CALCULATION OF THE AERODYNAMIC FORCES ON AN MICRO AIR VEHICLE IN FORWARD FLAPPING FLIGHT 2014

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Flapping-wing micro air vehicles (MAVs) are small size flying vehicles, that are designed for inspection of confined spaces such as buildings, tunnels, shafts and so on. Another kind of missions the MAVs can undertake are the outdoors, urban reconnaissance in dangerous environments such as contaminated areas, because the fixed wing vehicles are too fast to fly among the buildings. These purposes require some peculiarities of which one can mention their capability of low speed flying and hovering, high manoeuvrability and stability.

“DelFly”, Delft University of Technology
Agenda

Objectives (main)

» Theoretical approach (Aerodynamics and Mechanics of flapping flight)
» Experimental approach
» Wing and mechanism design
Main Objective

To provide a method of calculation of the aerodynamic forces and moments on a MAV performing a straight avian-type flight.

Example: ’Micro-bat”, University of California
Theoretical Approach

Aerodynamics of flapping wings
- Engineering models
  (similar to “blade element” theory)
- Aerodynamic modeling
  - Potential modeling
  - CFD (Navier-Stokes equations)

Mechanics of the flapping mechanism
Mechanics of flight

Experimental Approach
Design Model:

Simplified insect thorax
Experimental approach

Experimental mechanism

Contract 113 “FLAWIAS”/2007
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Characteristic size and mass of the MAV

$b \approx 8 \text{ cm}, m < 30 \text{ g}$

Flapping frequency

$f > 10 \text{ Hz}$
Mechanism design

Designer: eng. Mihai DUMBRAVA
Mechanism design - detail
The Mechanism
The Flapper Mechanism
Theoretical Approach

Flapping Wing Aerodynamics
(using potential flow approximation)
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\[
\begin{align*}
\frac{1}{8\pi} \int_{(W_0)} K_0(x, y, z; \xi, \eta, \zeta; M) p_0^*(\xi, \eta, \zeta) dS &= w_0(x, y, z) \quad (I) \\
\frac{1}{8\pi} \int_{(W_0)} K_1(x, y, z; \xi, \eta, \zeta; M; k) p_1^*(\xi, \eta, \zeta) dS &= w_1(x, y, z; k) \quad (II)
\end{align*}
\]

\[
(x, y, z) \in (W_0), \quad (\xi, \eta, \zeta) \in (W_0)
\]

\[
k = \frac{\omega l_{ref}}{U_\infty} \quad \text{The reduced frequency}
\]
\[ w_0 = -n_{0x} \quad \text{Steady flow normalwash} \]
\[ w_1 = -n_{1x} + ik\tilde{O}_1\tilde{n}_0 \quad \text{Oscillatory flow normalwash} \]

**Negative frequency. Conjugate of the integral equation**

\[ w_1(x, y, z; -k) = \overline{w}_1(x, y, z; k) \]
\[ K_1(x, y, \ldots; -k) = \overline{K}_1(x, y, \ldots; k) \]

\[
\begin{aligned}
\begin{cases}
  w_1(x, y, z; k) = \frac{1}{8\pi} \int K_1 \cdot p_1^* dS \\
  \overline{w}_1(x, y, z; k) = \frac{1}{8\pi} \int \overline{K}_1 \cdot \overline{p}_1^* dS
\end{cases}
\end{aligned}
\]
Methods of Solving the integral equations

- **DLM**
- **Akamatsu-Dat**

References


[5] Y. Akamatsu R. Dat, Calcul, par la méthode du potentiel, des forces instationnaires agissant sur un ensemble de surfaces portantes. (Calculation of the instationary forces which are effective on a ensemble of airfoils with the potential method). (French), Recherche Aerosp. pp 283-295,1971
Consequences

• Harmonic oscillation

\[ \tilde{O}_c(\lambda, s, t) = l \cdot \tilde{\sigma}(\lambda, s) \cos \omega \cdot t \]

\[ \tilde{O}_c(\lambda, s, t) = l \cdot \text{Re}[\tilde{\sigma}(\lambda, s) \cdot e^{\omega \cdot t}] = \frac{1}{2} l \cdot \tilde{\sigma}(\lambda, s)(e^{\omega \cdot t} + e^{-\omega \cdot t}) \]

\[
\begin{align*}
O_+(\lambda, s, t) &= \frac{1}{2} l \cdot \tilde{\sigma}(\lambda, s, t)e^{i\omega t} \\
O_-(\lambda, s, t) &= \frac{1}{2} l \cdot \tilde{\sigma}(\lambda, s, t)e^{-i\omega t}
\end{align*}
\]

\[
\begin{align*}
P_+(\lambda, s, t) &= p^* e^{i\omega t} \\
P_-(\lambda, s, t) &= \overline{p}^* e^{-i\omega t} = \overline{p}^* e^{-i\omega t} = p^* e^{i\omega t} = \overline{P}_+(\lambda, s, t)
\end{align*}
\]

\[ P_c(\lambda, s, t) = 2\left[\text{Re}\left(p^*\right)\cos \omega \cdot t - \text{Im}\left(p^*\right)\sin \omega \cdot t\right] \]
• General periodic oscillation

\[ \tilde{O}(\lambda, s, t) = l \cdot \tilde{o}(\lambda, s) q(t) \]  
where \( q(t) = q(t+T) \)

\[ q(t) = q_0 \cdot \left[ \frac{a_0}{2} + \sum_{n=1}^{N} \left( a_n \cos \frac{2\pi}{T} nt + b_n \sin \frac{2\pi}{T} nt \right) \right] = q_0 \cdot \sum_{n=-N}^{N} c_n e^{i \omega_n t} = q_0 \sum_{n=-N}^{N} c_n e^{i \omega_n t} \]

\( q_0 \) is the amplitude of the oscillation; 
\( a_0, a_n, b_n \) and \( c_n \) are the Fourier series coefficients

\[ \omega_n = \frac{2\pi}{T} n, \ n \in \{-N, N\} \]

\[ P(\lambda, s, t) = 2 \sum_{n=1}^{N} \left[ \text{Re}(c_n \cdot p^{*(n)}) \cos \omega_n t - \text{Im}(c_n \cdot p^{*(n)}) \sin \omega_n t \right] + p_0^* \]
• Case when $q(t)$ can be expressed as a Fourier integral

Wing displacement

$$\tilde{O}(\lambda, s, t) = l \cdot \tilde{o}(\lambda, s) q(t)$$

Then

$$q(t) = \frac{1}{2\pi} \int_{-\infty}^{\infty} d\omega \cdot \int_{-\infty}^{\infty} q(\tau) e^{i\omega(t-\tau)} d\tau$$

Separate the Fourier transform of $q(t)$ and its inverse

$$\hat{q}(\omega) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} q(\tau) e^{-i\omega \tau} d\tau \quad q(t) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} \hat{q}(\omega) e^{i\omega t} d\omega$$

The normalwash

$$\bar{w}_1(\lambda, s; t) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} \hat{q}(\omega) \tilde{w}_{osc}(\lambda, s; \omega) e^{i\omega t} d\omega$$

where

$$\tilde{w}_{osc}(\lambda, s; \omega) = -n_{1x}(\lambda, s) + i \frac{\omega \cdot l}{U_\infty} [\tilde{o}(\lambda, s) \cdot \tilde{n}_0(\lambda, s)]$$
Then

\[ p_1^*(\lambda, s; t) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\infty} \hat{q}(\omega) \hat{p}_1^*(\lambda, s; \omega) e^{i\omega t} d\omega \]

### Numerical Example

Consider a rectangular wing \((c=1\text{m}, b=3\text{m})\). The wind speed is \((M = 0.147)\).

Consider a **pitching motion:**

\[
\begin{align*}
q(t) &= 1.5 \quad (t = -1, 0, 1) \\
\end{align*}
\]

\[
\begin{align*}
CL_{rezul_{in}} &= 2 \\
CL_{rezull_{in}} &= 1.611 \\
\end{align*}
\]
Symmetric Flapping and Pitching

The two flapping wings at rest; at $x_{ac}=0.25c$ are the pitching hinges

$$
\begin{align*}
    z_1(y, t) &= A_f \frac{|y|}{s} \cos \omega t \\
    z_2(x, t) &= A_p \frac{x - x_{ac}}{l_{ref}} b_p(t)
\end{align*}
$$

$$
b_p(t) \approx 1.25 \sin \omega_1 t + 0.3829 \sin \omega_3 t + 0.2213 \sin \omega_5 t + 0.1543 \sin \omega_7 t;
$$

$$
\omega_p = \frac{2\pi}{T} p, \quad T = 0.1s, \quad p = 1; 3; 5; 7
$$
The time functions for flapping ($b_f(t) = \cos \omega t$) and pitching modes ($b_p(t)$); the pitching mode is approximated by a Fourier series with 7 terms.

**DLM code used:**

$NC = 10$ boxes in chord and $NS = 15$ boxes in span and $k_p = 0.157; 0.471; 0.785; 1.1$. 
Spanwise load due to flapping mode, $A_f=1$, $A_p=1$

Spanwise load due to pitching mode, $A_p=1$
Global force normal to the wings, $A_f=1$, $A_p=1$
CONCLUSIONS

1. This is the first step towards the study of the aerodynamics of the flapping wings. There are several parts of the problem to be clarified. For example, we mention the suction force and wing induced drag, inviscid induced power and viscous power.

2. The forces and moments that are calculated with the present method can be expressed in closed forms. This is a great advantage over the pure numerical methods.
THANK YOU!