IC1301 -WiPE

Wireless Power Transmission for Sustainable Electronics

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

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COST IC1301

European Science Foundation

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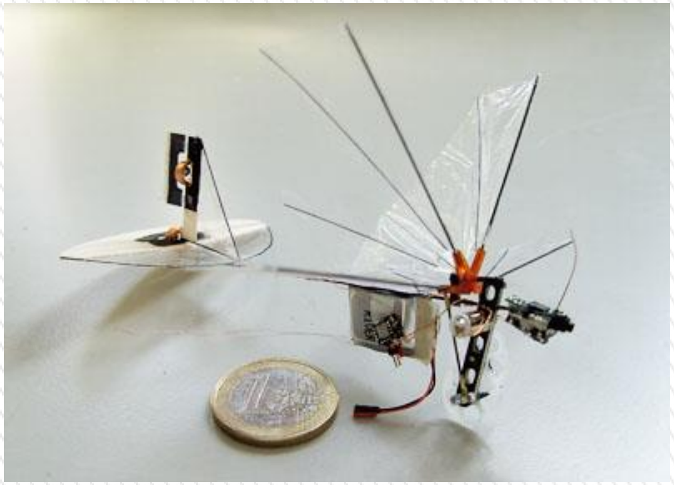
Flapping- wing **m**icro **a**ir **v**ehicles (MAVs) are small size flying vehicles, that are designed for inspection of confined spaces such as buildings, tunnels, shafts and so on. Another kind of missions the MAVs can undertake are the outdoors, urban reconnaissance in dangerous environments such 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*

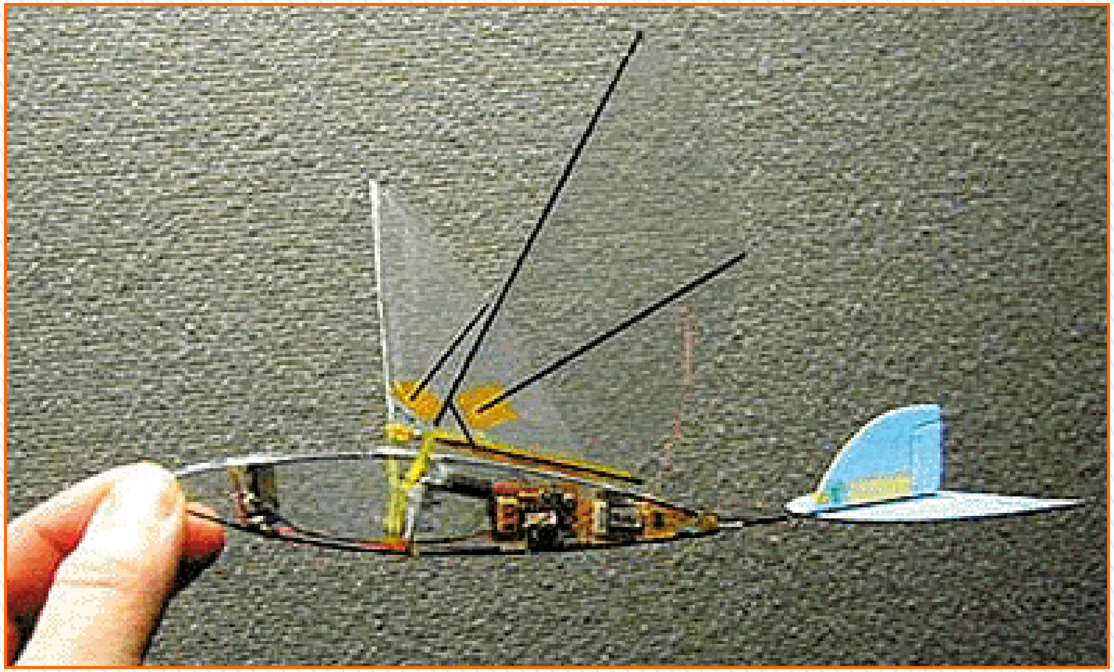
Agenda

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

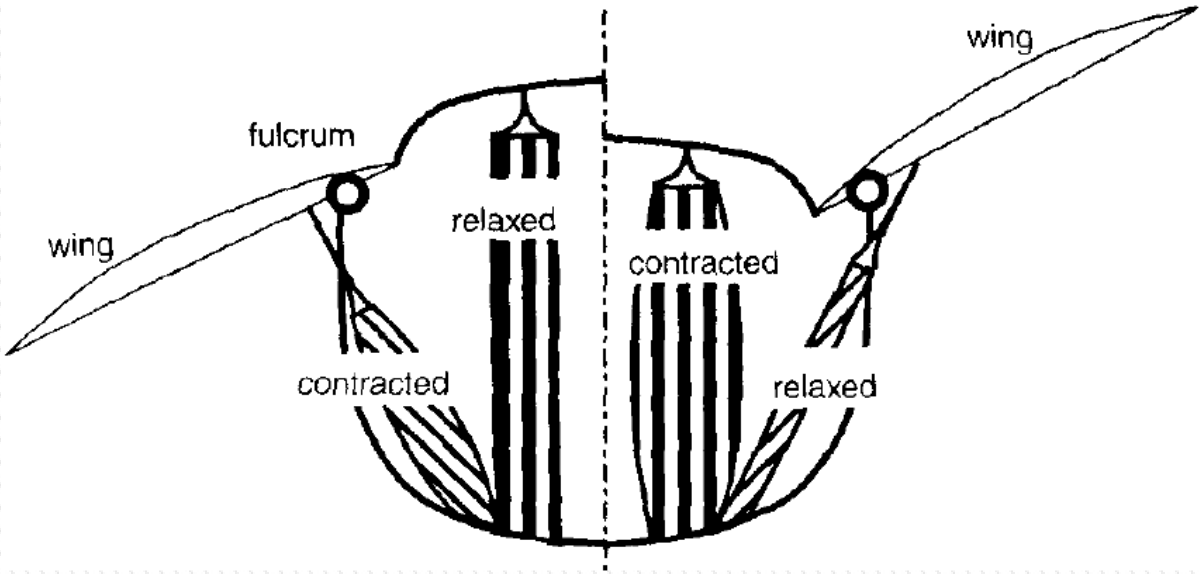
Mechanics of flight

Experimental Approach

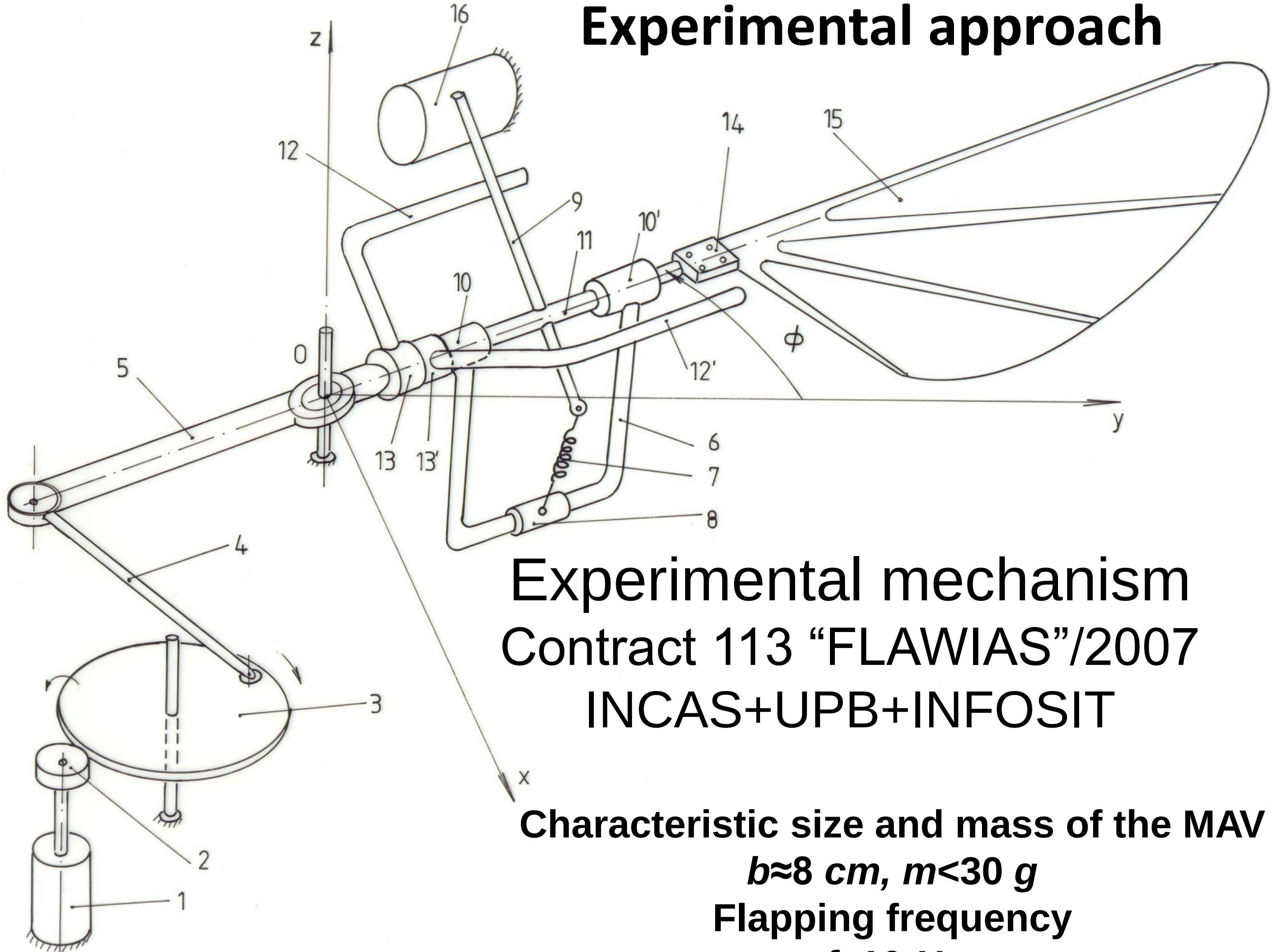
cost

Design Model:

Simplified insect thorax



Experimental approach



Experimental mechanism

Contract 113 “FLAWIAS”/2007

INCAS+UPB+INFOSIT

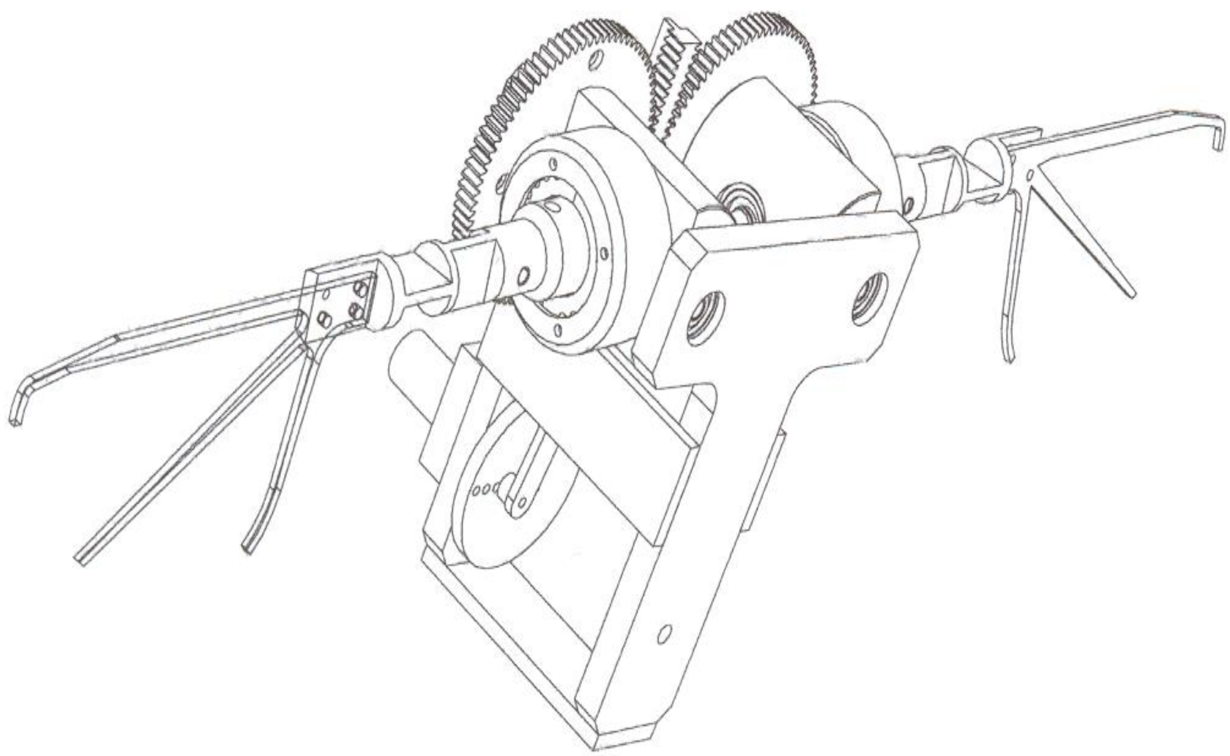
Characteristic size and mass of the MAV

b*≈8 *cm*, *m*<30 *g

Flapping frequency

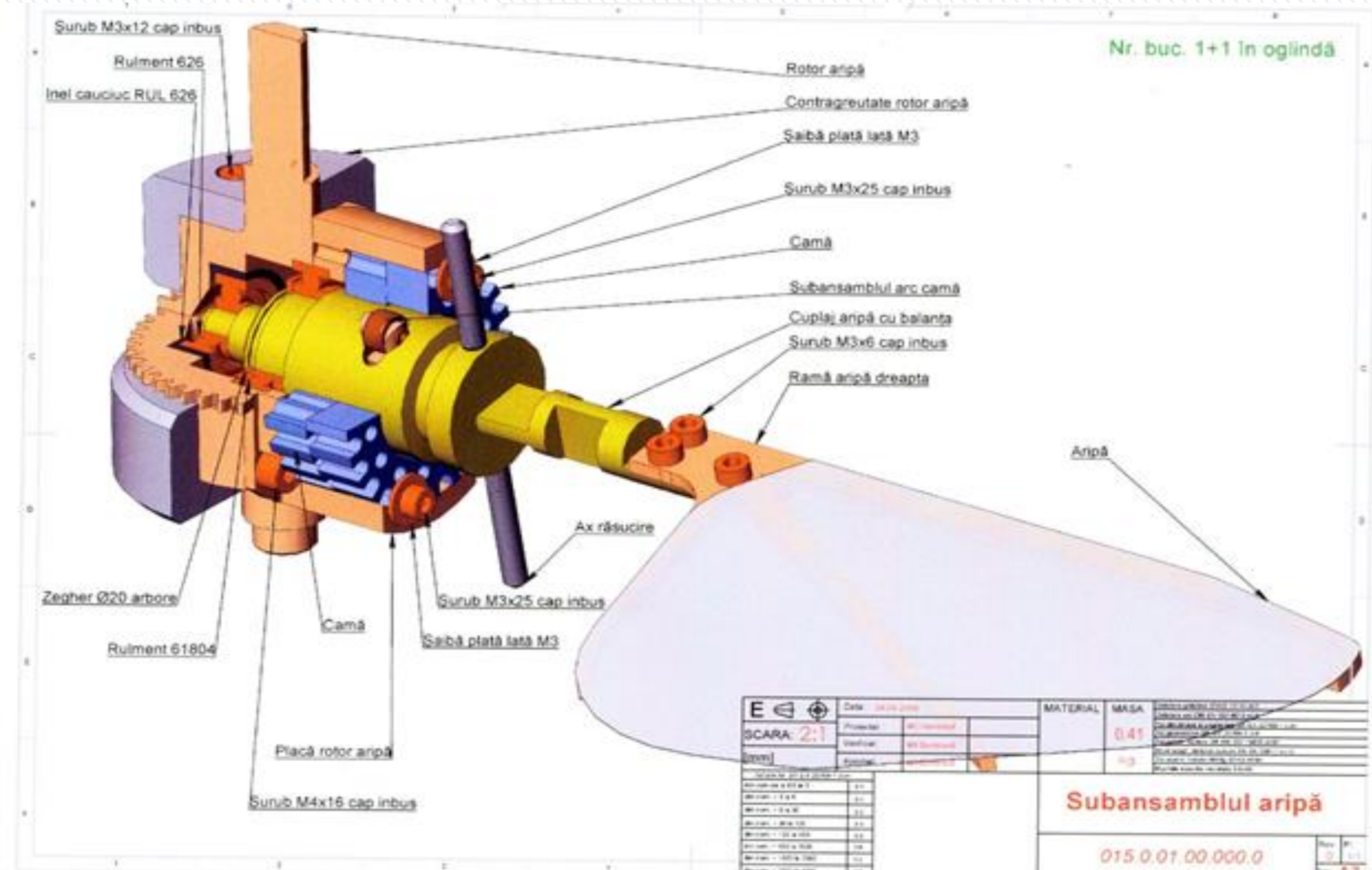
f*>10 *Hz

Mechanism design



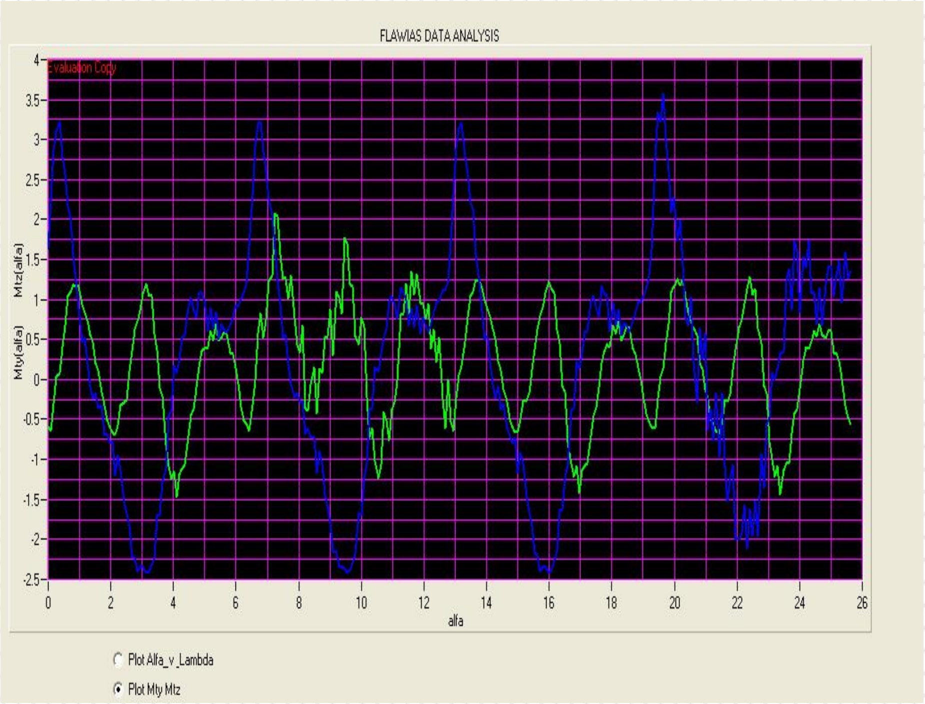
Designer: eng. Mihai DUMBRAVA

Mechanism design- detail



The Mechanism

The Flapper Mechanism



Theoretical Approach

Flapping Wing Aerodynamics
(using potential flow approximation)

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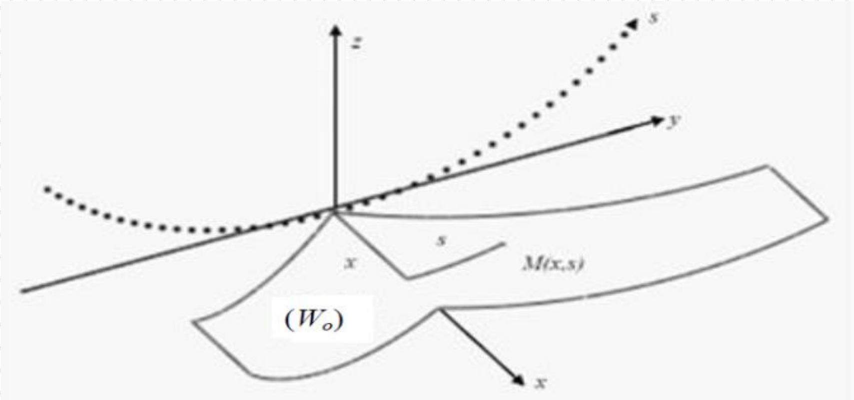


$$
\begin{cases}
\frac{1}{8\pi} \int\limits_{(W_0)} K_0(x, y, z; \xi, \eta, \zeta; M \quad) p_0^*(\xi, \eta, \zeta) dS = w_0(x, y, z) & \text{(I)} \\
\frac{1}{8\pi} \int\limits_{(W_0)} K_1(x, y, z; \xi, \eta, \zeta; M; k) p_1^*(\xi, \eta, \zeta) dS = w_1(x, y, z; k) & \text{(II)}
\end{cases}
$$

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

$$
k = \frac{\omega l_{ref}}{U_\infty}
$$

The reduced frequency

$$w_0 = -n_{0x}$$

Steady flow normalwash

$$w_1 = -n_{1x} + ik\vec{O}_1\vec{n}_0$$

Oscillatory flow normalwash

Negative frequency. Conjugate of the integral equation

$$w_1(x, y, z; -k) = \overline{w}_1(x, y, z; k)$$

$$K_1(x, y, \ldots; -k) = \overline{K}_1(x, y, \ldots; k)$$

$$\begin{cases} w_1(x, y, z; k) = \frac{1}{8\pi} \int\limits_{(W_0)} K_1 \cdot p_1^* dS \\ \overline{w}_1(x, y, z; k) = \frac{1}{8\pi} \int\limits_{(W_0)} \overline{K}_1 \cdot \overline{p}_1^* dS \end{cases}$$

Methods of Solving the integral equations

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

References

[1] W. P. Rodden, P. Taylor, S. C. McIntosh, Jr., *Improvements to the Doublet-Lattice Method in MSC/NASTRAN*, 2012.

[2] L.H. van Zyl, Robustness of the Subsonic Doublet Lattice Method, *The Aeronautical Journal*, May 2003, pp 257-262.

[4] J. P. Giesing, T. P. Kalman and W. P. Rodden, Subsonic Steady and Oscillating Aerodynamics for Multiple Interfering Wings, *Journal of Aircraft* , Vol. **9** , No. 10 , Oct., pp 693-702, 1972.

[3] R. Dat, La theorie de la surface portante appliquee a l'aile fixe et a l'helice, *Rech. Aerosp.*, No 4, Juillet - Aout 1973

[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**

$$\vec{O}_c(\lambda, s, t) = l \cdot \vec{o}(\lambda, s) \cos\omega \cdot t$$

$$\vec{O}_c(\lambda, s, t) = l \cdot \mathrm{Re}\left[\vec{o}(\lambda, s) \cdot e^{\omega \cdot t}\right] = \tfrac{1}{2} l \cdot \vec{o}(\lambda, s)\left(e^{\omega \cdot t} + e^{-\omega \cdot t}\right)$$

$$\begin{cases} O_+(\lambda, s, t) = \tfrac{1}{2} l \cdot \vec{o}(\lambda, s, t) e^{i\omega t} \\ O_-(\lambda, s, t) = \tfrac{1}{2} l \cdot \vec{o}(\lambda, s, t) e^{-i\omega t} \end{cases} \qquad \begin{cases} w_+ = n_{1x} + ik \cdot \tfrac{1}{2} \vec{o} \cdot \vec{n}_0 = w \\ w_- = n_{1x} - ik \cdot \tfrac{1}{2} \vec{o} \cdot \vec{n}_0 = \overline{w} \end{cases}$$

$$\begin{cases} P_+(\lambda, s, t) = p^* e^{i\omega t} \\ P_-(\lambda, s, t) = \overline{p}^* e^{-i\omega t} = \overline{p}^* e^{-i\omega t} = \overline{p^* e^{i\omega t}} = \overline{P_+(\lambda, s, t)} \end{cases}$$

$$P_c(\lambda, s, t) = 2\left[\mathrm{Re}\left(p^*\right) \cos\omega \cdot t - \mathrm{Im}\left(p^*\right) \sin\omega \cdot t\right]$$

- **General periodic oscillation**

$$\vec{O}(\lambda, s, t) = l \cdot \vec{o}(\lambda, s) q(t) \qquad \textit{where } q(t) = q(t+T)$$

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

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

$$\omega_n = \frac{2\pi}{T} n, \;\; n \in \{-N, N\}$$

$$P(\lambda, s, t) = 2 \sum_{n=1}^{N} \left[\mathrm{Re}\left(c_n \cdot p^{*(n)}\right) \cos \omega_n t - \mathrm{Im}\left(c_n \cdot p^{*(n)}\right) \sin \omega_n t \right] + p_0^*$$

- **Case when *q(t)* can be expressed as a Fourier integral**

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

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

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

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

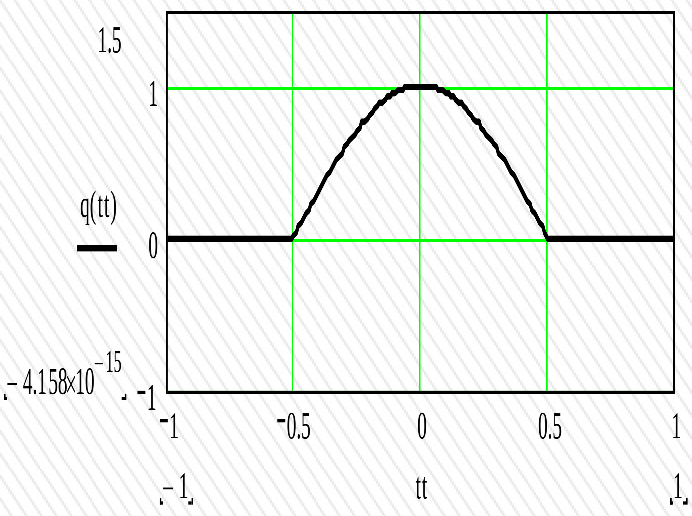
where $$\tilde{w}_{osc}(\lambda, s; \omega) = -n_{1x}(\lambda, s) + i \frac{\omega \cdot l}{U_\infty} [\vec{o}(\lambda, s) \cdot \vec{n}_0(\lambda, s)]$$

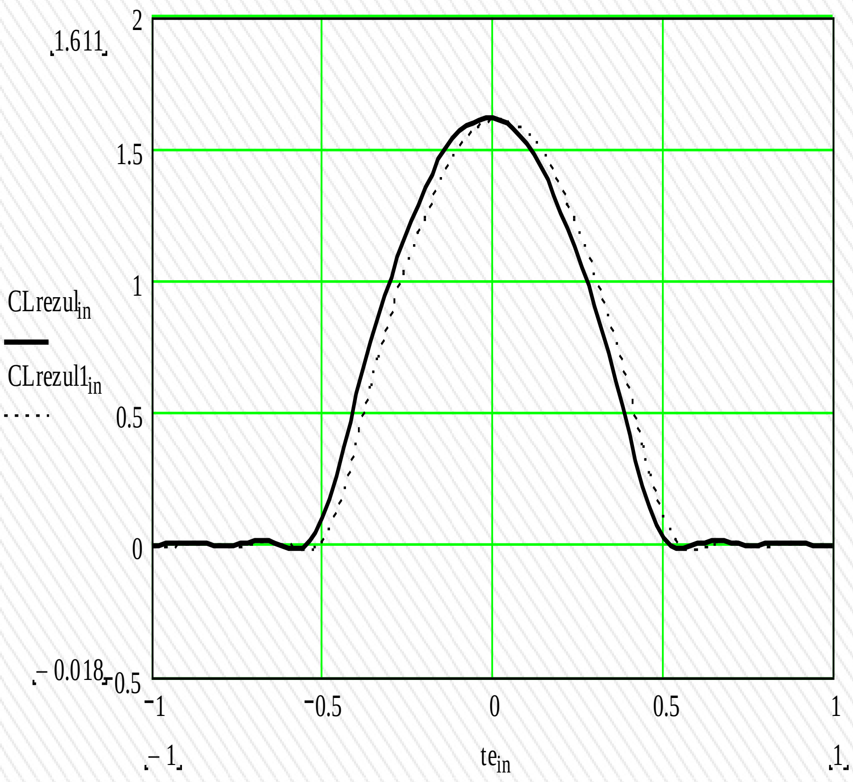
Then $$p_1^*(\lambda,s;t)=\frac{1}{\sqrt{2\pi}}\int_{-\infty}^{\infty}\hat{q}(\omega)\tilde{p}_1^*(\lambda,s;\omega)e^{i\omega t}d\omega$$

Numerical Example

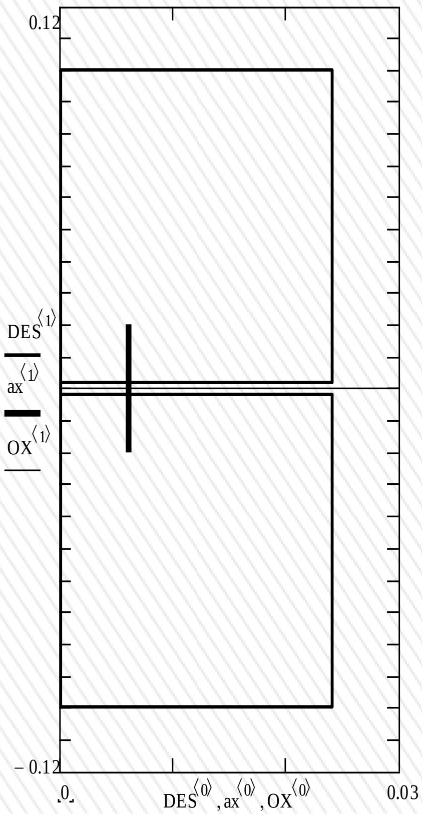
Consider a rectangular wing (c=1m, b=3m).
The wind speed is (M = 0.147).

Consider a **pitching motion:**





Symmetric Flapping and Pitching

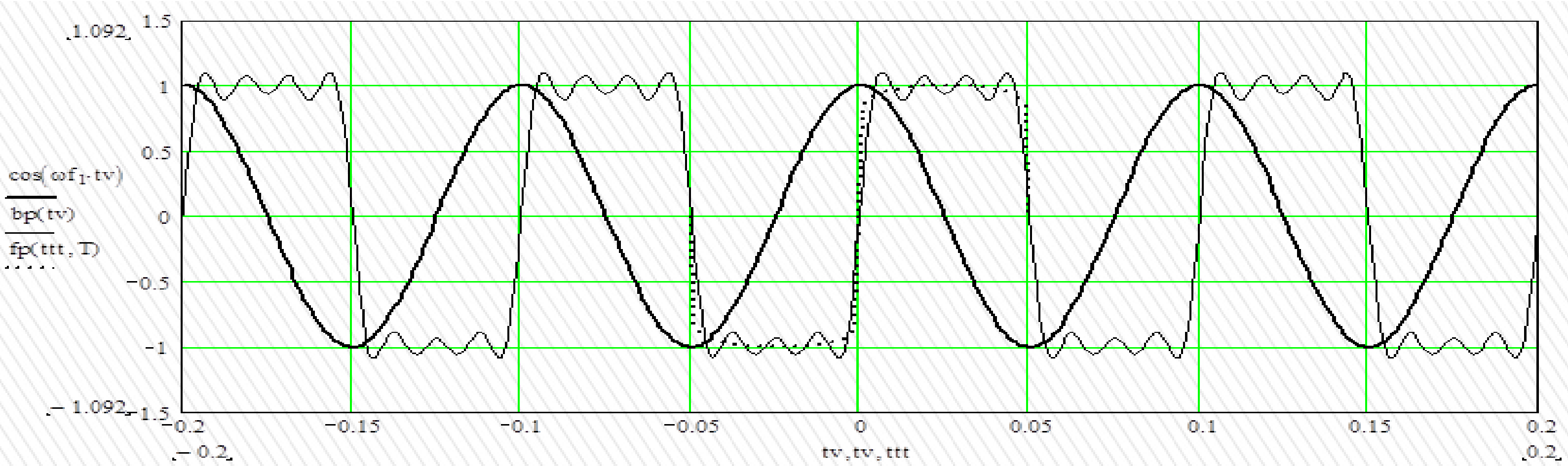


The two flapping wings at rest; at x_{ac}=0.25c are the pitching hinges

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

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

$$\omega_p = \frac{2\pi}{T} p, \qquad T = 0.1s, \qquad p = 1;3;5;7$$

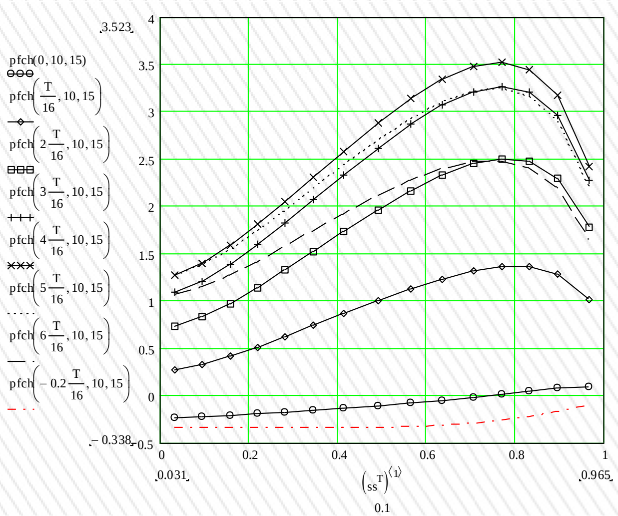


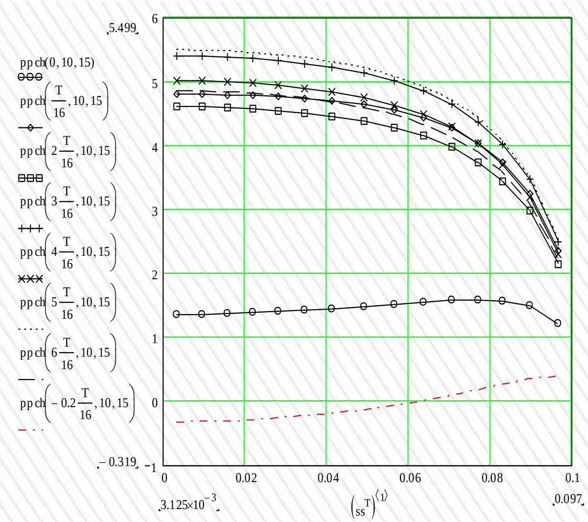
The time functions for flapping ($b_f(t)=\cos\omega t$) and pitching modes ($b_p(t)$); the pitching mode is approximated by a Fourier series with 7 terms

DLM code used:

NC = 10 boxes in chord and *NS*=15 boxes in span and

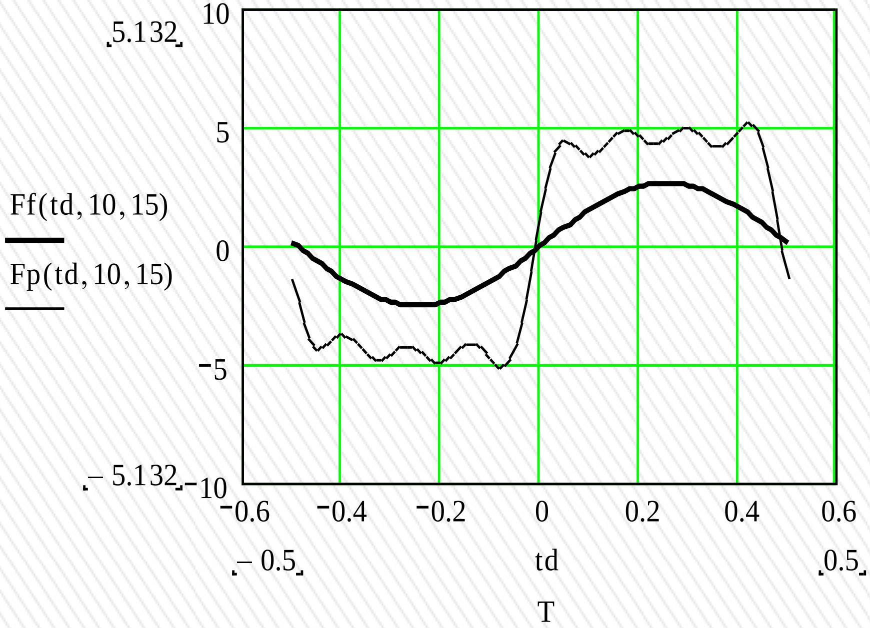
k_p = 0.157; 0.471; 0.785; 1.1.





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!

INCAS