CONSIDERATIONS UPON THE SYMMETRICAL HORIZONTAL FLIGHT OF A FLAPPING-WING MICRO AIR VEHICLE

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Se determină valorile instantanee, precum şi cele mediate pe durata unei perioade, ale forței de sustentație, respectiv ale celei de tracțiune, în zborul simetric al unui microvehicul aerian cu aripi batante (MVAB). Metodele de studiu abordate sunt aplicate pe un model simplificat, dar au caracter general, permițând, fără modificări de principiu, adoptarea unor modele aerodinamice perfecționate.

The instantaneous values and the time-averaged values, respectively, are determined for the lift force and thrust generated during symmetrical horizontal flight of a flapping-wing micro air vehicle (FWMAV). The study methods are applied on a simplified but general model, which can be used, without fundamental modifications, on more elaborated aerodynamical models.

Keywords: flapping-wing, micro air vehicle.

1. Introduction

Micro air vehicles (MAV) are small size flight apparatuses designed to work in closed space (such as in the interior of buildings or tunnels etc.), as well as in open space, in high risk environment (war zones, polluted or contaminated terrains etc.).

Advantages of this type of apparatuses (low cost, operation without threat of human life or health, reduced losses in case of accidents etc.) have attracted in U. S. A. the involvement of governmental organizations. Thus, Defense Advanced Research Projects Agency (DARPA) has launched since 1996 a program intended to create a MAV with maximum dimensions of 15.2 cm, capable to transport payloads, and in 2005 a more ambitious one, aiming to develop a vehicle of maximum 7.5 cm, weighing at most 10g, capable of flying with 5-10 m/s, up to 1000 m altitude [4].

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Special characteristics of MAV flight (3-D flows, at low Reynolds numbers, with predominance of unsteady phenomena) [5] need new study methods in aerodynamics and in flight mechanics, but the present-day multiple and diverse achievements world-wide are encouraging and motivate further research activities in the field. Some of the most notable achievements are presented in [6].

Existing MAVs are grouped into three types, which differ by the constructive solution, by performances, as well as by the theoretical knowledge level of the involved mechanical and aerodynamical phenomena [3].

The first type, of the fixed-wing apparatuses, is the most developed, but it has the major disadvantage of not being able to hover or to operate at low velocities.

This disadvantage is eluded by the second type, the rotary-wing MAVs, which, on the other hand, are inefficient from the point of view of flight autonomy, are vulnerable to external perturbations, such as wing gusts, and are slow in response [9].

In the last years, the third type, less studied, of flapping-wing micro air vehicles (FWMAV) arouses increasing interest for solutions, inspired from the kinematical analysis of bird and insect wings [10].

The paper presents some original results obtained by a research team, joining specialists from the National Institute for Aerospace Research "Elie Carafoli" - I.N.C.A.S. Bucharest and professors from the Department of Mechanics at the University “Politehnica” of Bucharest, Romania. The team aims to design from the aerodynamics, as well as from the flight mechanics and dynamics point of view, a FWMAV, with the wing span of 250 mm or less. Other achievements of the team, in the same field, have been published in reference [1].

The instantaneous values and the time-averaged values, respectively, are determined for the lift force and thrust generated during symmetrical horizontal flight of a FWMAV.

The study methods are applied on a simplified but general model, which can be used, without fundamental modifications, on more elaborated aerodynamical models, developed as new theoretical and experimental data become available.

2. Model of the studied system

The motions of the FWMAV and of its right wing are studied with respect to the following reference systems:

- I ($O_IX_IY_IZ_I$), fixed (Fig. 1);
- I' ($CX'_IY'_IZ'_I$), translated with respect to the fixed one, with the origin in the mass center C of the vehicle (Fig. 1);

- b ($Cx_by_bz_b$), connected to the body of the apparatus, with the origin in the mass center C of the vehicle (Fig. 1);
- b' ($O_wx_{'b}y_{'b}z_{'b}$), connected to the body of the apparatus, translated with respect to system b, with the origin in the spherical joint O_w of the right wing (Fig. 2);
- S ($O_wx_Sy_Sz_S$), of the stroke plane of the right wing, also connected to the body of the apparatus, with the origin in the spherical joint O_w of the right wing, but rotated with respect to system b'(Fig. 2-3); plane $O_wx_Sy_S$ is called stroke plane;
- w ($O_wx_wy_wz_w$), connected to the right wing, with the origin in O_w (Fig. 3).

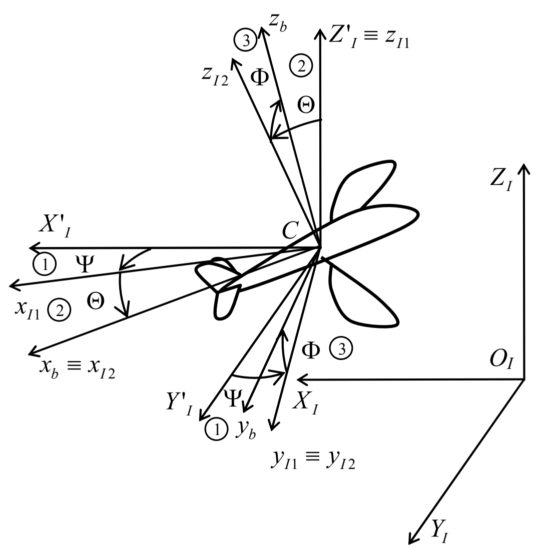


Fig. 1. *I*, *I*' and *b* reference systems

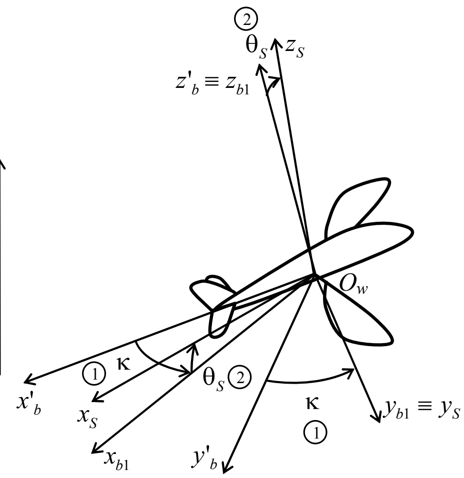


Fig. 2. *b*' and *S* reference systems

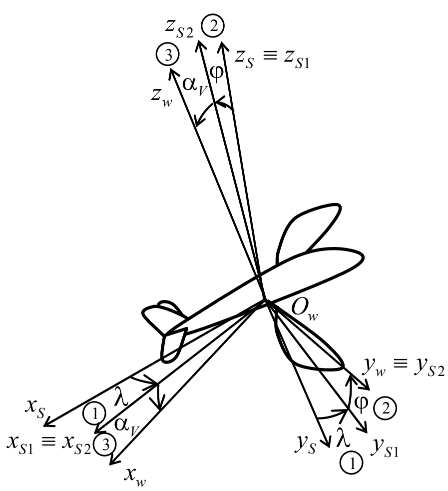


Fig. 3. *S* and *w* reference systems

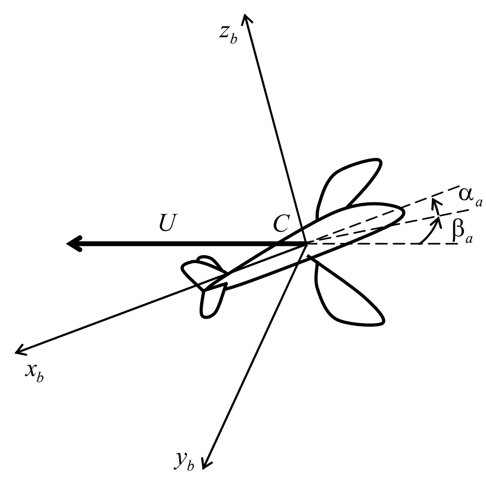


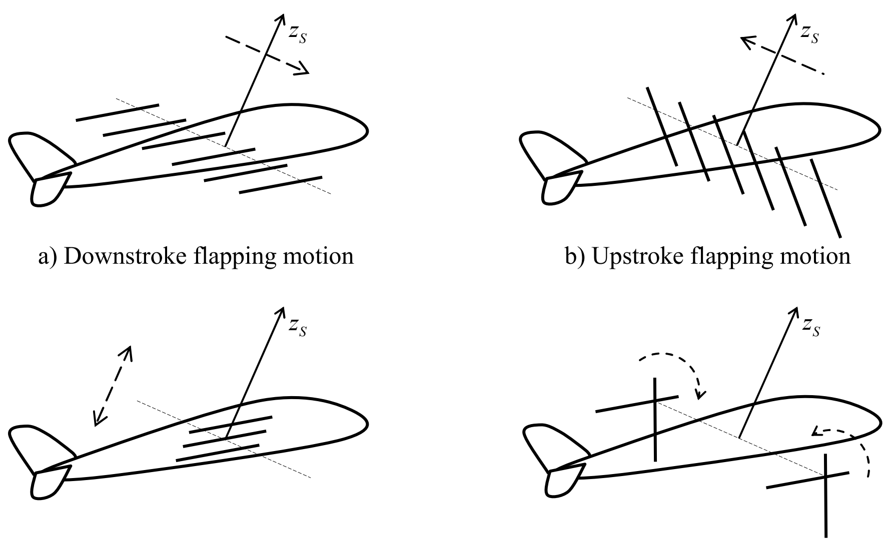
Fig. 4. Angle of incidence and angle of side-slip

The orientation of the velocity vector $\overline{U}$, of the unperturbed air flow, opposite to the velocity vector of the vehicle with respect to the air (Fig. 4), is defined by the angles

- of incidence of the apparatus, α_a;
- of side-slip of the apparatus, β_a, considered null in the present paper, since only symmetrical motions are studied.

The motion of the wing with respect to the body of the apparatus (relative to the stroke plane reference system – Fig. 3) is of a rigid body with a fixed point (O_w) and represents the result of the composition of three oscillating rotations:

- flapping, in the stroke plane $O_w x_S y_S$, with the angle λ (Fig. 5 a, b); this motion provides the velocity of the wing plane with respect to the air, in order to produce the aerodynamical force;
- lagging, about the axis $O_w x_{S1}$, with the angle φ (Fig. 5 c);
- feathering, about the longitudinal axis of the wing $O_w y_w$, with the angle α_V (Fig. 5 d); this motion takes place at the ends of the flapping motion, in order to modify the angle of incidence of the wing, in correspondence with the resulted sense reversal; at the same time, feathering produces unsteady phenomena which amplifies the aerodynamical force [3].



a) Downstroke flapping motion b) Upstroke flapping motion

c) Lagging motion d) Feathering motion

Fig. 5. Rotations of the wing with respect to the vehicle body

Flapping and feathering are the main contributors to the generation of the aerodynamical forces, which is reflected in the flapping wing model of most insects, based exclusively on these two motions [7], [10]. As a consequence, the lagging, less important for producing aerodynamical forces, is ignored in the present paper.

The transformation of the components of an arbitrary vector $\bar{v}$, from a reference system, *i*, to a rotated one, *j*, is made by means of the rotation matrix $[T]_{ij}$, according to formula [8]

$$\{v\}_i = [T]_{ij}\{v\}_j . \tag{1}$$

For the systems presented above, the rotation matrices are:

– from system *I* or *I'*, to system *b* (Fig. 1),

$$[T]_{Ib}=\begin{bmatrix} \cos\Psi\cos\Theta & \cos\Psi\sin\Phi\sin\Theta-\cos\Phi\sin\Psi & \sin\Phi\sin\Psi+\cos\Phi\cos\Psi\sin\Theta \\ \cos\Theta\sin\Psi & \cos\Phi\cos\Psi+\sin\Phi\sin\Psi\sin\Theta & \cos\Phi\sin\Psi\sin\Theta-\cos\Psi\sin\Phi \\ -\sin\Theta & \cos\Theta\sin\Phi & \cos\Phi\cos\Theta \end{bmatrix}; \tag{2}$$

– from system *b* or *b'*, to system *S* (Fig. 2),

$$[T]_{bS}=\begin{bmatrix} \cos\kappa\cos\theta_S & -\sin\kappa & -\cos\kappa\sin\theta_S \\ \sin\kappa\cos\theta_S & \cos\kappa & -\sin\kappa\sin\theta_S \\ \sin\theta_S & 0 & \cos\theta_S \end{bmatrix}; \tag{3}$$

– from system *S*, to system *w* (Fig. 3),

$$[T]_{Sw}=\begin{bmatrix} \cos\lambda\cos\alpha_V-\sin\varphi\sin\lambda\sin\alpha_V & -\cos\varphi\sin\lambda & \cos\lambda\sin\alpha_V+\sin\varphi\sin\lambda\cos\alpha_V \\ \sin\lambda\cos\alpha_V+\cos\lambda\sin\varphi\sin\alpha_V & \cos\varphi\cos\lambda & \sin\lambda\sin\alpha_V-\cos\lambda\sin\varphi\cos\alpha_V \\ -\cos\varphi\sin\alpha_V & \sin\varphi & \cos\varphi\cos\alpha_V \end{bmatrix}. \tag{4}$$

In order to determine the angular velocity vector, the following matrix is also used:

$$[T]_{S_1w}=\begin{bmatrix} \cos\alpha_V & 0 & \sin\alpha_V \\ \sin\varphi\sin\alpha_V & \cos\varphi & -\sin\varphi\cos\alpha_V \\ -\cos\varphi\sin\alpha_V & \sin\varphi & \cos\varphi\cos\alpha_V \end{bmatrix}. \tag{5}$$

Vector $\bar{U}$ is expressed with respect to the body reference system by matrix

$$\{U\}_b=\begin{Bmatrix} U\cos\alpha_a\cos\beta_a \\ -U\sin\beta_a \\ U\sin\alpha_a\cos\beta_a \end{Bmatrix}=\begin{Bmatrix} U\cos\alpha_a \\ 0 \\ U\sin\alpha_a \end{Bmatrix}. \tag{6}$$

With respect to the wing reference system, this vector takes the form

$$\{U\}_w=[T]_{wb}\{U\}_b=[T]_{wS}[T]_{Sb}\{U\}_b=[T]_{Sw}^T[T]_{bS}^T\{U\}_b . \tag{7}$$

The following simplifying hypotheses are used:

– the aerodynamical characteristics of the FWMAV are described by simplified curves;

– the drag and the lift of the fuselage were neglected;

– the aerodynamical and mechanical effects generated by the oscillation of the components about the mass center of the apparatus were neglected;

– the effect of the variation of the local angle of incidence along the span of the wing was neglected; computations are made in a conventional point.

The simplified variation laws of the aerodynamical coefficients of the wing C_L and C_D, respectively, with the local angle of incidence α are shown in Figures 6-7.

The lift coefficient is

$$C_L = \begin{cases} C_{L\alpha}\alpha, & \text{if } |\alpha| \le \pi/2 \\ C_{L\alpha}(\alpha-\pi) & \text{if } \alpha > \pi/2 \\ C_{L\alpha}(\alpha+\pi) & \text{if } \alpha < -\pi/2. \end{cases} \quad (8)$$

The horizontal lines of the graph result by truncation to the value taken for the angle of incidence of 50°.

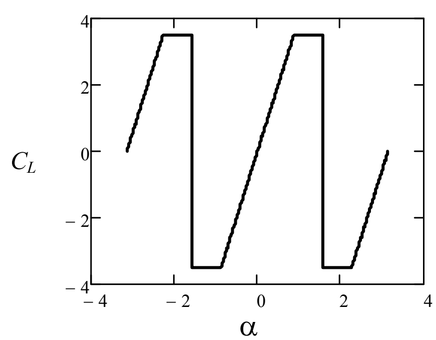


Fig. 6. Lift coefficient

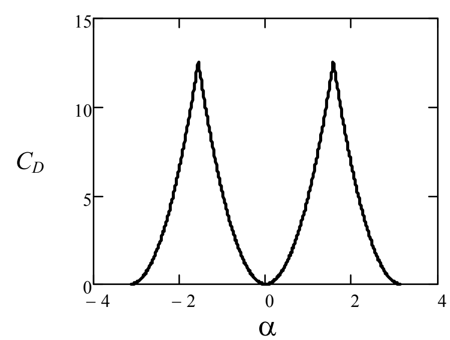


Fig. 7. Drag coefficient

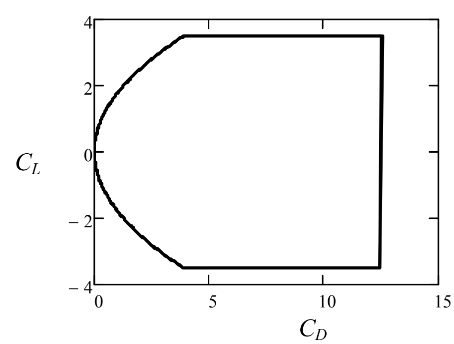


Fig. 8. Wing polar

By introducing the factor

$$\Lambda = \frac{b^2}{S}, \quad (9)$$

where b is the span of the wing, while S is its area, the drag coefficient results:

$$C_D = \begin{cases} \frac{1}{\pi\Lambda}\left(C_{L\alpha}\alpha\right)^2, & \text{if} \quad |\alpha| \le \frac{\pi}{2} \\ \frac{1}{\pi\Lambda}\left[C_{L\alpha}\left(\pi-\alpha\right)\right]^2, & \text{if} \quad |\alpha| > \frac{\pi}{2}. \end{cases} \tag{10}$$

The wing polar is presented in Figure 8.

3. Relative velocity of the air with respect to the wing

The angular velocity of the wing with respect to the body of the apparatus is determined by using the unit vectors of the axes about which the stroke plane reference system rotates, in order to obtain the wing reference system

The unit vectors, expressed with respect to the wing reference system, are:

$$\begin{aligned} \{k_S\}_w &= [T]_{wS} \cdot \{k_S\}_S = [T]^T_{Sw} \cdot (0 \quad 0 \quad 1)^T = \\ &= \left(-\cos\varphi \sin\alpha_V \quad \sin\varphi \quad \cos\varphi\cos\alpha_V\right)^T, \end{aligned} \tag{11}$$

$$\left\{i_{S_1}\right\}_w = [T]_{wS_1} \cdot \left\{i_{S_1}\right\}_{S_1} = [T]^T_{S_1 w} \cdot (1 \quad 0 \quad 0)^T = \left(\cos\alpha_V \quad 0 \quad \sin\alpha_V\right)^T, \tag{12}$$

$$\left\{j_{S_2}\right\}_w = \left\{j_{S_2}\right\}_{S_2} = (0 \quad 1 \quad 0)^T. \tag{13}$$

The angular velocity vector results:

$$\{\omega_{wS}\}_w = \dot\lambda\,\{k_S\}_w + \dot\varphi\left\{i_{S_1}\right\}_w + \dot\alpha_V\left\{j_{S_2}\right\}_w = \begin{Bmatrix} \dot\varphi\cos\alpha_V - \dot\lambda\cos\varphi\sin\alpha_V \\ \dot\alpha_V + \dot\lambda\sin\varphi \\ \dot\varphi\sin\alpha_V + \dot\lambda\cos\varphi\cos\alpha_V \end{Bmatrix}. \tag{14}$$

By considering a conventional computation point on the wing, defined by the vector

$$\{r_{CP}\}_w = \left(0 \quad b_{CP} \quad 0\right)^T, \tag{15}$$

the velocity of the wing with respect to the body of the apparatus is determined [2],

$$\overline{V}_{rot} = \overline{\omega} \times \overline{r}_{CP}, \tag{16}$$

$$\{V_{rot}\}_w = \begin{Bmatrix} -b_{CP}(\dot\varphi\sin\alpha_V + \dot\lambda\cos\varphi\sin\alpha_V) \\ 0 \\ b_{CP}(\dot\varphi\cos\alpha_V - \dot\lambda\cos\varphi\sin\alpha_V) \end{Bmatrix}. \tag{17}$$

The relative velocity of the air with respect to the wing is obtained by composing the velocity of the unperturbed air flow with the velocity of the wing with respect to the body of the apparatus:

$$\{V\}_w = \{U\}_w - \{V_{rot}\}_w, \tag{18}$$

$$\left|\overline{V}\right| = \sqrt{V_{xw}^2 + V_{yw}^2 + V_{zw}^2}. \tag{19}$$

4. Aerodynamical forces

The angle of incidence of the wing is:

$$\alpha = \begin{cases} \operatorname{atan}(V_{zw}/V_{xw}) & \text{if } V_{xw} \geq 0 \\ \pi + \operatorname{atan}(V_{zw}/V_{xw}) & \text{if } V_{xw} < 0 \quad \text{şi} \quad V_{yw} \geq 0 \\ -\pi + \operatorname{atan}(V_{zw}/V_{xw}) & \text{if } V_{xw} < 0 \quad \text{şi} \quad V_{yw} < 0. \end{cases} \tag{20}$$

The aerodynamical coefficients with respect to the chosen reference systems are:

$$\{C\}_w = \begin{pmatrix} C_D \cos\alpha - C_L \sin\alpha & 0 & C_D \sin\alpha + C_L \cos\alpha \end{pmatrix}^T, \tag{21}$$

$$\{C\}_S = [T]_{Sw} \{C\}_w, \tag{22}$$

$$\{C\}_b = [T]_{bS} \{C\}_S, \tag{23}$$

$$\{C\}_I = [T]_{Ib} \{C\}_b, \tag{24}$$

The aerodynamical force, with respect to the fixed reference system, is

$$\{F_a\}_I = \frac{1}{2} \rho U^2 S \{C\}_I, \tag{25}$$

where the density of the air ρ has been introduced.

The component F_{azI} represents the lift force, while component F_{axI}, with reversed sign, represents the thrust, both generated only by one wing.

5. Numerical results

Computations have been made considering the following numerical values: $\rho = 1.2\,\text{kg/m}^3$, $b = 0.15\,\text{m}$, $b_{CP} = 0.75b$, $S = 0.025\,\text{m}^2$, $C_{L\alpha} = 4$, $U = 1\,\text{m/s}$.

The frequency of the flapping and feathering motions $f = 7\,\text{Hz}$ has been chosen, corresponding to the circular frequency $\omega = 2\pi f \cong 44\,\text{s}^{-1}$ and to the period $T = 0.143\,\text{s}$.

Angles $\kappa = 0$, $\theta_S = 45°$, $\Phi = 0$, $\Theta = 25°$, $\Psi = 0$ have been chosen.

For the flapping motion, a harmonic law has been taken, of amplitude $\lambda_0 = 50°$ (Fig. 9):

$$\lambda(t) = \lambda_0 \cos \omega t, \tag{26}$$

For the feathering motion, a periodical non-harmonic law has been admitted, of amplitude $\alpha_0 = 30°$ (Fig. 9),

$$\alpha(t) = \alpha_0 \left[90 - 140 g\left(t + \frac{\pi}{2\omega} \right) \right], \tag{27}$$

where

$$g(t) = 0.5\left[g_1(t) - g_1\left(t + \frac{\pi}{\omega}\right)\right], \tag{28}$$

with

$$g_1(t) = \frac{5}{\left[2\sin\left(\frac{\omega t}{2}\right)\right]^6 + 6}. \tag{29}$$

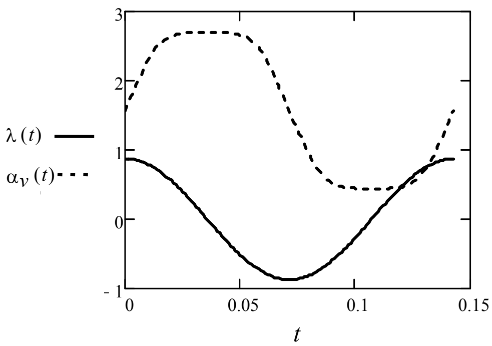


Fig. 9. Variation of the flapping angle and of the feathering angle

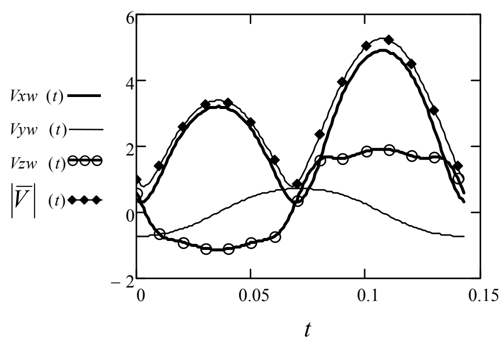


Fig. 10. Variation of the velocity of the wing with respect to the air

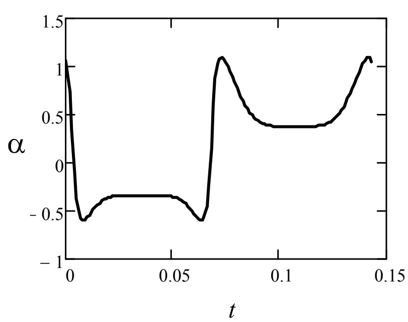


Fig. 11. Variation of the angle of incidence

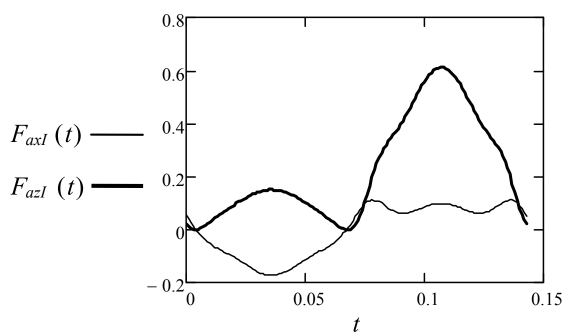


Fig. 12. Variation of the aerodinamical forces

The variations of the components of the relative velocity of the air with respect to the wing are shown in Figure 10.

The variation of the angle of incidence of the wing is shown in Figure 11.

The variations of the lift force and of the thrust are shown in Figure 12.

The time-averaged values of these forces are:

$$F_{a\,xI\,med} = \frac{1}{T}\int_0^T F_{a\,xI}(t)\,\mathrm{d}t = \text{-}0.00248\,\mathrm{N}, \qquad F_{a\,zI\,med} = \frac{1}{T}\int_0^T F_{a\,zI}(t)\,\mathrm{d}t = 0.226\,\mathrm{N}.$$

6. Conclusions

The results of the present study prove that the constructive solution chosen for the FWMAV is viable, the flapping-wing system being able to develop a positive lift force. By choosing an appropriate flight attitude, also a positive thrust is generated, capable to produce the horizontal motion of the apparatus.

The considerations presented in the paper allow for further developments, by refining the aerodynamical model used in the computations.

7. Acknowledgements

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