DESIGN AND DEVELOPMENT OF A MICRO AIR VEHICLE (μAV) CONCEPT: *PROJECT BIDULE*

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Abstract

This paper presents an analysis of the concept of ***Miniature Air Vehicles*** *and* ***Micro Air Vehicles*** *(respectively* ***mAV*** *and* ***μAV****) mainly carried out through the development of a mAV prototype called "Bidule", which was first successfully flown in 1998. The final objective of the project is to reduce the size of this miniature demonstrator to a micro sized vehicle. This paper presents the initial work done to achieve this goal with a particular interest in the aerodynamics of the present vehicle. In keeping with the context of a vehicle's size reduction, a preliminary quantitative approach of the concept shows that the tiny size of mAVs and μAVs creates a strong coupling between the different design fields and requires a high degree of integration. Therefore, reducing the size of an aerial vehicle has major consequences on the performance, especially in terms of endurance. Conserving the operational capabilities of the "Bidule" then requires considering the interactions between the different design parameters, with a particular attention being paid to the wing loading and a high maximum lift. The wind tunnel testing of a propelled model of the "Bidule" prototype shows that the basic design benefits from the prop-wash effect in terms of increased lift. In the context of size reduction to the present vehicle, the results suggest keeping the idea of a wing body immersed in a propeller slipstream, providing that the destabilising effects due to the power system and the prop-wash can be kept to an acceptable level.*

Keywords: micro Unmanned Aerial Vehicles (UAVs), design, propeller effects, wind tunnel.

Introduction

The concept of micro-sized Unmanned Aerial Vehicles (UAVs) or micro Air Vehicles (μAVs) has gained increasing interest over the past few years, with the principal aim of carrying out surveillance missions. The primary payload of these tiny aircraft (~15 centimetres or 6 inches wingspan) is usually a miniature image sensor. Operating in an approximate radius of 600 metres from the launch point, μAVs are used to acquire real-time visual information for a wide range of applications. According to DARPA (Defense Advanced Research project Agency) in reference 1, μAVs are "*six-degree-of-freedom aerial robots, whose mobility can deploy a useful micro payload to a remote or otherwise hazardous location where it may perform any of a variety of missions, including reconnaissance and surveillance, targeting, tagging and bio-chemical sensing*."

In keeping with the general theme for rapid-prototyping low-cost concept demonstrators, an electric-motor powered demonstrator of 410 mm in wingspan was built and flown in 1998. This aircraft, now called "*Bidule*" (Figure 1) is what would be considered a miniature Air Vehicle (mAV) by

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Figure 1 "*Bidule*" mAV Prototype

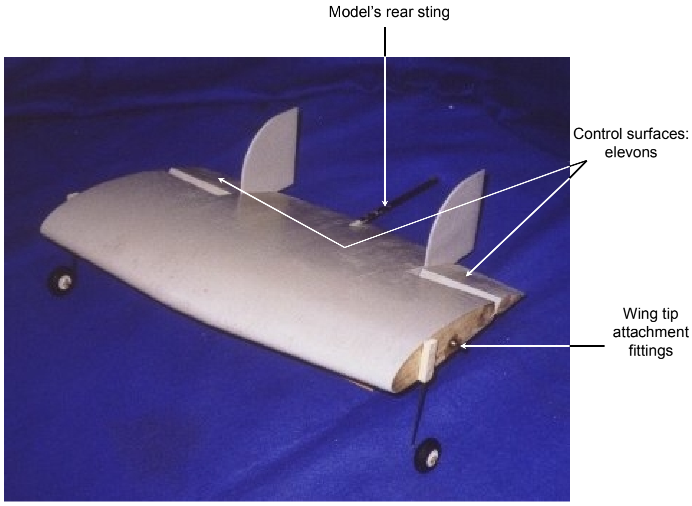

Figure 2 Non-powered "*Bidule*" model

DARPA's definition. As a demonstrator, its purpose was to initially validate the basic design through remote-controlled indoor free-flight tests before considering a possible reduction to a real "micro" size. The current configuration is a flying wing powered by two electric mtors. Ninety percent of the wingspan is immersed in the prop-wash, giving the "*Bidule*" excellent low speed flight capabilities. The aerofoil section used is an unstable (for flying wings) NACA 4418 section. Longitudinal and lateral control are achieved utilising a pair of elevons, and twin rudders allow the directional control. As the flight tests were successful, the development of the concept presently involves the following steps:

- Concept analysis and size reduction effect investigation;
- wind tunnel testing of a full-size model of the "*Bidule*" to quantify the general aerodynamics – special attentions being paid to the influence of the Reynolds number and the prop-wash effect.

"*Bidule*" Size Reduction Analysis

The endurance of an aeroplane can be written as a function of the power: Endurance = f(1/P). Recalling the required power to maintain steady level flight, where *m (kg)* is the vehicle's weight, *S* (m^2) is the wing area, *CL & CD* are the lift and drag coefficients, ρ (kg/m^3) the air density and η the propeller efficiency:

$$P = \frac{m}{\eta}\left(\frac{m}{S}\right)^{\frac{1}{2}}\left(\frac{2}{\rho}\right)^{\frac{1}{2}}\left(\frac{C_D}{C_L^{3/2}}\right)$$

The previous equation shows that maximising the endurance requires minimising the power. The vehicle's weight and the wing loading are of major importance and have to be minimised as much as possible. The propeller efficiency also directly affects the power and has to be maximised. The flight level should be as high as possible to minimise the air density. The lift-to-drag ratio (C_L/C_D) has to be maximised as well. The vehicle's weight and the produced lift are apparently more critical than the other parameters, as they appear with a greater exponent in the equation of power. Finally, as mass and wing area deal with structure, lift-to-drag ratio involves aerodynamics, power is linked to available energy and propulsion, and the air density involves the mission profile, the equation of power clearly shows the strong coupling between the different design fields.

Aerodynamics
The equation of the power suggests that increasing the lift-to-drag ratio would be done preferably by increasing the lift, rather than focusing on a drastic drag reduction. The small size and low speed of μAVs also result in an unusually low Reynolds numbers. As the main constraint with the flight platform size mainly restricts the wingspan, high chord length might be achieved in the design process to increase the wing area. As a result, μAV configurations often have a low aspect ratio involving fully tridimensional aerodynamics. Moreover, at these low Reynolds numbers, the propeller efficiency is highly degraded.

Structure
In order to reduce the wing loading, the most critical parameter to work on is the weight of the airframe for a given wing area. In addition, the vehicle's high surface area-to-volume ratio limits the available volume for the payload. This is especially true for flying-wings, as the proportion of the empty room for the payload becomes a relatively flat volume and may be divided by structure spars and ribs. A high degree of integration is necessary for μAVs, as size and functional complexity have contradicting constraints.

Propulsion
The difference of power and energy density between electrical and thermal power sources is known to have a great influence on a vehicle's endurance. The difference of power density (usually expressed in W/kg) between an electric battery and combustible fuel is one of the major differences that strongly influence the vehicle endurance. Internal combustion engine powered vehicles also benefit from the weight reduction due to fuel usage. The present "*Bidule*" is a twin engine configuration. From an endurance point of view, each motor of a twin engine configuration requires less power than a single engine solution to maintain flight conditions. However, it is not yet clear whether the addition of important losses due to the low terminal efficiencies (also due to the low Reynolds number) would be lesser for a twin engine configuration than that for a single engine, with regard to energy penalty.

Stability
Attention is to be paid to the longitudinal stability margin and the lateral manoeuvrability. The stability margin needs to be rather high for two reasons. Firstly, the drone must be able to fly smoothly to achieve exploitable observations; secondly, the vehicle is expected to fly at low altitude in a turbulent atmosphere, and thus should be stable enough to be as unaffected as possible by gust perturbations. The lateral manoeuvrability should allow tight turns.

Synthesis
The aerodynamics is strongly affected by the Reynolds number drop, which increases the drag and produces fully tridimensional phenomena. This low Reynolds number also influences the propulsion system global efficiency. When dealing with endurance, the most critical parameters are apparently to minimise the weight in order to decrease the wing loading, and to maximise the lift in order to increase the L/D ratio. The power density and energy density also seem to have a great importance, but investigations into this still need to be done. Attention has also to be paid to the number of engines, especially to account for the effect of mechanical losses.

Wind Tunnel Testing of A Propelled Model of the "*Bidule*" mAV

A full-scale model of the "*Bidule*" (Figure 2) was built without propellers for non-propelled wind tunnel tests, after which motors (WES DC6-8.5) and propellers (7"x 3") were integrated for propelled tests. The model was fitted with adjustable elevons. Testing the model at different Reynolds numbers was achieved by varying the tunnel dynamic pressure. Testing was done at two

Reynolds numbers: $Re1 = 1.84 \times 10^5$; and $Re2 = 3.,95 \times 10^5$. Aerodynamic loads were recorded for a range of angles of attack from –10° to +30° for the non-propelled model, and from –10° to +15° for the propelled model. Propelled tests were performed at Re1 only and two engine-ratings were considered: RPM1 = 4000 RPM and RPM2 = 4200 RPM. The experimental data were corrected for any errors due to instrument drift, balance misalignment, drag and interference of the supporting system, model weight effects, and tunnel wall boundary effect. The blockage evaluation showed that the maximum total blockage value was below 2%, what was considered low enough to ignore the blockage correction. The Reynolds number effect was interpreted through the non-propelled results and the prop-wash effect was analysed through the propelled session data.

Influence of Reynolds Number

As Re2 represents more than double the magnitude of Re1, the tests were performed at significantly different freestream conditions. However, the effect of the Reynolds number is not as important as expected, in particular when considering the drag variation, the maximum lift coefficient and the static stability. The drag polar (Figure 3 left) shows that the maximum-Drag increase due to the Reynolds number drop is generally low (of the order of +22%). The CD_{0min} value is not significantly modified (0.032 at Re1 and 0.034 at Re2) and no "chaotic" behaviour was noticed. A noticeable effect of the Reynolds number on the Lift is a delay of the stall at a higher Reynolds number (CL_{max} = 1.16 at Re1, CL_{max} = 1.2 at Re2). The Reynolds number affects the general trend of the Pitching Moment (Figure 3 right), especially at low angles of attack. At this region, the static stability is slightly degraded as the slope (dCm/dCL) of the linearised curve changes +21% from Re1 to Re2. It can be concluded that, from Re1 to Re2, variations in parameters such as zero lift angle of attack, yawing moment coefficient and elevon efficiency are much more relevant to a pure effect of speed variation that decreases the aerodynamic loads, than the result of a viscous interactions as for example when a laminar bubble appears on a profile. In the context of the "Bidule" size reduction, the Reynolds number drop is then not a critical parameter. It affects the static stability slightly, however its effect on the lift is not significant and the drag degradation is low.

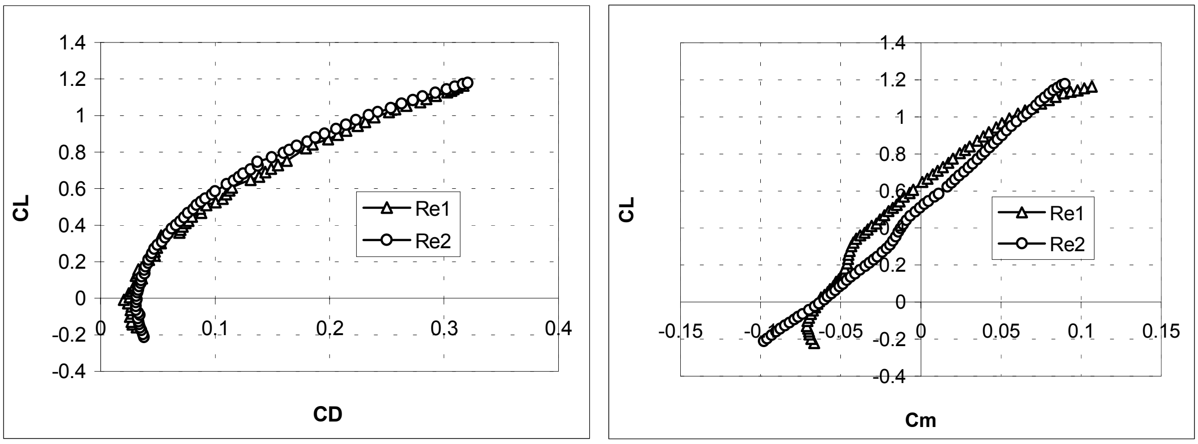

Figure 3 Corrected Longitudinal Coefficients, Non-Propelled Model

Prop-Wash Effect

An evaluation of the thrust produced by the power system was conducted to approximate the thrust coefficient commonly used in power system analysis. In the present conditions the evaluated thrust can not be disconnected from the interaction drag due to the power system and the slipstream. Thus the real engines' thrust coefficients are higher than the values considered here. The expression of the thrust coefficient is recalled, where *T (N)* is the thrust, *ρ (kg/m3)* is the air density, *n* is the number of revolutions per second = RPM/60 and *D (m)* is the propeller diameter:

$$C_T = \frac{T}{\rho \cdot n^2 \cdot D^4}$$

The corrected results are shown on Figure 4. As can be seen, Lift benefits from both the presence of the slipstream and the thrust, as they increase the magnitude of the lift, as well as the lift curve slope. The comparison with the non-propelled model shows an increase of the lift curve slope (+15% at RPM1 and +17% at RPM2) and an increase of the lift coefficient at zero angle of attack from 0.11 to 0.19 (+72%). The slope change of the Pitching Moment is very low with power variation. The difference with the non-propelled results is clear however, as an increase of the pitching moment curve slope of about 30% is noticed when the model is powered. Thus the presence of the power system creates a longitudinal destabilising effect. Nevertheless, in the present test conditions this effect is not significantly accentuated when the power is increased. Moreover, due to the thrust line not passing through the centre of gravity, a parasitic yawing moment appears.

To conclude about power effects, it has been shown that the prop-wash effect modifies the wing's overall aerodynamics. Lift benefits from both the vertical thrust component and the presence of the slipstream. This is important, as it validates the basic design of the "*Bidule*". Power was shown to be stabilising both longitudinally and directionally. These phenomena are of low magnitude on the "*Bidule*" however. In keeping with the size reduction of the "*Bidule*", the present results analysis suggest the retention of the idea of a wing immersed in the propellers' slipstream, providing that the destabilising effects due to the power system and the prop-wash can be kept as low as possible so as not to interfere with the payload efficiency.

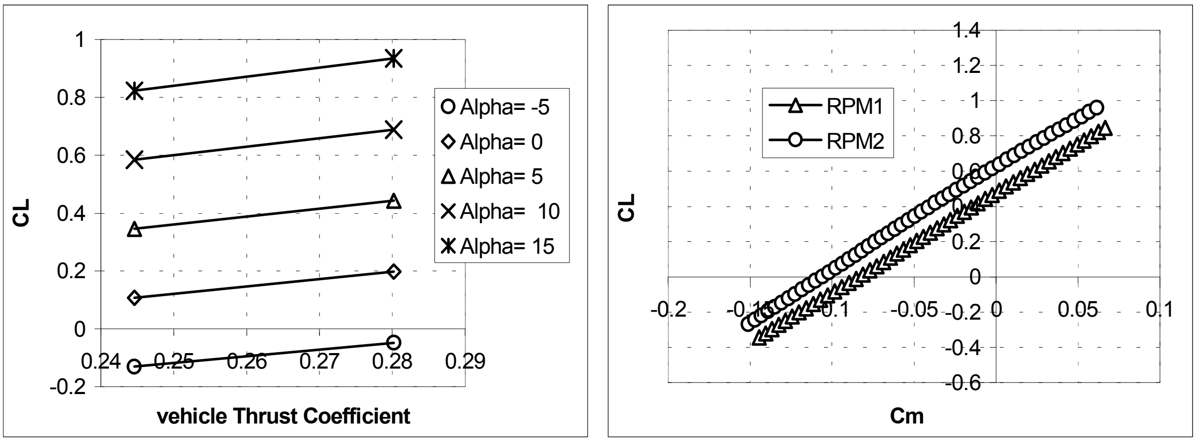

Figure 4 Change in Total Corrected Lift and Pitching Moment due to Power Increase

Conclusion

It has been qualitatively shown that the design of micro sized vehicles is not a simple problem. The high degree of integration resulting from the size of these vehicles and the operational requirements has a tremendous effect on their global endurance, which is the most important of any operational capabilities. With reference to the "*Bidule*" which was evaluated, the wind tunnel results have also shown that the basic design was valid, as the prop-wash effect significantly enhances the low flight capabilities of the vehicle.

REFERENCES

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