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ANIMALOPTERS – TOWARDS A NEW DIMENSION OF FLIGHT MECHANICS

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Abstract. Recently, it has been recognised that flapping wing propulsion can be more efficient than conventional propellers if applied to very small-scale vehicles, so-called MAVs (*micro air vehicles*). Extraordinary possibilities of such objects, particularly in the context of special missions, are discussed. Flapping flight is more complicated than flight with fixed or rotating wings. Therefore, there is a need to understand the mechanisms of force generation by flapping wings in a more comprehensive way. The paper describes the current work on flapping wing conducted by the *Flying & Swimming Puzzle Group*. The key to understand the mechanisms of flapping flight is the adequate physical and mathematical modelling; modelling problems of flow and motion are emphasised. Sample calculations illustrating current capabilities of the method have been performed. The effect of feathering amplitude, flapping amplitude, and phase shifting on the MAV's control effectiveness has been examined. It has been discovered that the parameters mentioned above can be considered as control parameters of "flapping wing" MAVs, especially in lateral direction. Research programmes for the construction of MAVs concentrate on understanding the mechanisms of animal flight and on creating smart structures which would enable flight in micro-scale.

Keywords: micro air vehicles, flapping flight, flight mechanics, mathematical modelling, panel method, wing control.

1. Introduction

Nowadays a great interest in the development and applications of *unmanned air vehicles* (UAVs) exists. The main advantage of UAVs over piloted aircraft is no risk of pilot life in the hazardous environment both military and civil applications. Without pilot and only equipment on board, UAVs may be much smaller than "normal" aircraft. This includes an interest to a very small aircraft, generally referred to as *micro air vehicles* (MAVs).

Recently it has been recognised that flapping wing propulsion can be more efficient than conventional propellers, if applied just to MAVs. Most flying insects, birds and bats employ a flapping flight. The fact that they can quickly change the direction of motion, yet keeping perfect attitude control, as a result of millions years of evolution, has given them the appellative of perfect flying machines. Therefore, the interest of many aeronautical researches focuses now on the bio-fluid-dynamics [1].

The current research on flying-animal like MAV resulted in the new term *animalopter* (including *entomopters* and *ornithopters*) describing the similarity of MAV to real flying-animal (i.e. insects and/or birds and bats). Animalopter means the animal-like flying objects with moving wings. An animal wing is a multifunctional device providing lift, propulsion and flight control and performing a complex motion relative to the "aircraft" body, which shows the analogy with a helicopter rotor.

The MAV is of comparable size of small birds and big insects (Fig 1). It stimulates interest of designing the flapping wing for MAV as an attractive alternative for fixed or rotating wing configurations. However, flapping flight is more complicated than flight with fixed or rotating wings. Because of the reciprocating motions involved, the analysis of animal flight is probably one of the more complex aerodynamic problems examined.

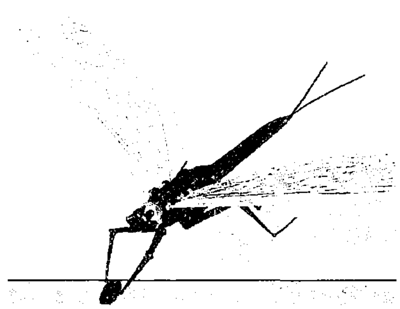

Fig 1. The entomopter as a robotic insect

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True enough, experimental observations provide information on the geometry and strength of the flow fields, but these quantities may also be predicted by means of mathematical modelling, in which the properties of animal wings acting as aerofoils are modelled by CFD (*computational fluid dynamics*) methods, mainly by panel methods.

The paper describes the current work [2–7] on flapping wing conducted by the *Flying & Swimming Puzzle Group*. The key to understand the mechanisms of flapping flight is the adequate physical and mathematical modelling. Therefore, the main body of the paper is constituted by chapters 4 to 6 in which the most important elements of animalopter's flight modelling are described.

2. Micro Air Vehicles – New Challenges for Flight mechanics

2.1. What is a micro air vehicle?

The term Micro Air Vehicle may be somewhat misleading if interpreted too literally. MAVs are not small versions of a larger aircraft. For is reason we prefer the name ANIMALOPTERs. The definition employed in the DARPA's (Defence Advanced Research Project Agency) program limits the MAVs to a size less than 15 cm in length, width or height. This physical size puts this class of vehicle at least an order of magnitude smaller than any missionized UAV developed to date. The MAV is of comparable size of small birds (or bats) and big insects. Several types of such vehicles have already been built (e.g., such as in Fig 2, where dimensions of the wings can be compared to one-cent coin) and currently are applied in various missions.

There are two prominent features of MAV flight: 1) small physical dimensions, resulting in certain favourable scaling characteristics including structural strength, reduced stall speed, and low inertia; 2) low Reynolds number (104 – 105), resulting in unfavourable aerodynamic conditions to support controlled flight. This leads to the requirement of a distinct flight envelope with emphasis on ability to hover, and agility at low speeds.

The shape of MAVs depends very much on their mission requirements. A MAV that must travel appreciable distances at relatively high speed would probably be best suited to a fixed wing design. Alternatively, a MAV with a requirement for hover or agile manoeuvrability would best benefit from flapping wing or rotary-motion propulsion. To the authors' knowledge there have been no published attempts to estimate the influence on feathering and flapping amplitude as well as phase shift on the magnitude of animalopters control forces and moments.

2.2. Applications envisioned for MAVs

In contrast to higher-level reconnaissance assets like satellites and high altitude UAVs, MAVs will be operated by and for the individual soldier in the field as a platoon-level asset, providing local reconnaissance or other sensor information on demand, where and when it is needful. MAVs may also be used for tagging, targeting, and communications and may eventually find application as weapons as well.

MAVs will be capable of a wide range of useful military missions. The one most often identified is "over the hill" reconnaissance mission (Fig 3 on the left). The current concept suggests that such MAVs need to range out to 10 km, remain aloft for up to an hour, reach speeds of 10 to 20 m/s, and be capable of real time day/night imagery. At the same, MAVs must be operated relatively simply with an easy-to-operate ground station.

In urban operations (Fig 3 on the right) MAVs acting in small co-operative groups, will enable reconnaissance and surveillance of inner city areas, and may serve as communication relays. They may also enable observations through windows and sensor placement on elevated and even vertical surfaces. Their application to building interiors is the most demanding envisioned.

2.3. Features of animal flight versus aircraft flight

As it has been mentioned above, what differentiates MAVs from ordinary radio-controlled model aircraft are mainly the small size and flight operation mostly beyond the visual range of the operator, in very low Reynolds number regimes. The aerodynamics of low Reynolds number flight possesses a major challenge in terms of adequate

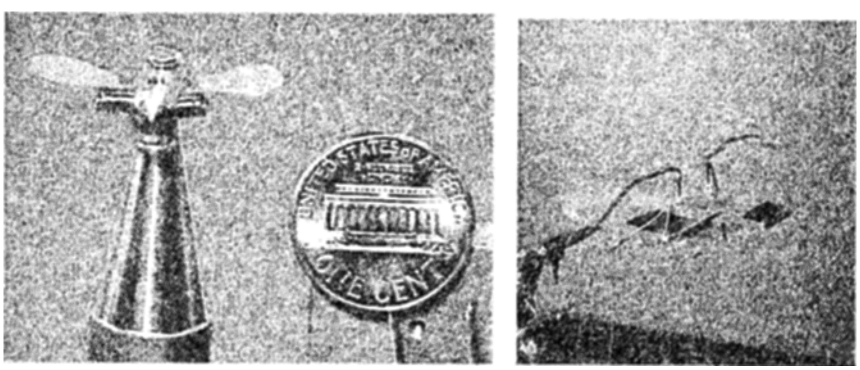

Fig 2. The prototype of entomopter wings and its research device

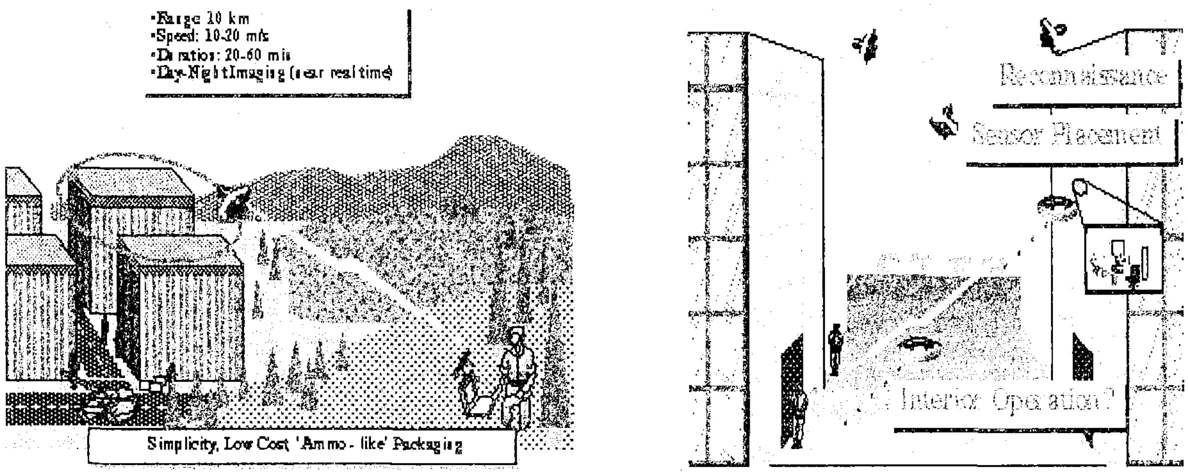

Fig 3. Examples of reconnaissance performed by MAVs

lift generation as well as stability and control requirements. Data on how wing and body movements change with flight speed are not only of interest in their own right, they are also essential for aerodynamic modelling and for the consideration of the aerodynamic mechanisms being employed. There remain some subtle but important differences between bird and aircraft models. These arise from the fundamental aerodynamic difference between the two models of Fig 3. Examples of reconnaissance performed by MAVslight, which is that birds must flap their wings to generate both weight support and thrust; aircraft wings must generate only lift, and an aircraft obtains thrust by essentially separate engines.

To fully appreciate the scale implications we can compare this class of vehicle with the other familiar systems shown in Fig 4. This is the plot of vehicle gross weight vs Reynolds number. As it can be seen, the low Reynolds number regime is a fundamental shift in physical behaviour at MAV scales and speeds - the environment more common to the smallest birds and largest insects.

Conventional airplanes with fixed wings are by comparison very simple. The forward motion relative to the air causes the wings to produce the lift. However, in animal flight the wings not only move forward relative to the air, they also flap up and down, plunge, and sweep. To attain the appropriate effective angle of attack throughout the entire wing-stroke, the wings must constantly twist. Animals do not, in general, have any rotating parts that execute a full circular motion, whereas propulsion systems of the conventional aircraft are characterized by a continuous cyclic motion.

2.4. Some problems to be explored

The flapping wings operate in regimes where unsteady and non-linear aerodynamic effects can be of exceptional importance and many simple theories from textbooks break down when applied to flying animals. This difficulty has even made its way into an urban story of proof by an engineer that a bumblebee can not fly.

Many experiments show that for unsteady flows at high reduced frequencies the flow in the region of the trailing edge departs significantly from that predicted by the steady Kutta-Joukowski condition. When the reduced frequency is high, the kinematic velocity normal to the trailing edge becomes as greater compared with the translation velocity. This feature affects the angle at which the flow leaves the trailing edges. Whether or not this assumption is valid for large amplitude, high frequency motions have been a source of much controversy, and a decisive test can only be accomplished comparing the measured instantaneous wing forces with those predicted by the assumption.

The cruising birds and bats fly with their flapping axes aligned close to the horizontal. This could produce an interesting dilemma for the upstroke. Namely, except for a certain average positive lift produced by a fixed camber, the positive thrust on the upstroke will produce a negative lift, and the positive lift on the upstroke will produce a negative thrust. There arouses also some controversy in the literature whether or not the tip vorcity is shed during the upstroke.

While flapping the animals systematically twist their wings to produce an aerodynamic effect similar to that produced by the ailerons on the wings of conventional airplanes. The point is what should be the effect of the phase shifting between left and right wings on the MAV's control effectiveness?

Considerable debate surrounds the nature of the power curve; although such curves have been familiar from modelling of flight performance since 1920 and are widely used in predicting flight behaviour, migration strategy and the like, it has been difficult to confirm the geometry of the curves theoretically. Moreover, the existence of the power-speed curve in the perception of a bird or bat has never been confirmed! We cannot be certain that there are no constraints restricting the flight of any individual

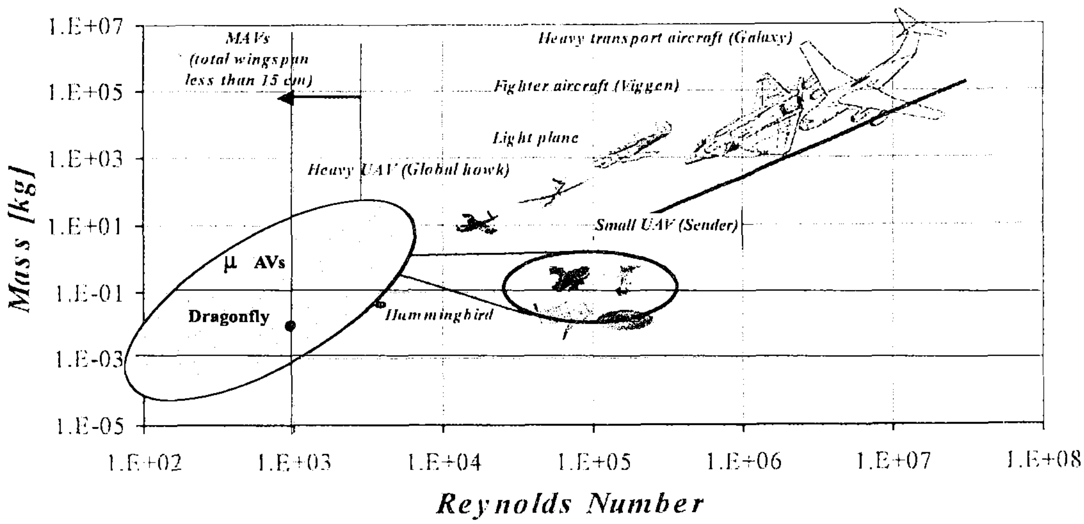

Fig 4. Microairvehicles compared to existing flight vehicles

bird to a limited range of speeds, or that the curve is continuos across flight speeds in all birds.

Last but not least, the development and fielding of military useful MAVs will require overcoming a host of significant technology and operational obstacles. The physical integration challenge is believed to be the most difficult problem. The and below the 15 cm scale size (see Sec. 2.1), the concept of "stuffing" an airframe with subsystems – as in conventional approach – becomes extremely difficult. An examination of the range of system elements illustrates the problem (Fig 5). From electronic perspective the on-board processor and communication electronics form the core of the vehicle. They provide critical links between the sensor systems and the ground station and they are vital to the flight and propulsion control systems.

3. Mathematical Modelling of Animalopter's Flight

3.1. Degrees of freedom

Detailed analyses of kinematics are crucial in the full understanding of animal flight. This requires a universal joint similar to a shoulder in a human body. A good model of such a joint is the articulated rotor hub (Fig 6). Four degrees of freedom in each wing are used to achieve flight in the Nature: flapping, lagging, feathering, and spanning.

The *flapping* is an angular motion about an axis in the direction of flight; the *lagging* is an angular motion about the vertical axis which effectively moves the wing forward and backward parallel to the body; the *feathering* is an angular motion about the axis in the centre of the wing which tilts the wing to change its angle of attack; the *spanning* is expanding and contracting of the wingspan.

Not all flying animals implement all of these motions. Unlike birds, most insects do not use the spanning technique. Thus, the flapping flight is possible only with two degrees of freedom: flapping and feathering. In the simplest physical models heaving and pitching represent these degrees of freedom. The moving airfoil is specified by the oscillatory motion:

$$h = h_0 \cos(kt), \quad \alpha = \alpha_0 \cos(kt + \varphi) \qquad (1)$$

where h_0 is the plunge amplitude (normalised with the airfoil chord), α_0 denotes the pitch amplitude, k is the reduced frequency (of course t is the nondimensional time), and φ is the leading phase angle between the pitching and plunging motions.

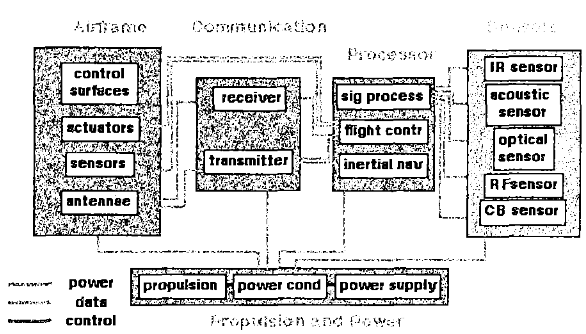

Fig 5. MAV system integration

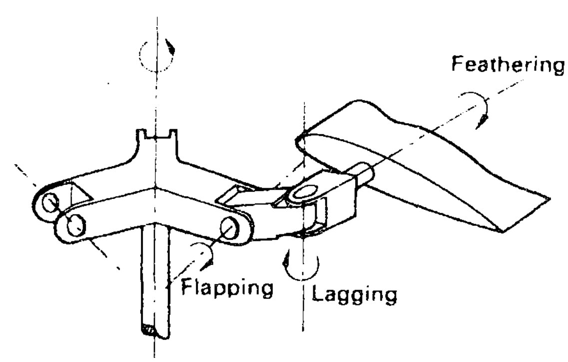

Fig 6. Articulated rotor hub model

3.2. Formulation of equations of motion

In flight mechanics there are some approaches to the generation of equations of motion, e.g. *Lagrange* or *Boltzmann-Hamel* techniques uses standard aviation co-ordinate systems like in Fig 7. So far, these techniques were not used in animalopter's flight mechanics. We also take into account only the classical approach. Thus, general form of the equations of motion done by the theoretical mechanics is as follows:

$$\frac{d\Pi}{dt}+\Omega\times\Pi=F$$
$$\frac{dK_0}{dt}+\Omega\times K_0+V_0\times\Pi=M_0 \qquad (2)$$

where: Π – the *momentum*, represents the product of particle mass and velocity; K_0 – the *moment of* momentum; F – external forces; Ω – angular velocity of *Oxyz* system; V_0 – velocity of co-ordinate system centre (Fig 7).

3.3. Aerodynamic modelling

Animal flapping flight represents an unusual aerodynamic problem because of the inherent "unsteadiness" and the low Reynolds number of the airflow. Usually *unsteady flow* is defined as that in which aerodynamic characteristics depend on time. Among various unsteady flows the linear, harmonic flows are especially important. The linearity means that amplitudes of oscillations are small and that separation does not take place. For such flows it is sufficient that aerodynamic characteristics are presented versus a frequency parameter. Time does not appear explicit in the function describing these characteristics.

To find the flow around wing at *a high angle of attack* it requires having a non-linear governing equation as well as non-linear boundary conditions due to the edge separation. Hence, the problem may be seen as having nonlinearities in two aspects.

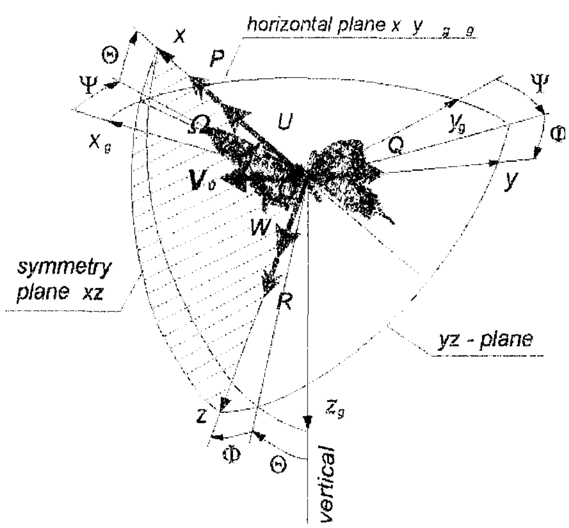

Fig 7. Body and air-flow coordinate systems

When the fluid is assumed to be incompressible and external forces and heat sources are not taken into account, the governing equations for such fluid are as follows:

$$\frac{dV}{dt}+(V\cdot\nabla)V=-\frac{1}{\rho}\nabla\rho+\nu\nabla^2V \qquad (3)$$

$$\nabla V=0\,. \qquad (4)$$

where V is the velocity vector, ρ is the fluid density, and ν is the kinematic viscosity. Such model is well known as Navier-Stokes one. However, the basic principle, as in all engineering activity, is "to try simple things first". If a simpler model gives satisfactory behaviour, there is no need to bring in the Navier-Stokes solver.

A large number of models for animal flight have been formulated and they have been categorised and evaluated in recent review by Pietrucha *et al.* [7]. The techniques currently used for the calculations of aerodynamic loads on flapping wings can be essentially divided into the following three categories: 1) before-panel methods (traditional approach); 2) panel methods; 3) post-panel methods (so called computational fluid dynamic (CFD) modelling).

Before-panel models are insensitive to variability in the wingbeat kinematics and bear no relation to the true dynamics of vortex flows in the wake. As a result they do not predict the rise in induced power at high speeds which represents the need for some momentum in the wake to provide an increasing forward thrust to balance the friction drags.

The comprehensive approach to the problem under consideration would be to solve the complete viscous flow near the animal. However, a solution of the full Navier-Stokes model for 3 D, unsteady flowfield is a challenge. For the flow around variable geometry bodies it will be complicated even more.

Therefore we prefer other computational methods that are also available to compute the flow about animal wings, but are considerable simpler, namely *panel methods*. Recently these methods have been used to model unsteady and even non-linear flows with encouraging results (see Chaps 5 and 7).

3.4. Control modelling

Animal wing control is similar to rotorcraft control, even more than to fixed wing control. Control of the animalopter in any flight conditions involves the proper orientation of the flapping wings lift force vector. It is similar like in rotorcraft (see Fig 6). During forward flight, however, longitudinal control of an animalopter can be achieved providing an increment tail lift force on tail lifting surfaces (like in a fixed wing aircraft). That force can be produced deflecting the entire lifting surface or deflecting a flap incorporated in the lifting surface. Lateral control forces and moments must be achieved, however, by the proper orientation of flapping wings lift force. This orientation can be achieved by proper changing of the shape of wing. That approach is recently implemented in helicopter control and is known as *wing shape control*. This concept has been inspired by insect wing anatomy [5].

Wings of insects may have various shapes, but their internal structure is similar to the majority of species. Usually the insect wing is composed of two membranes. It is a sandwich structure with two layers made of chitin of the thickness of micrometer order. The fibres going along the span fold the surface. These fibres (similar to ribs in aircraft structure) concentrated mainly in the vicinity of leading edge, act as stiffening elements and may form various patterns.

4. Equations of animalopter's plane motion

Flying creatures are very complicated mechanical systems so the investigation of their flight mechanics should be started with simplified models. Let's consider the plane motion for that we have: $F=[F_x, F_z]^T; V_0=[U, W]^T$; $\Omega=[Q]$ – angular velocity of *Oxyz* system (see Fig 7). The following assumptions are taken into consideration:

$$\dot{I}_y^R = \frac{\partial I_y^R}{\partial \delta}\dot{\delta}\ ;\ \dot{S}_z^w = m_s\eta_s\delta_0\omega\cos\delta\cos\omega t\ ;\ \dot{S}_x^w = 0\ ;$$

$$\delta=\delta_0\sin\omega t\ ;\ \dot{\delta}=\delta_0\omega\cos\omega t\ ,$$

where: δ – flapping angle of wings; ω– frequency of wing motion respect to the body; S_x, S_z – static moments ornithopter without wings; S_x^w, S_z^w – static moments ornithopter with wings; η_s – position of wing mass centre along span; I_y – inertial moment of ornithopter without wings; I_y^R, I_y^L – inertial moments of right and left wing, respectively.

We assume that aerodynamic forces are non-linear functions of angle of attack α, feathering angle γ, flapping angle δ, and their derivatives:

$$F_x=\frac{1}{2}\rho V_0^2 SC_x[C_L(\alpha,u),C_D(\alpha,u)] \tag{5}$$

$$F_z=\frac{1}{2}\rho V_0^2 SC_z[C_L(\alpha,u),C_D(\alpha,u)] \tag{6}$$

$$M_y=\frac{1}{2}\rho V_0^2 S\cdot c\cdot C_m[C_L(\alpha,u),C_D(\alpha,u),Cm_0,\alpha] \tag{7}$$

where: C_L – lift coefficient; C_D – drag coefficient; C_{m0} – aerodynamic moment respect to the quarter of rootchorde; u is the control vector in the form

$$u=[\delta_0,\gamma_0,\omega,\lambda]^T \tag{8}$$

where λ is phase shifting between feathering and flapping.

Substituting formulae (5)-(8) to Eq. (2) we can obtain

$$m(\dot{U}+Q\cdot W)+S_z\dot{Q}-S_xQ^2+Q\dot{S}_z= =\frac{1}{2}\rho V_0^2 SC_x[C_L(\alpha,u),C_D(\alpha,u)]-mg\sin\theta \tag{9}$$

$$m(\dot{W}-Q\cdot U)-S_x\dot{Q}-S_zQ^2-Q\dot{S}_z= =\frac{1}{2}\rho V_0^2 SC_z(C_L(\alpha,u),C_D(\alpha,u))+mg\cos\theta \tag{10}$$

$$\begin{aligned}&\left(I_y+I_y^R+I_y^L\right)\dot{Q}+(S_z+S_z^w)\dot{U}-\left(S_x+S_x^w\right)\dot{W}+\\&+\dot{S}_z^wU+(S_xU+S_zW)Q+\left(\dot{I}_y^R+\dot{I}_y^L\right)Q=\\&=\frac{1}{2}\rho V_0^2S\cdot c\cdot C_m[C_L(\alpha,u),C_D(\alpha,u),C_{m0},\alpha]-\\&-(x_c+z_c)\cdot mg\cos\theta+\left(I_{xy}^L-I_{xy}^R\right)\cdot\ddot{\delta}-\\&-\left(I_y^R+I_y^L\right)\cdot\ddot{\gamma}+\left(-\frac{\partial I_{xy}^R}{\partial\delta}+\frac{\partial I_{xy}^L}{\partial\delta}\right)\cdot\dot{\delta}^2-\\&-\left(\frac{\partial I_y^R}{\partial\delta}+\frac{\partial I_y^L}{\partial\delta}\right)\cdot\dot{\gamma}\cdot\dot{\delta}\end{aligned} \tag{11}$$

It should be noticed that Eqs. (9)-(11) differ from classical equations of aircraft motion (see, e.g. [8]). In Eqs. (9)-(11) there are static moments' derivatives S_z^S, S_x^S and inertia moments' derivatives I_y^R, I_y^L of left and right wings with respect to time, as well as additional state variables – angles of wings' flapping and feathering. However, these angles are present in helicopters' dynamics.

5. Loads on Flapping Wings via Panel Methods

The starting point for the various panel methods formulations is the *Euler* model with the assumption:

$$\nabla\phi\equiv\text{grad}\phi=V \tag{12}$$

what means that the fluid is assumed to be inviscid. Combining momentum equation (3) with the condition (12) one can obtain a very popular form of Bernoulli equation:

$$\frac{p_\infty-p}{\rho}=\frac{1}{2}(\nabla\varphi)^2+\frac{\partial\varphi}{\partial t}-\frac{1}{2}U_\infty^2 \tag{13}$$

Eq. (4) with the condition (12) may be written as the Poisson equation:

$$\nabla^2\varphi=-\frac{1}{\rho}(\nabla\rho\nabla\varphi) \tag{14}$$

Assuming that $\phi=\phi_\infty+\varphi$, where φ is the perturbation potential, we can obtained the Laplace equation

$$\nabla^2 \varphi = 0 \qquad (15)$$

Although Eq. (15) governs the velocity potential variation throughout the flow field, it does not give any information on the flow evaluation in time. This temporal dependency has to be introduced through the boundary conditions. Since the body is assumed to be solid, the velocity normal to its surface must be zero:

$$V \bullet n = (\nabla\varphi(r,t) - V_S(r,t)) \bullet n(r,t) = 0 \qquad (16)$$

where the surface velocity V_S given as

$$V_S = V_0(t) + \Omega(t) \times r(t) + V_r(r,t) \qquad (17)$$

where V_r accounts for any relative motion of the surface within the body-fixed system *xyz* (see Fig 7).

The important point in the modelling of vortex sheet is the choice of proper boundary conditions because they control the wake geometry. Usually, the obvious assumption is made that the wake could not generate the lift. Hence, taking into consideration *the Kutta-Joukowski* theorem one can obtain

$$V \times \gamma_w = 0 \qquad (18)$$

what means that the circulation vector γ_w is parallel to the local velocity vector. This condition can be met moving the wake to a force free position at every time step.

The solution of Eq. (15), with applicable boundary conditions can be obtained distributing the *elementary solutions* (as *sources* with strength σ or *doublets* with strength μ) on the surface boundaries: S_b for the body, and S_w for the wake. Thus, the general solution of Eq. (15) is given as

$$4\pi\phi = \int_{S_b} \left(\frac{\sigma}{r} - \mu\frac{\partial}{\partial n}\left(\frac{1}{r}\right)\right)dS - \int_{S_w} \mu\frac{\partial}{\partial n}\left(\frac{1}{r}\right)dS \qquad (19)$$

To solve numerically Eq. (19) the surfaces are divided into a set of panels and a singularity distribution is given on each panel. A survey of various panel methods can be found in [3].

A typical configuration of the physical model is shown in Fig 8 where a plate shape similar to the real butterfly wing is represented by a simple form in order to simplify the calculation. The bound vortex is settled on the plate and the wake of the vortex sheet is on the surface swept by the line E.

6. Animal's Wing Control Proposals

6.1. Application of actively controlled elements

Emerging "smart structure technology" is widely investigated for application to enhance rotorcraft performance [5, 6]. Application of smart structures to shape control for adapting rotor behaviour to surrounding conditions and to a flight regime is a new concept giving prospect of combination into one mechanism primary and additional controls of a helicopter rotor. Changing of the blade cross section shape using different active materials is also considered (see Fig 9).

The idea of controlling blade shape can be put into practice using smart composite in the form of either fibres or rods embedded inside the blades. Active composites are offered now by some manufacturers and are being used to change the blade structure.

The facts described above form the background for undertaking the study in which a model of elastic blade is modified by the application of actively controlled elements.

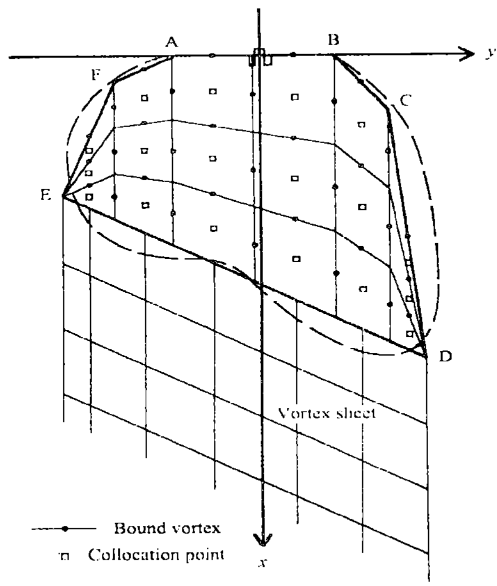

Fig 8. Configuration of the panel model

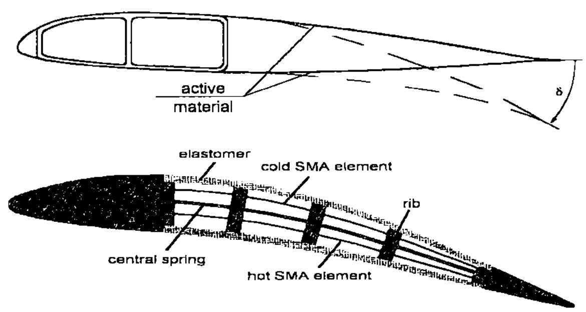

Fig 9. Model of an active changing of blade shape

6.2. Application of actively twisting the joints

In [9] other approach of shape wing control is described. This approach can be named as "control via multiwire wing structure" (Fig 10). The chief function of the veins is to provide support for the wing and act as cantilever beams and elastically transmit force. A great variety of often-complicated venation schemes occurs in insects. However, selecting the structurally important spars and ignoring those with less obvious mechanical functions can simplify the wing design for an MAV. Such an efficient pattern is observed in flies which are excellent flyers. The occurrence of one or more supporting veins

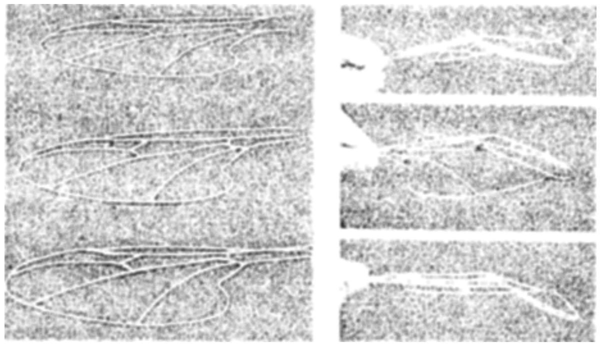

Fig 10. Three models offive-spar metal wire wings

near the leading edge of the wing allows modifying the angle of attack during flapping cycle actively twisting the joints. This action is performed against the aerodynamic and inertial moments and is the torsional elasticity of the wing base.

Rather than subject spars to high loads, hinges are used to create preferred directions of high deformations. At Shrivenham, two engineering implementations of this concept are used: (1) heat shrinking polypropylene; (2) metal springs.

6.3. Future development

It seems to us that every control system for MAVs should be planed as multilevel hierarchical system with fuzzy logic and learning features (Fig 11; about $\dot{\phi}, \dot{\theta}, \dot{\Psi}$ see Fig 7). Fuzzy logic algorithm will be constructed and implemented in wing control system, and ANN (*Artificial Neural Network*) controller will be a part of flight control system which will be aided by an expert system also. Such approach requires identification techniques and control synthesis carried into effect as a whole.

7. Results

During the calculations the following assumptions were taken into account:

1) The motion of the animal body is known (prescribed);

2) The effect of the body is not considered;

3) Each wing is assumed as solid and rotates on a common axis;

4) The wing vortices are generated at the trailing edge only;

5) The flow behind the animal is considered to be laminar with the vortices having no time to dissipate under the influence of viscous effects;

6) The rounded leading edges the wings inhibit the leading-edge separation;

7) The flow is assumed to leave the trailing edge along the bisector and then to follow the local stream direction;

8) The shape of trailing wake is determined from calculations (using a time-stepping solution procedure).

Sample calculations have been performed for a rectangular wing with a constant aerofoil section along the wingspan moving with a low speed (8 m/s) forward flight. A symmetric NACA 0009 aerofoil was chosen as a starting point of investigation. A choice of wing positions was dictated by typical changes of the rotational angels around the Cartesian x, y, z axes, with x, z defining an airfoil plane and y oriented from the root to the tip of a wing (see Fig 7). The flapping frequency assumed in the calculations was equal to 2 Hz.

It was assumed that during one cycle:

- the rotation angle with respect to flapping hinge (flapping angle) will vary between –45° and 45°;
- the rotation angle with respect to feathering hinge (feathering angle) will vary between –5° and 5°;
- the rotation angle with respect to lagging hinge is constant (no lagging motion).

Figs 11 – 13 pictured exemplary results of our calculations. The following denotations are applied:

κ_ε – proportion of feathering amplitudes right vs left wings;

ε - phase shifting between right and left wing feathering motion;

κ - proportion of flapping amplitudes right vs left wings.

Analysis of the the mentioned figures shows that the difference between feathering and flapping amplitudes during left and right wings motion lead to appearance of rolling (C_l) and yawing (C_n) moments and side force (C_y). Therefore, feathering and flapping amplitude of each wing can be considered as control inputs. However, the most effective is phase shifting between right and left wing feathering oscillations.

8. Conclusions

The animal flight mechanics may find practical application in constructing micro flying vehicles. The needs

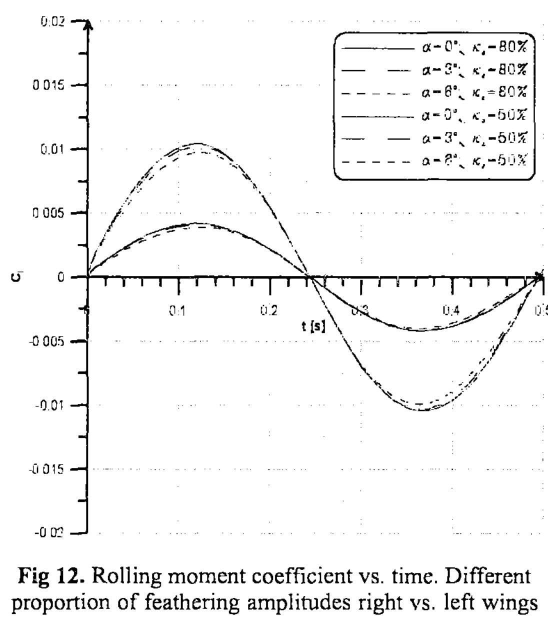

Fig 12. Rolling moment coefficient vs. time. Different proportion of feathering amplitudes right vs. left wings

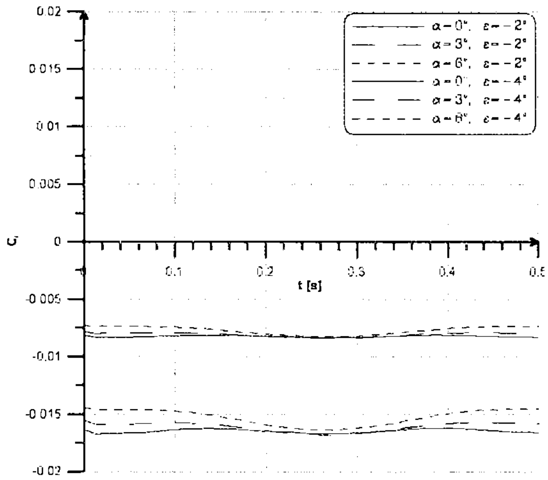

Fig 12. Rolling moment coefficient vs. time. Different phase shifting between right and left wing feathering motion

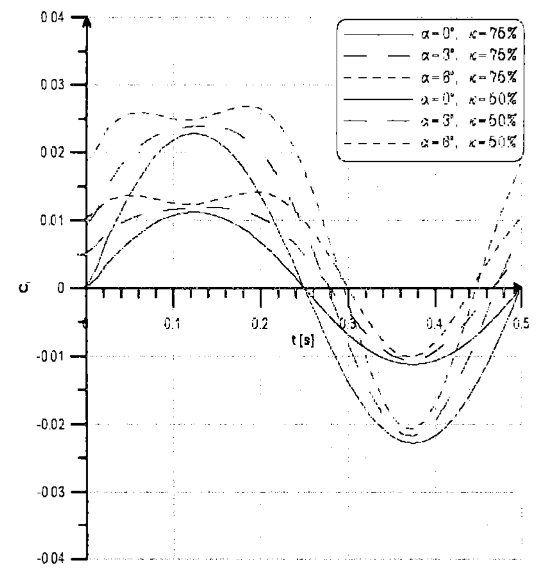

Fig 13. Rolling moment coefficient vs. time. Different proportion of flapping amplitudes right vs. left wings.

for efficiency in terms of lift and propulsion generation becomes more evident when the size of a flying vehicle is reduced.

Further studies are needful to explore the combined pitch-and-plunge oscillations at high angles of attack. Recent panel methods are more advanced than their predecessors in considering trailing wake vorticity and dynamic effects, but they still have important shortages. In particular, they do not yet incorporate the leading-edge vortices that have a decisive influence on the flow around animal wings at all speeds.

The effect of feathering amplitude, flapping amplitude, and phase shifting on the MAV's control effectiveness has been examined. It has been discovered that the parameters mentioned above can be considered as control parameters of "flapping wing" MAV, especially in lateral direction.

Study of control techniques (based on fluid control) will be used to optimise the wing shape and actuation patterns. The control of the wing as a flexible structure with distributed actuators and sensors will also be used to improve performance.

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