An analysis of the efficiency of the functional matching between a flying wing MAV airframe and different types of micro propellers

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***Abstract**: This paper aims to present specific methods for optimizing the design of micro propellers for small Reynolds numbers. In order to better understand the aim of this contribution, the effects of a micro propeller on the aerodynamic surfaces of a micro air vehicle (for example a flying wing configuration) are presented together with the analysis of the specific tools for the design of micro propellers. The final part aims to renew the interest in predicting the influence of the propeller-wing flow interaction on the aerodynamic characteristics of deflected slipstream and small flying wing MAV.*

Keywords: MAV (micro air vehicle), micro propeller, interaction effects, scalability

1. INTRODUCTION

Micro propellers for MAV are different from those for conventional aircrafts and it is not obvious a scalability. Micro propellers are available in wood, nylon and reinforced plastics.

The reinforced plastic propellers present the advantages of their ruggedness and efficiency, even though they weigh roughly twice the weight of their wooden equivalents.

We have presented the basics of the interaction between the propeller and the different aerodynamic surfaces. We have also analyzed the tools used for micro propeller design.

The design philosophy (with multiple capabilities, aerodynamics, structural and acoustics) integrates MAV aerodynamics and electric engine characteristics in three different optimizations and includes a high number of variables and constraints. The focus is on the global optimal compromise between different goals, under different constraints.

2. MAV Global Performances And Micro Propeller Effects

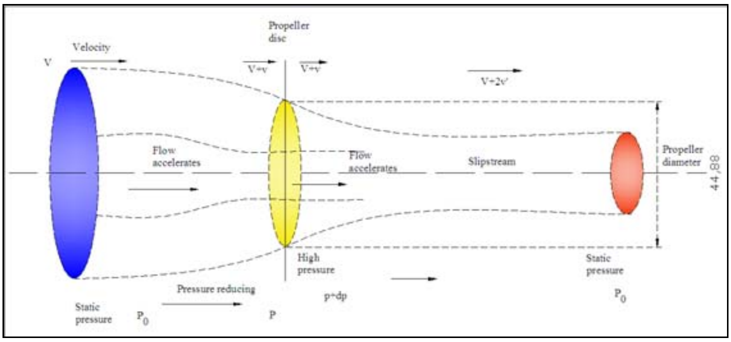

Fig. 1 Slipstream

- **Slipstream.** The slipstream moves (see Fig. 1 above) as a helix rotating around the airplane in the same direction as the propeller's rotation, but at higher than flight speed. It strikes body, wing and tail surfaces at angles and increases the drag of any obstacle in its path. Its most unfavorable impact is on the vertical tail surface – it causes yawing that calls for rudder-trim correction.

The increase in the velocity of the oncoming relative wind reduces the propellers effective pitch, as does one blade's downwash on the next. Such downwash further reduces the propeller's efficiency. The situation is made worse with three or more blades. For model airplanes, such multi-blade propellers aren't recommended, except for scale models of aircraft so equipped.

In full scale aircraft, multi-blade propellers are used to absorb the high power of modern piston and turbo-prop engines. They also reduce the propeller's diameter so as to avoid compressibility effects from tip speeds close to the speed of sound. The loss of efficiency in this reduction must be accepted.

- **Asymmetric blade effect.** When the plane of the propeller is inclined to the direction of flight, the advancing blade operates at a higher AoA than the retreating blade. Thrust on the advancing side is higher than on the retreating side. This causes a pitching or yawing couple.
- **Pitching moment.** When the thrust line is tilted, a vector is introduced that introduced that causes a pitching moment. It may combine with the asymmetric blade effect.
- **Torque.** The resistance to rotation caused by the propeller's drag tries to rotate the whole airplane in the opposite direction. This is particularly true in a steep climbing attitude at low forward speed and maximum rpm where the propeller is operating at high AoAs, such as just after liftoff. A touch of opposite aileron input may be needed to off set the torque.
- **Gyroscopic precession.** Like a gyroscope, a rotating propeller resists any effort to change the direction of its axis. The heavier the propeller and the higher the rpm, the greater this resistance. If a force is applied to tilt the plane of the propeller's rotation, it is "precessed" 90 degrees onward, in the direction of the propeller's rotation. This effect is essential on tail-dragger takeoffs if the tail is lifted too soon and too high. Precession causes a yaw to the left (for propellers rotating clockwise, viewed from behind) that could result in a ground loop unless corrected by rudder action.

One of the most important systems that determine the performances of the MAVs is the propulsion system (electric engine, batteries, micro propeller). The designer could also select the number of engines/ propellers according to the missions and payload. The interaction between the propeller and aerodynamic surfaces is an important task in MAV design strategy because of the influence on stability, performance, energy consumption and noise. In MAV design there are a lot of constraints given by the equipments and their loading restrictions, the significant differences given by the aerodynamics at very low Re numbers. In addition in the practical design it is possible to sacrifice the level of stability to achieve a better maneuverability or to reduce further the size of MAV.

The effects of micro propeller size and placement (with respect to the airframe) on performance and stability need some additional considerations. The MAV design must be stable and controllable while minimizing electric power consumption. But these are *conflicting requirements*. For example, the movement of the MAV's central of gravity to a forward position to improve the natural stability requires a forward movement of the central of lift, to maintain a proper pitch moment; this fact reduces the distance between the wing and the propeller, and this might influence the propeller efficiency and the overall torque budget. In the literature there are different experimental approaches, with advantages/ limitations: an approach based on a physical separation of the power plant; a strategy to measure/ computationally predict characteristics of the resulting pattern of velocities within the flow field.

Force and moment measurements provide a single useful value, whereas more intensive velocity measurements can yield inside into a closer relation between the particular result and the given geometry. Our focus is to use both types of tools to develop a better framework for understanding the propeller airframe interference effects for a flying wing MAV and to develop a better knowledge of the wing position.

3. AN ANALYSIS OF MICRO PROPELLER DESIGN TOOLS

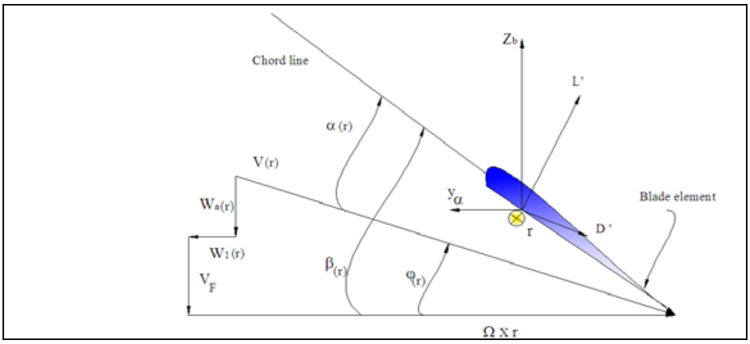

Fig. 2 Blade element

The basic tools in the literature include: an aerodynamic model, an acoustic model and a structural model. The optimization framework involves a very high number of iterations and the models should be accurate and efficient.

In the aerodynamic model the focus is on the distribution of the aerodynamic loads along the blades, necessary to obtain the propeller thrust and required power. Blade element models are based on the segmentation of each blade into small elements, which is equivalent with 2D analysis (Fig. 2).

The cross section is defined by it's radial coordinate, r, with y_B and z_B the cross sectional coordinates. The resultant cross sectional velocity V is the sum of the vehicle air speed V_f, the circumferential velocity $\Omega \times r$ and the induced velocity components w_a and w_t. The angle of attack, α, is obtained by subtracting the inflow angle, φ, from the pitch angle, β. The 2D performance coefficients C_x, C_z are obtained by using aerodynamic database. The lift and drag per unit length, are:

$$P = \frac{1}{2}\rho V^2(r)c(r)C_z \tag{1}$$

$$R = \frac{1}{2}\rho V^2(r)c(r)C_x \tag{2}$$

The induced velocity components are calculated with the moment theory in an actuator disk model. The equations that express the conservation of axial and rotational momentum are:

$$dT(r) = 4 \cdot \pi \cdot \rho \cdot w_d(r) \cdot [V_F + w_a(r)] \cdot r \cdot dr \tag{3}$$

$$dQ(r) = 4 \cdot \pi \cdot \rho \cdot w_t(r) \cdot r \cdot [V_F + w_a(r)] \cdot r \cdot dr \tag{4}$$

The acoustic model is used to compute the noise generated by the propeller and is based on the Ffowes Williams/Hawkings equation:

$$\frac{1}{a^2} \cdot \frac{\partial^2(\Delta p)}{\partial t^2} - \frac{\partial^2(\Delta p)}{\partial \tilde{x}_i^2} = \frac{\partial^2 T_{ij}}{\partial \tilde{x}_i \partial \tilde{x}_j} + \frac{\partial}{\partial t}\left\{\rho_a \cdot V_i \cdot \delta(f) \cdot \frac{\partial f}{\partial \tilde{x}_i}\right\} - \nabla\left\{\Delta p_{ij} \cdot \delta(f) \cdot \frac{\partial f}{\partial \tilde{x}_j}\right\} \tag{5}$$

where a is the speed of sound, Δp is the static pressure, t is the time and $\tilde{x}$ is the location vector of the noise source relative to a stationary system of coordinates. T_{ij} is the Lighthill stress tensor, Δp_{ij} is the generalized stress tensor, v is the source velocity vector and δ is the Kronecker's delta function, f is a function that defines the surface of the body that produces the pressure wave.

The expression for the loading and thickness noise are:

$$\Delta p_{load}(\tilde{x}, t) = \frac{1}{4\pi} \sum_k \left\{ \frac{\dot{F} \cdot \hat{r}_{rel} + F \cdot \hat{r}_{rel} \cdot \dfrac{\dot{M} \cdot \hat{r}_{rel}}{1 - M_r}}{r_{rel} \cdot a \cdot (1 - M_r)^2} + \frac{F \cdot \hat{r}_{rel} \cdot \dfrac{1 - M \cdot M}{1 - M_r} - F \cdot M}{r^2{}_{rel} \cdot (1 - M_r)^2} \right\} \tag{6}$$

$$\Delta p_{thick}(\tilde{x}, t) = \frac{\rho}{4 \cdot \pi} \sum_k \left\{ \frac{\psi_0}{r_{rel} \cdot (1 - M_r)^3} \cdot \left[\begin{array}{l} \dfrac{\ddot{M}_r}{1 - M_r} + 3 \cdot \left(\dfrac{\dot{M}_r}{1 - M_r} \right)^2 \\ + \dfrac{\dot{M}_r \cdot a \cdot (1 + 2M_r)}{r_{rel} \cdot (1 - M_r)} + 2\left(\dfrac{M_r \cdot a}{r_{rel}} \right)^2 \end{array} \right] \right\}_k \tag{7}$$

It is also important to ensure that the blades will be able to withstand the aerodynamic and directional loads.

The main assumptions in the structural model are: bending analysis is based on the fact that sections perpendicular to the elastic axis before deformation remain perpendicular to that axis; the torsion equation is based on the Saint Venant assumption. The axial stress is given by (Timosenko, Gaudier)

$$\begin{gathered} \sigma_{xx-(i)}\left(x_{(i)}, y_{(i)}, z_{(i)}\right) = \\ E \cdot \left[\frac{P_{(i)}\left(x_{(i)}\right)}{(EA)_{(i)}} + \frac{d^2 V_{(i)}\left(x_{(i)}\right)}{dx_{(i)}^2} \left[y_{C-(i)} - y_{(i)}\right] + \frac{d^2 w_{(i)}\left(x_{(i)}\right)}{dx_{(i)}^2} \cdot \left[z_{C-(i)} - z_{(i)}\right] \right] \end{gathered} \tag{8}$$

where E is the material tension modulus of elasticity, EA is the cross sectional stiffness in tension, $y_{C-(i)}$ and $z_{C-(i)}$ are the coordinates of the cross sectional tension center.

The cross sectional shear stress components are computed based on the components of the cross sectional resultant shear force. The maximum Von Misess is given by:

$$\overline{\sigma}_{(i)}\left(x_{(i)}, y_{(i)}, z_{(i)}\right) = \sqrt{\left[\sigma_{xx-(i)}\left(x_{(i)}, y_{(i)}, z_{(i)}\right)\right]^2 + 3\left(\tau_{xy-(i)}^2 + \tau_{xz-(i)}^2 + \tau_{yz-(i)}^2\right)} \tag{9}$$

4. EFFORTS TOWARD A GLOBAL OPTIMIZATION OF THE MICRO PROPELLER DESIGN

The method for optimization uses the three design tools already presented, that include the three major disciplines: aerodynamics, acoustics and structural analysis. Giving the disciplines equal importance in the task of optimization and considering them all enables the designer to approach a variety of design problems.

Most of the researches concentrate on the design of the blades first and after that they search for an optimization of the propeller hub and spinner, as the latter two exert smaller influence on the propeller's performance.

In a traditional design process the variables are given by: the pitch angle distribution, the chord distribution and the thickness ratio distribution. By dividing the design variables we can deal with any design requirement easier. The main categories are:

- general design variables, affect the global configuration: number of propellers, engine gear ratio, number of propeller blades, propeller radius, rotational speed, airspeed.
- blade design variables, define the geometry and structure of the blade: pitch angle, chord, sweep angle, mass, dihedral angle, structural properties
- cross-sectional variables, define the cross-sectional airfoil geometry: thickness ratio, lift coefficient

Any optimization problem can be defined as a search for the minimum of a particular function f(x), called a cost function. The cost function is a measure of the quality of the design. So a general optimization problem can be described like this:

$$\min_{x\in\Re}\left[f(x)\right] \text{ subject to } g(x)=0,\ h(x)\leq 0 \tag{10}$$

With this design method more practical cost functions can be dealt with. For example, if there is the need for high endurance, the cost function becomes the required power of the batteries. Using a cost function like this takes into consideration not only the propeller characteristics but the entire propulsion system. But the cost function is not limited to one goal. It can represent a combination of, let's say, fuel flow and maximum airspeed.

There are also constraints to the optimization problem regarding mainly four categories: aerodynamic, structural, acoustic and side constraints. The focus is on three optimization schemes: a simple genetic algorithm, an enumerative scheme and a scheme that uses the steepest-descent method. The first method, as the name states is similar to an evolution process and starting from an initial random set of designs by using a genetic scheme leads to an improved population. Any cost function has more than one minimum, but only one of those is the global one, the advantage brought by this method being that it is capable of better predicting the region in which this global minimum is.

The next scheme used is the enumerative simplex scheme that is capable of dealing efficiently with a large number of design variables. The final stage of the search for the better design uses a derivative-based method that is very effective in the cases in which the cost function has only one minimum. The focus was set on the application of the steepest descent model that uses the gradient vector, involving the calculation of the N first derivatives of the cost function (where N is the number of design variables).

By using all these schemes at various stages of the design process we can optimize the final design. The designer's role in the optimization procedure is a very important one and is shown when the need arises for defining the various optimization elements (design variables, cost function and constraints).

5. ASPECTS REGARDING THE INTERACTION BETWEEN THE MICRO PROPELLER AND THE FLYING WING MAV

This part aims to renew the interest in predicting the influence of the propeller-wing flow interaction on the aerodynamic characteristics of deflected slipstream and tilt wing aircraft; in the case of a flying wing in a slipstream generated by one or more propellers with an external flow due to forward motion of the wing the following assumptions are made:

1. The fluid is inviscid and incompressible.
2. Rotation in the slipstream is ignored and it is treated as a uniform jet.
3. The jet boundary is assumed to extend back in parallel direction.

Under these assumptions the perturbation velocity due to the wing can be represented as the gradient of a velocity potential which satisfies Laplace's equation. At the boundary it is necessary to maintain continuity of both pressure and the traverse flow angle. Let V_j and V_i be the undisturbed velocities in the slipstream and the external flow. Then if Bernoulli's equation is linearized, the boundary conditions can be expressed as:

$$\phi_j = \mu\phi_0 \tag{11}$$

$$\mu\frac{\partial\phi_j}{\partial n} = \frac{\partial\phi_0}{\partial n} \tag{12}$$

where $\Phi_j = \mu\Phi_0$ is the interior potential, Φ_0 is the exterior potential, and μ is the velocity ratio

$$\mu = \frac{V_0}{V_j} \tag{13}$$

In order to estimate the lift of a propeller-wing combination at an angle of attach it is necessary to allow for the direct contribution of the propeller thrust, the propeller normal force due to the inclined inflow, and change in the wing lift due to the propeller. The propeller slipstream has three principal effects on the wing: it increases the dynamic pressure, it alters the angle of attack, and it decreases the lift slope. All three effects must be estimated. Assuming that the effect of the jet is small on the part of the wing outside the jet, it is possible to make an estimate by using superposition. The increase in lift of the blown part of the wing, treated as if it were an independent plan form, is added to the lift of the whole wing in a free stream.

Provided that the wing completely spans the jet, the increase in angle of attack on one side of the jet should be compensated by the decrease on the other side, so the total lift should be about the same, although its distribution is altered.

6. CONCLUSIONS

We have presented the basics of the interaction between the propeller and the different aerodynamic surfaces. We have also analyzed the tools used for micro propeller design.

We have presented a method for designing propellers that includes three analysis capabilities: aerodynamics, structural and acoustics. By combining all these analysis into one tool for designing propellers we can better account for the characteristics of the entire air vehicle in the design process.

The new design method integrates vehicle aerodynamics and engine characteristics into the design process and we can safely say that the method for combining three different optimization schemes is beneficial when the design problem includes a high number of variables and constraints.

Another advantage of the new design method is that it allows for the definition of any practical cost function, leading to an optimal compromise between different goals. It is also important to mention that the new design method is capable of designing propellers under various constraints, such as acoustic or structural.

The part about the analysis of the interaction between the propeller and the wing for a flying wing MAV aims to renew the interest in predicting the influence of the propeller-wing flow interaction on the aerodynamic characteristics of deflected slipstream and tilt wing aircraft;

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