vortex lattice method) capable of capturing the fundamental aerodynamics and approximating the forces and moments generated over a wide range of wing motions, was developed and used to identify optimum wing shape and motion.

This Technical Note describes the data presentation considered and used for the Aero-NAV project. Because of the complex flapping wing motion, there are many ways of presenting the results. Therefore, throughout the project, it was important to have consistent method in the presentation of the results.

This work was carried out under the Technology Investment Fund project “Flapping wings for nano air vehicles – Aero-NAV” (12pz12).

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2 Terminology

2.1 Terms

Due to the complex geometry or complex motion, there are many terms used in the world of flapping wings aerodynamics. It is important that their definition be clear to their users.

- *Chord - c* [m]
- *Planform area – S* [m^2]
- *Angular frequency -* $\omega = 2\pi f$ [rad/s]
- *Freestream velocity* - U_∞ [m^2]
- *Phase angle between pitch and plunge:* δ [rad]
- *Plunge* – rectilinear motion (at the pivot point) normal to the plane of a model, typically sinusoidal: $y(t) = H\sin(\omega t + \delta)$ [m]
- *Plunge velocity*: $V_y(t) = H\omega\cos(\omega t + \delta)$ [m/s]
- *Reduced plunging amplitude* - $h = H/c$, where H = single-sided plunge amplitude
- *Maximum plunging-induced velocity* - $V_y \max = H\omega = hc * 2kU_\infty / c = 2hkU_\infty$ [m/s]
- *RMS plunging-induced velocity* - $\frac{H\omega}{\sqrt{2}}$ [m/s]
- *Pitch* (also called *Geometric angle of attack*) – angle that wing chord makes relative to free-stream flow; typically sinusoidal variation; pivot point needs specification, but is typically the leading edge;
  $\theta(t) = \theta_0 \sin(\omega t)$ [rad]
- *Pitch rate:* $q = \dot{\theta} = \theta_0\omega\cos(\omega t)$ [rad/s]
- *Nondimensional pitch rate -* $p = qc/(2U_\infty)$
- *Maximum nondimensional pitch rate* – $p_{max} = \theta_0 \omega c / 2U_\infty$
- *Reduced frequency* – ratio of wing velocity to body velocity; dimensionless flapping frequency;
  $k = \pi fc/U_\infty = \omega c/(2U_\infty) = p_{max}/\theta_0$
- Strouhal number based on chord - $fc/U_\infty = k/\pi$
- *Advance ratio* – ratio of flight speed to speed of the wing tip; typically smaller than one for insects
  $$J = \frac{U_\infty}{\omega H} = \frac{1}{2kh}$$
- *Strouhal number based on H* – ratio of maximum flapping velocity to forward velocity; $St = fH/U_\infty = kh/\pi = 1/(2\pi J)$
- *Angle of attack due to plunge –*

$$\alpha_{\text{plunge}} = \tan^{-1}\left(\frac{-V_y}{U_\infty}\right) \text{ [rad]}$$

- *Maximum angle of attack due to plunge –*

$$\alpha_{\text{plungeMax}} = \tan^{-1}\left(\frac{H\omega}{U_\infty}\right) = \tan^{-1}\left(\frac{hc\omega}{U_\infty}\right) = \tan^{-1}(2hk) \text{ [rad]}$$

- *Effective (aerodynamic) angle of attack* – angle that wing chord makes relative to the locally deflected flow: $\alpha_{eff} = \alpha_{plunge}(t) - \theta(t)$ [rad]
- *pitch/plunge "advance ratio"* -

$$\lambda = \frac{\theta_0}{\alpha_{\text{plungeMax}}} = \frac{\theta_0}{\tan^{-1}(2hk)}; \quad => \quad \theta_0 = \tan^{-1}(\lambda \times 2hk)$$

- *Reference velocity* – Because the free stream velocity may be zero or small compared to the airfoil's velocity, it may be inappropriate and possibly misleading to use the freestream velocity for non-dimensionalisation. A representative velocity is therefore used for calculation of Reynolds number and aerodynamic coefficients. Here it is defined as the vector sum of the freestream velocity and the maximum plunging-induced velocity ($V_y$max). This reference velocity could also be used in the calculation of nondimensional pitch rate, reduced frequency, Strouhal number, advance ratio.

$$U_{ref} = \left\| U_\infty + V_{\text{y Max}} \right\|$$

- *Reynolds number* - $\text{Re} = U_{ref} \cdot c / \nu$;
- *Thrust efficiency (Q)* – $\dfrac{< F_x(t) > U_0}{< F_y(t) V_y(t) >}$
- *Dynamic scaling* – simultaneous scaling of Reynolds number, reduced frequency and normalized plunge amplitude
- *Aspect ratio* – span to mean chord
- *Slide* – rectilinear motion parallel to the free stream
- *Flap* – "armwaving" motion in 3D pivoting at the root of the wing, with maximal excursion at the tip. The motion can be thought of as a time-varying dihedral.
- *Swing* – akin to a cross between the slide and the flap; pivot at the root of the wing with maximal excursion at the tip, but motion is in the plane of the wing planform.
- *Rotation* – reversal of leading edge (LE) and trailing edge (TE) upon completion of a swing, as is done for example by fruit flies in hover.
- *Normal hover* (2D) – $U_\infty = 0$, airfoil commences translation normal to its chord, together with a pitch; then reverses the pitch at the opposite end of the translation stroke, stops, reverses the motion and returns to its original position.
- *Water treading* (2D) – similar to normal hover, except that the translation of the airfoil is parallel to its chord.
- *Supination* – rotation that brings the ventral surface of the wing to face upward
- *Pronation* – rotation that brings the ventral surface of the wing to face downward

2.2 Reference axes

This section presents the references axes used for the two-dimensional and the three-dimensional test cases.

2.2.1 Two-dimensional axes

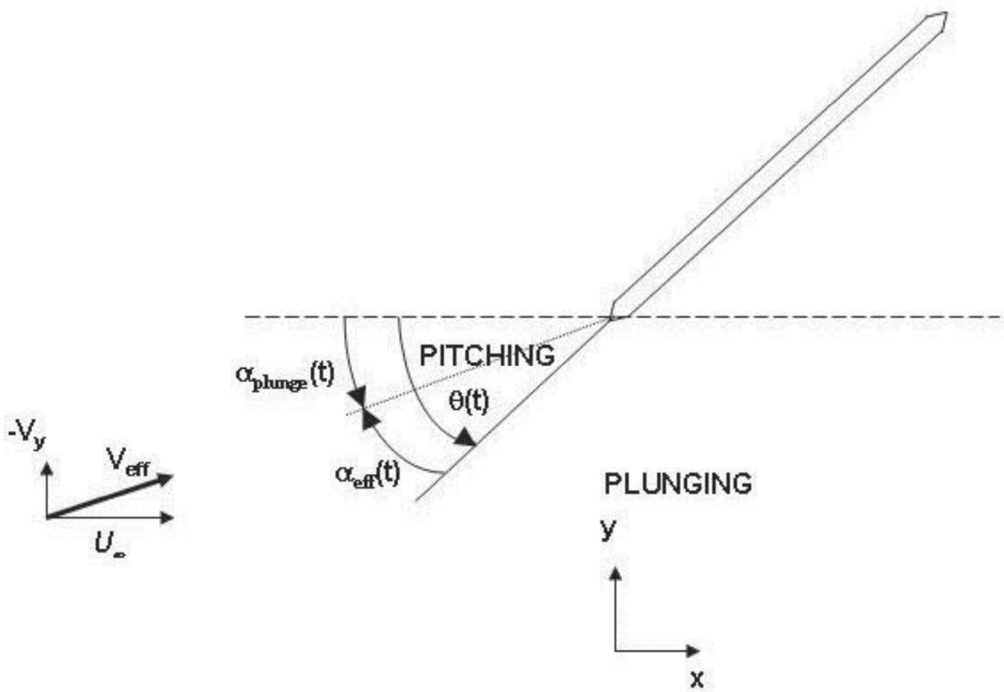


Figure 1 : Reference axes for 2D motion

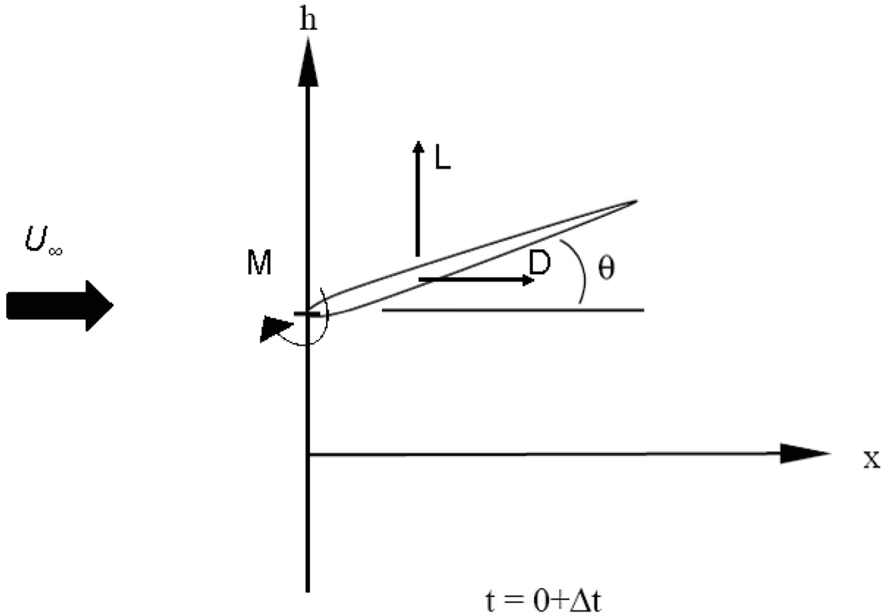


Figure 2 : Reference axes for 2D forces and moments

2.2.2 Reference axes for insect-like wing

The water tunnel 3DOF system used in the Aero-NAV project controlled three angular motions: pitch motion (α), dihedral motion (γ) and sweep motion (Λ). The standard terminologies and nomenclatures used in fixed wing aerodynamics are adopted here. The body axes system is shown in Figure 3. Three angles are taken as the motion parameters, i.e. angle of attack (α), sweep angle (Λ) and dihedral angle (γ), corresponding to feathering motion angle, elevation angle and position angle in some bioflight literature. Pitch angle is mechanically independent but sweep angle and dihedral angle are mechanically linked such that actuating either motor caused the other angle to move. The interaction relationship between sweep angle and dihedral angle is 1:1, degree for degree. Therefore the equations of motion for these two axes will reflect the interdependent relationship by subtracting one angle from the other.

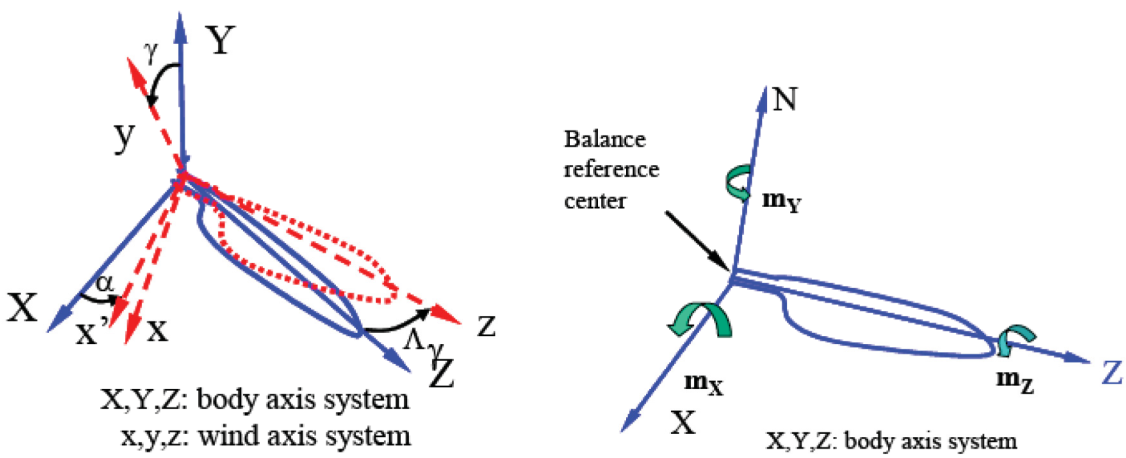


Figure 3: Reference axes for 3D cases

3 Data presentation

Because of the complex flapping wing motion, there are many ways of presenting the results. Therefore, throughout the project, it is important to have consistency in the presentation of the results.

For presentation of data, dimensional values should be used as a minimum. This has the advantage of removing all ambiguity as to how the values may have been non-dimensionalised. In addition to dimensional values, all parameters useful in non-dimensionalisation must be reported so that the reader may non-dimensionalised in the manner of their choosing.

There are, at least, five categories of data:

- problem definition (wing geometry and motion, not time dependent)

- time varying kinematics calculated form the problem definition or measured or estimated

- time varying forces and moments and their non-dimensional coefficients

- time averaged forces or coefficients

- time varying field data (pressure, Mach, vorticity, etc.)

3.1 Angle of attack

It is essential to clearly define “angle of attack” as there are many possible definitions. There are at least three different possibilities for measures of angle of attack. The first one is the geometric angle of attack which is the angle between the freestream velocity and the airfoil chord. It is independent of the position on the airfoil. The second one is referred to as the `kinematic angle of attack'. The kinematic angle of attack depends on the airfoil's motion and the position on the airfoil at which the angle of attack is being measured. It is obtained by summing the geometric angle of attack with the angle of attack due to the local airfoil velocity. The third measure of angle of attack is referred to as the `true local angle of attack'. The true local angle of attack is also a function of the kinematics, the position on the airfoil, but also the disturbances in the flow field. In other words, the wake and bound vorticity will affect the fluid flow and therefore the angle of attack. This is because the presence of the airfoil modifies the local flow differently at different positions near the airfoil. This disturbance component to the angle of attack is however difficult to obtain.

Because the kinematic angle of attack is intuitive and well understood, a measurement position for the kinematic angle of attack that is a good predictor of the true angle of attack for the entire airfoil in the unsteady case was sought. It was shown [3]that the kinematic three-quarter chord angle of attack does this. Though not perfect, it was substantially better than the other measures of angle of attack that were considered.

Note that there are two main roles to the true angle of attack in the program: (1) as a trigger for the stall model of the VLM, and (2) conceptually as a way to tie unsteady circulatory force to angle of attack.

For the 3/4-chord, time-varying values are calculated as follows (the pivot point is at the leading edge (LE)):

- ¾-chord displacement with respect to LE: ¾ c $\sin\theta(t)$
- Total ¾-chord plunge: $y(t)_{@LE}$ + ¾ c $\sin\theta(t)$
- ¾-chord velocity with respect to LE: $q(t)$ ¾ c = ¾ $\omega c \theta_0 \cos(\omega t)$
- ¾-chord total vertical velocity: $V_{y\,3/4}(t) = q(t)\cos\theta(t)$ ¾ c + $V_y(t)$
- ¾-chord total horizontal velocity: $V_{x\,3/4}(t) = q(t)\sin\theta(t)$ ¾ c
- AOA due to plunge at the ¾-chord: $\tan^{-1}(-V_{y\,3/4}(t)/(U_\infty - V_{x\,3/4}(t)))$
- Kinematic AOA at the ¾-chord: $\tan^{-1}(-V_{y\,3/4}(t)/(U_\infty - V_{x\,3/4}(t))) - \theta(t)$

3.2 Problem definition

In two dimensions, the parameters defining the problem include, but are not limited to the following:

- wing chord
- wing span of tested item (to transform measured force in force per unit length)
- airfoil profile (NACA 0005, flat plate, …)
- plunging amplitude
- plunging equation
- pitching amplitude
- pitching equation
- phase angle between plunging and pitching
- frequency
- freestream velocity
- reference velocity : $U_{ref} = \left\| U_\infty + V_{\text{y Max}} \right\|$
- time increment for data presentation
- fluid density
- any other pertinent kinematic information

In three dimensions, there are more parameters defining the problem and they include, but are not limited to the following:

- wing chord at the root (c_{root})
- wing chord at the tip (c_{tip})
- distance between the flap axis and the root chord (b_{root})

- distance between the flap axis and the tip chord (b_{tip})
- distance parallel to the flap axis from the LE of the root chord to the LE of the tip chord (d_{tip})
- mean aerodynamic chord (or reference chord)
- flapping amplitude
- flapping equation
- twist (pitching) amplitude
- twist equation
- phase angle between flapping and twisting
- frequency
- freestream velocity
- reference velocity : $U_{ref} = \left\| U_{\infty} + V_{\text{y Max}} \right\|$
- time increment for data presentation
- fluid density
- any other pertinent kinematic information

3.3 Time varying kinematics

Various characteristics of the two-dimensional motion can then be calculated as a function of time such as:

- LE position (m)
- pitch angle (rad)
- TE wrt LE position (m)
- TE position (m)
- LE plunge velocity (m/s)
- pitch rate (rad/s)
- 3/4 chord velocity magnitude (m/s)
- 3/4 chord velocity X component (m/s)
- 3/4 chord velocity Y component (m/s)
- 3/4 chord AOA plunge pitch (rad)
- 3/4 chord kinematic AOA (rad)

For three-dimensional problems, the motion is very complex. It is therefore useful to define a reference chord representative of the working section and to calculate the two-dimensional motion at that chord position as above.

It may also be possible to have measured values of motion (position, rates, etc…) resulting from water tunnel tests or even CFD. These will be listed along with the calculated values as a function of time.

Typical graphical representations of the motions are shown in the following Figures. Figure 4 shows the pitch and plunge motions. The pitch motion lags the plunge motion by a quarter of a cycle.

The plunging motion causes the airfoil to experience an effective velocity (sum of freestream and plunging) acting at an effective angle of attack (kinematic angle of attack). Figure 5 shows the geometric angle of attack (pitch), the angle of attack due to plunge (at the LE) and the kinematic angle of attack (at the LE).

The position of the trailing edge with respect to the leading edge is based on the imposed pitch cycle (Figure 6). The total plunge position of the trailing edge is sum of the leading edge position and the relative position of the TE with respect to the LE. The maximum excursion of the trailing edge is larger than that of the leading edge.

The velocity of the trailing edge follows the same pattern as its position (Figure 7).

The angle of attack due to the plunge velocity and the effective velocity of the trailing edge is calculated as for the leading edge (Figure 8). The maximum kinematic angle of attack is larger at the trailing edge than it is at the leading edge (Figure 9).

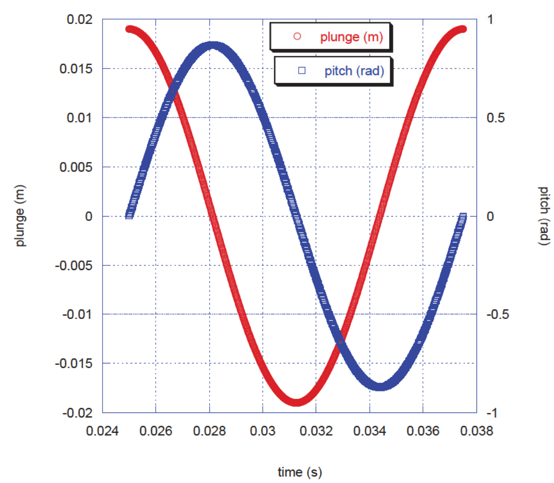


Figure 4 : Plunge and pitch cycle

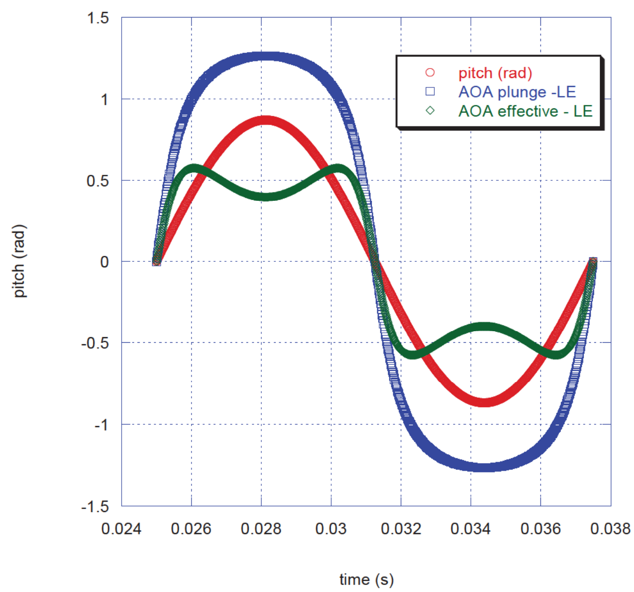


Figure 5: Angle of attack due to plunge and effective

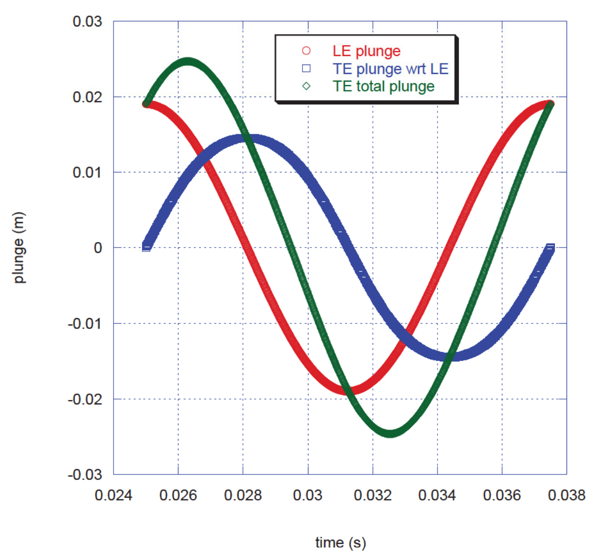


Figure 6: TE position

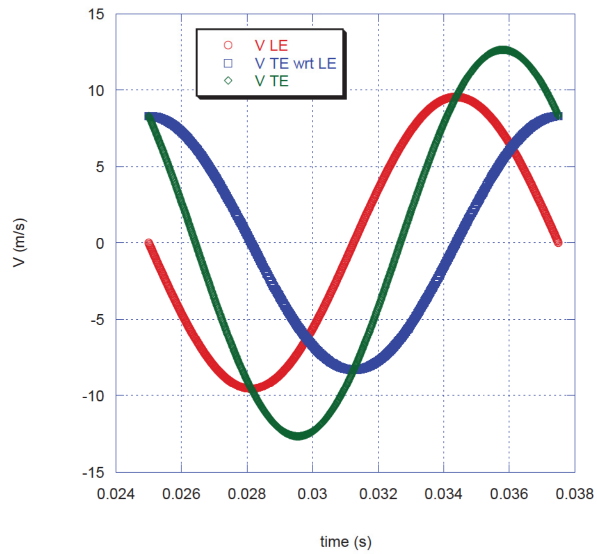


Figure 7: Leading and trailing edge velocity

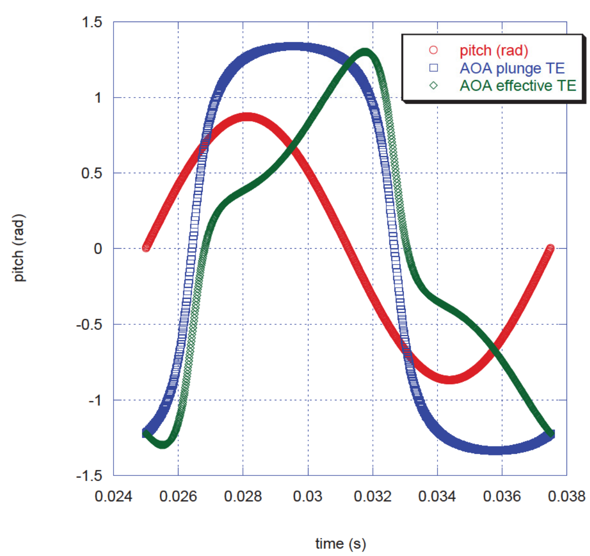


Figure 8: Trailing edge angles

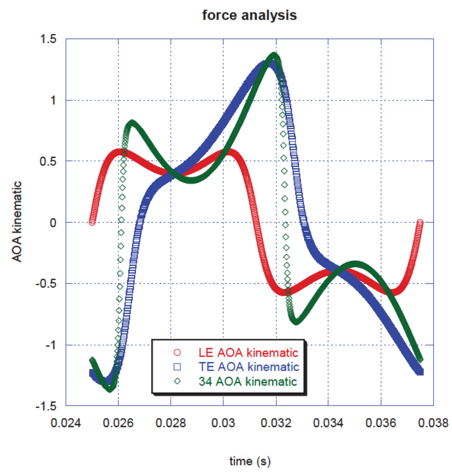


Figure 9: Leading and trailing edge angles and ¾ chord angles

3.4 Time varying forces and moments

Forces will be measured or calculated for each time increment. The cycle number at which these forces are observed is important and will be noted. It may take a large number of cycles before a steady state is reached, therefore, the importance of the cycle at which the information is obtained.

For the two-dimensional problems, the measured or predicted forces in engineering units are typically:

- L = Lift per unit length [N/m]
- D = Drag per unit length [N/m]
- N = Normal force per unit length [N/m]
- A = Axial force per unit length [N/m]
- M = Pitching moment about the leading edge per unit length [Nm/m]

Non-dimensional coefficients, if desired, should be calculated as follows:

$$C_l = \frac{2L}{\rho U_{ref}^2 c}$$

$$C_d = \frac{2D}{\rho U_{ref}^2 c}$$

$$T = -D$$

$$C_t = \frac{2T}{\rho U_{ref}^2 c}$$

$$C_m = \frac{2M}{\rho U_{ref}^2 c^2}$$

Non-dimensional power input: $C_1 \cdot {V_y}/{U_{ref}} + C_m \cdot {\Omega c}/{U_{Ref}}$

Non-dimensional power output: $C_d \cdot {U_\infty}/{U_{ref}}$ (for hover, U_∞ is taken as $V_{induced} = \sqrt{\frac{T}{2\rho A}}$)

Efficiency: power output / power input

All the values from this section are instantaneous values. It may also be useful to take a point-by-point average over several cycles to obtain an ensemble-averaged multiple-cycle time-series. For this case, the same characteristics (force, coefficients, efficiency) as for the instantaneous situation can be calculated.

The time varying forces and moments will typically be plotted as a function of the ¾-chord kinematic AOA, such as shown in Figure 10 or as a function of time, such as shown in Figure 11. It may be useful to present and analyze the results as a function of both, as shown in Figure 12. In such a case, it is useful to identify points of interest on both plots.

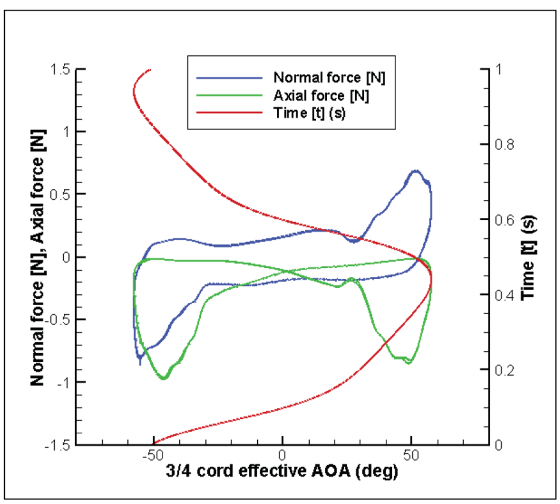


Figure 10: Forces as a function of angle of attack

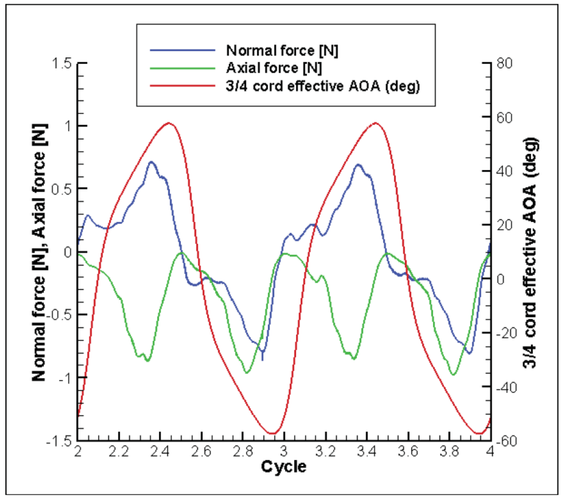


Figure 11: Forces as a function of time

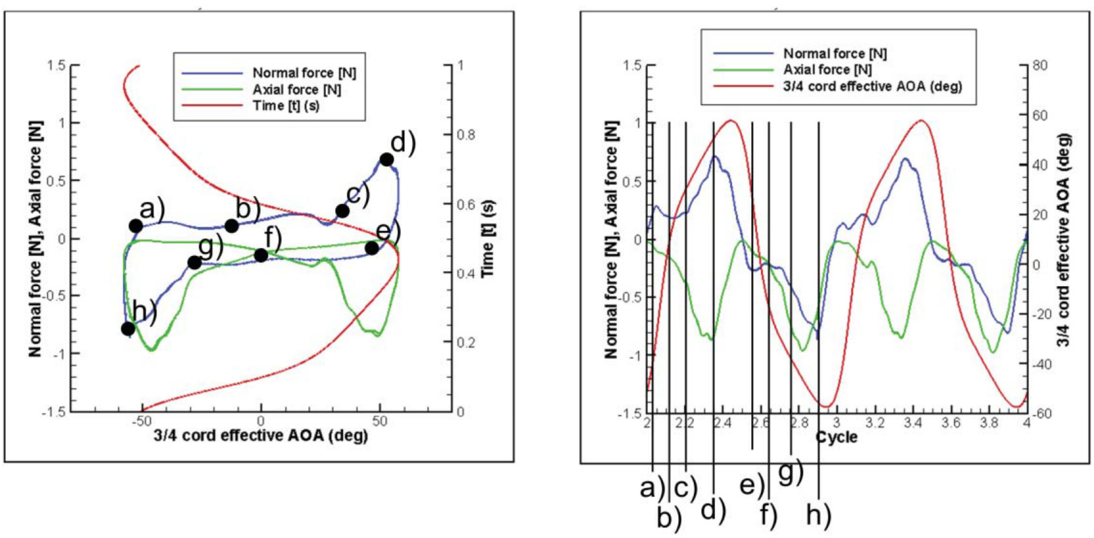


Figure 12 : Forces as a function of angle of attack and time with critical points

The forces can be represented in terms of axial and normal force (Figure 11) or in terms of lift and drag (Figure 13). The forces in terms of lift and drag are more appropriate in some cases such as water tunnel test results where only the lift is measured. The forces in terms of axial and normal forces are probably better suited to analyse the phenomena as it will be a better indicator of features such as stall. For instance, there is a clear break in the normal force curve (Figure 10) near +/- 30 degrees likely linked to stall.

Figure 13 shows a typical CFD result (Fluent) in terms of lift and drag coefficients. The negative part of the drag curve, which accounts for a large part of the cycle, represents thrust. There are two twin curves which represent the downstroke followed by the upstroke. The lift coefficient has also two twin parts but the downstroke is of opposite sign to the upstroke.

An indicator of power input and power output is the force coefficient multiplied by its velocity (Figure 14). For drag, the velocity is constant at the freestream value. For the lift, the velocity is the plunge velocity of the leading edge. The ratio of the average power output to power input is the thrust efficiency which in this case is around 33%.

The forces for the three-dimensional cases are treated similarly.

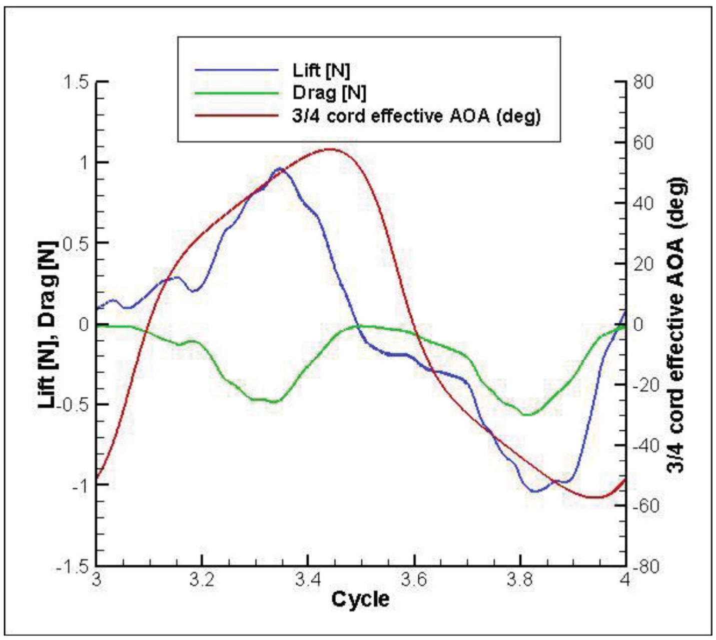


Figure 13: Typical lift and drag as a function of cycle position

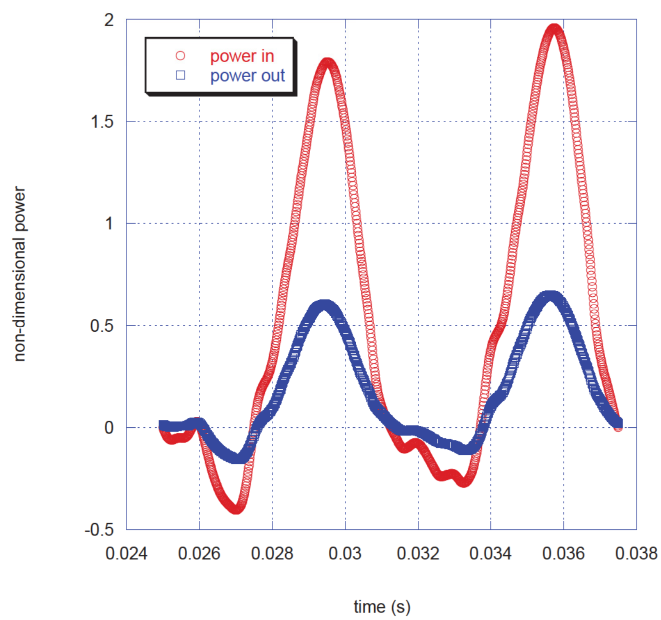


Figure 14: Power input and output

3.5 Time averaged forces

For the values of the previous section, an average over one cycle or multiple cycles or over one cycle of an ensemble-averaged cycle can be obtained. The average is calculated for the following characteristics:

- L = Lift per unit length [N/m]
- D = Drag per unit length [N/m]
- N = Normal force per unit length [N/m]
- A = Axial force per unit length [N/m]
- M = Pitching moment about the leading edge per unit length [Nm/m]

Non-dimensional coefficients, if desired, should be calculated as follows:

$$C_l = \frac{2L}{\rho U_{ref}^2 c}$$

$$C_d = \frac{2D}{\rho U_{ref}^2 c}$$

$$T = -D$$

$$C_t = \frac{2T}{\rho U_{ref}^2 c}$$

$$C_m = \frac{2M}{\rho U_{ref}^2 c^2}$$

Non-dimensional power input: $C_1 \cdot {V_y}/{U_{ref}} + C_m \cdot {\Omega c}/{U_{\mathrm{Re}f}}$

Non-dimensional power output: $C_d \cdot {U_\infty}/{U_{ref}}$ (for hover, U_∞ is taken as $V_{induced} = \sqrt{\frac{T}{2\rho A}}$)

Efficiency: power output / power input

3.6 Time varying field data

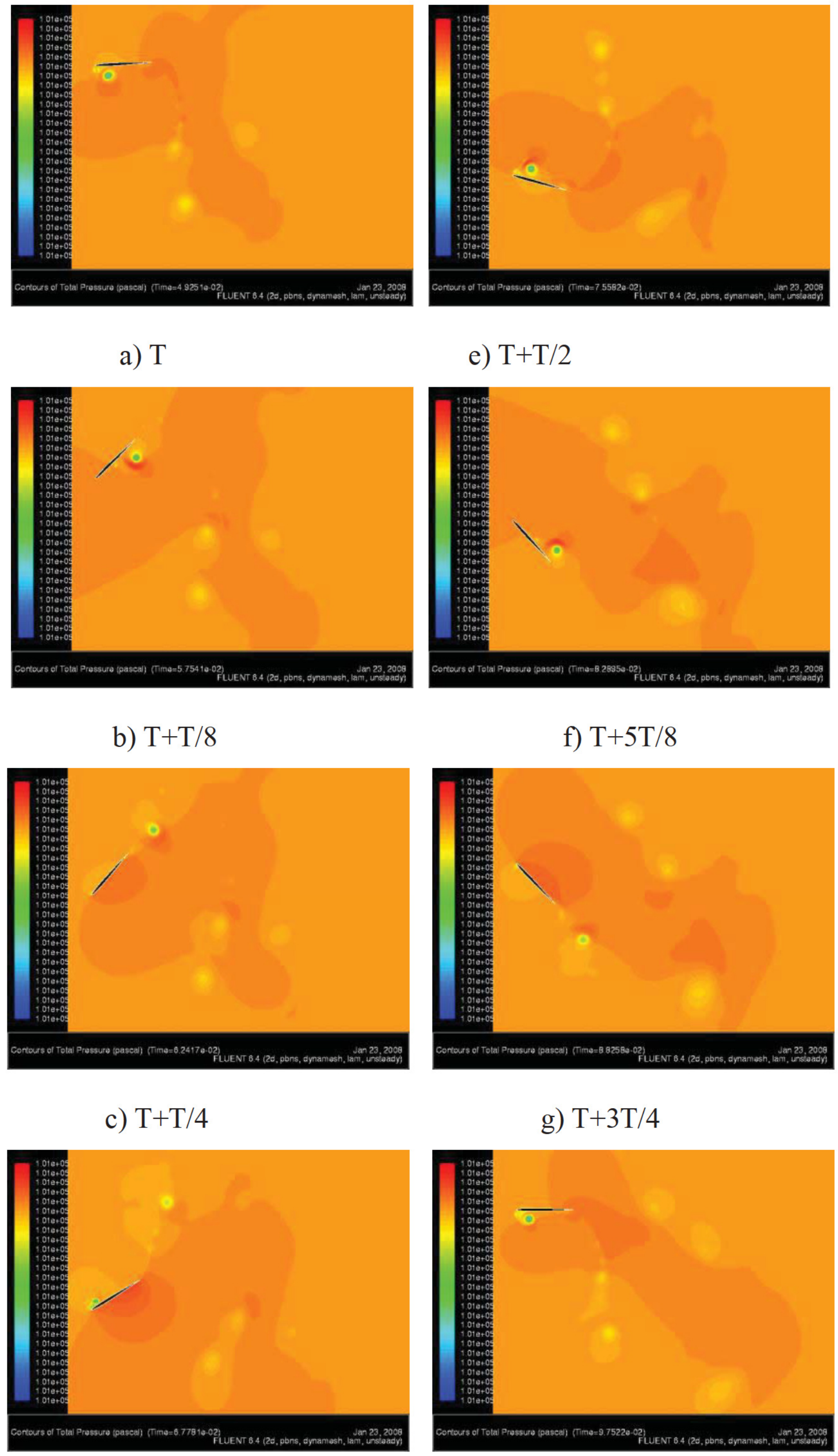
CFD and PIV will produce a large amount of data since the data covers the entire flowfield. The properties of interest are typically:

- pressure coefficient: $C_p = \frac{2(p - p_\infty)}{\rho U_{ref}^2}$

- spanwise vorticity

- velocity vectors

The unsteady flow can be presented in terms of the distribution of these properties over the flowfield at different instant during the cycle. A result at every 1/8 of the period appears to capture the main features of the flowfield (Figure 15). An uneven distribution of flowfield representations at time values more representative of changes in the flow features may also be used. For instance, it may be of interest to have flowfields at the 8 time values of Figure 12 (a to h).



a) T e) T+T/2

b) T+T/8 f) T+5T/8

c) T+T/4 g) T+3T/4

d) T+3T/8 h) T+7T/8

Figure 15: Total pressure field at 8 time values during a cycle

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4 References

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[3] Zdunich, P., "Development and Application of a 3D Vortex Panel Model With Leading Edge Separation Suitable for Hovering Flapping-Wing Flight", DRDC Valcartier CR 2010-124, April 2010

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The Aero-NAV TIF project at DRDC Valcartier investigated flapping wing aerodynamics for NAV applications. Tools and capabilities were developed by combining high-accuracy predictions and experimentations with engineering modelling. This Technical Note describes the data presentation considered and used for the Aero-NAV project. Because of the complex flapping wing motion, there are many ways of presenting the results. Therefore, throughout the project, it was important to have a consistent method in the presentation of the results.

Le projet FIT Aero-NAV à RDDC Valcartier a étudié l'aérodynamique du battement d'aile pour des applications aux nano-drones. On a développé des outils et des capacités en combinant des prédictions et des expérimentations de haute précision avec la modélisation d'ingénierie. Cette note technique décrit la présentation des données qui a été considérée et utilisée pendant le projet Aero-NAV. À cause du mouvement complexe du battement d'aile, il y a plusieurs façons de présenter les résultats. Ainsi, pendant le projet, il est important d'avoir une méthode consistante pour la présentation des résultats.

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