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Importance of Wind Tunnel Test in Design Process of Micro Air Vehicles

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Abstract

Micro Air Vehicles (MAVs) have been studied and researched for a ten year. Many platforms have been developed and numerous MAVs have been successfully flown. Due to their small size, there are a lot of challenges for engineers such as selection of materials, control system, and components. Aerodynamic is another issue which is most attractive for design of MAVs as well. Since they have very small size and fly at low speed, their low Reynolds number and laminar separation bubble result in very poor aerodynamic performance. In addition, due to limitation of size, fixed-wing MAVs are usually designed by very low aspect ratio wing. High completed 3D flow problem induces more difficulty for determination of aerodynamic characteristics. Moreover, aerodynamic-structure and aerodynamic-propulsion interactions strongly present in the design of fixed-wing MAVs. Most numerical simulations still cannot well determine a good result. Therefore wind tunnel and experimental tests are necessary for a good design process of MAVs.

***Keywords**:* Aerodynamic of Micro Air Vehicle, Design Process, Wind Tunnel Test

1. Introduction

Interests, demands [1] and challenges of a small-size unmanned air vehicle or Micro Air Vehicle (MAV) are very attractive for aerospace engineer, in particular an unconventional configuration MAVs. Several subjects involve in this design topic such as miniature structures, new materials, tiny electronic sensors and components and etc [2]. Very low Reynolds number is another importance topic in design of MAV. Although many platforms have been developed and numerous MAVs have been successfully flown, their aerodynamic characteristics are sometime still unidentified. This is due to its particular size and configuration. Aerodynamics of MAV is very complicate and it is still hard to determine only by theoretical, by analytical or by numerical methods. This paper introduces the main difficulty of aerodynamic problem and the importance of wind tunnel test for MAV design.

2. Design methodology

After the customer requirements and the specification of aircraft had been setup, design process of the aircraft is usually separated into 3 steps including the conceptual design, the preliminary design, and the detail design. Since aerodynamics of conventional airplane is well-known now, only analytical and calculation method will be used for the most of these design projects. Wind tunnel test may be introduced to the design process for some special requests and in particular at the end of design step. Wind tunnel test is applied in order to validate the result and to find out the aerodynamics characteristics. Reference 3 done by Werner-Westphal et al. used a multiple lifting line method to compute aerodynamic characteristics but finally the result was compared with wind tunnel data. NASA used only an analytical way to preliminary design of their HALE UAV [4]. Computational tool for aircraft preliminary design was studied by Ref. 5. However, many aircraft and UAV is successfully flown without the result by wind tunnel testing as well. Because of an advance of numerical simulation modelling and technology of computer machine, the numerical simulation now take over the experimental method such wind tunnel testing. Many calculation tools are also able to examine the multi-disciplinary problem such aeroeleastic problem as done by HALE Solar-powered UAV of the Turin Polytechnich University [6].

Design cycle of MAV and NAV is globally comparatively similar as the air vehicle design cycle which means conceptual design, preliminary design, and detail design. Yet, aerodynamic problem of this very small air vehicle differs from the large air vehicle due to several issues. This results in a difficulty of each aerodynamic design step in particular multi-mission MAV. The bulk of MAV design methodology is described in Ref.7. Presently, wind tunnel is highly required for design of MAV which involves in each design step. Figure 1 illustrates the task interacts of wind tunnel test used for design of ISAE's VTOL tilt-body MAVion MAV [8-9].

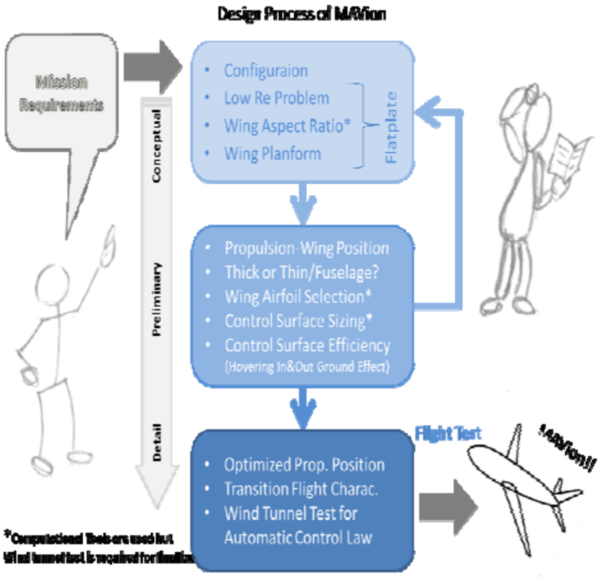
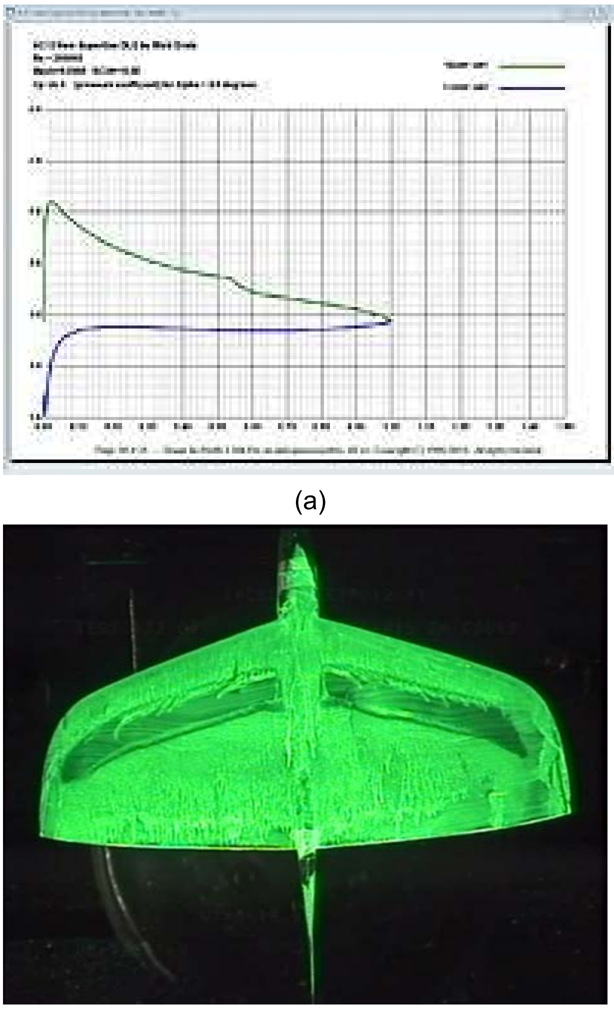


Figure 1: Design Process of MAVion MAV, one of the successful studies done at ISAE

3. Low aspect ratio low Reynolds number wing

First, we consider the 1 step of design process, wing without propulsion system. Since size and speed of MAV are very small, Reynolds number highly decreases. The laminar separation bubble is then occurring on the wing which results in a reduction of aerodynamic performance. This separation bubble is very important for aerodynamics of MAV since this small bubble is not small any more if it is compared with MAV's wing. The separation bubble strongly depends on different parameters such wing leading edge, angle of attack [10], wing surface roughness, turbulence intensity, and etc. Until present, this phenomenon is still hard to be well predicted by any analytical or any simulation method. Advance numerical methods such LES and DNS may able to well predict the low Re problem but experimental studies are still needed for validation of result [11].



(a)

(b)

Figure 2: Importance of Low Reynolds Number Laminar Separation Bubble
a: Pressure Coefficient around MAV wing, Calculation Result on Wing Section done by X-Foil Code
b: Separation Bubble on Strom-MAV Wing (Visualization from S4-Wind Tunnel Test of Murat Bronz, ISAE 2009)

Moreover, due to the limitation of dimension (15-20cm), MAVs are generally designed with very low aspect ratio wing. This wing geometry introduces high complex 3D flow. Even the effect of this very low aspect ratio was greatly studied as found in delta wing aerodynamic of fighters. Therefore it is not well reviewed for very low Reynolds number. Because of strong wingtip vortex on a wing surface, a stall angle of attack of LAR wing is delayed to 30-40 degree. Linear lift curve slope calculated by traditional formula is not efficient. Although some nonlinear formulas for LAR wing are proposed, wind tunnel test is still needed to determine aerodynamic coefficients [12]. Aerodynamics of LAR wing strongly depends on wing camber as well [13]. Due to this highly non-linear effect and high angle of attack, computational method does not well predict the separation of MAV wing. Figure 2 presents numerical and flow visualization result of Strom MAV wing. Disagreement of the separation bubble's location on the wing is illustrated.

Regarding from these two difficult aerodynamic problems and their combination problem, wind tunnel testing is required to determine an accurate aerodynamics characteristics in first design state.

4. Aerodynamics-propulsion interactions

After wing design is done, flying robot need power to go forward. Propeller is usually added. Beyond the low Reynolds number effects which also affect propulsion systems, MAV exhibits distinct features which are borne from the strong aerodynamics-propulsion coupling.

For example, as for propulsive tractor propeller vehicles, MAV are characterized by large propeller size compared with airframe dimensions. A strong prop wash flow directly impacts most of a wing area. In turn, wing performance, especially at low speed and high angle of attack is highly modified. Null and Shkarayev [14] had demonstrated a strong degradation of aerodynamic performance of MAV designed by propulsive induced flow at high angle of attack. But positive effects could be expected for other configurations such used by NRL configuration [15]. To enhance aerodynamic and flight performance of MAV, the design must carefully consider aerodynamic-propulsion interaction. Difference unconventional platform by fortunately integrating of propellers should able to improve MAV flight efficiency [16]. Due to the demand of using Mini UAV in a confined area, rotorcraft concept is also aroused because of its great hovering performance. Nevertheless, many ducted configurations were investigated because of its compactness [17-18]. Although disc actuator method is well predicting the effect of propulsive-induced flow of the lift created by ducted [19], the experimental result is required for the validation [20-21] of CFD result. In consequence, interaction between wing and propulsive system is important for MAV design so it has to be carefully studied.

The test of propulsion system, at high angle of attack, forms a specific challenge to experimentalists. Thick wakes, plumes impacting on wind tunnel walls usually direct users to set-up experiments in open jet facilities, even if this does not represent an ultimate solution. Standard wind tunnel corrections cannot be deployed in such conditions and it is likely that coupling of experiments with numerical simulations of the tested configuration is the most appropriate procedure.

5. Aerodynamics-structure interactions

An overview of flexible wing aerodynamics is proposed in the monograph of Shyy et al. [22] and in Mueller et al., 2007, pp 185-240. The general framework of the structural modelling is a membrane model.

Numerous flexible membrane wings have been studied at the University of Florida since 2002 [23]. Both simulation and flight test were performed to demonstrate the advantages of the flexible concept. They showed that flexible wings are more stable and less perturbed from external wind variation or wind gusts. Another advantage of flexible wing is that it is easy to modify camber. This may be useful for multi mission MAVs in term of optimizing induced drag. The flexible wing concept is also a focus of the current MAV project and its advantage will be experimentally investigated.

Micro Aerial Vehicle (MAV) has recently been developed to be multifunctional in order to offer a wide range of services. Extending the overall performance envelope of MAV, in terms of mission type, flight range, flight load, flight stability and so on, flight mode is expected to be changed from hover to vertical flight and vice-versa. Obviously, this change relies mainly upon the transition of MAV rotors. So, the geometry of propeller or rotor plays a dominant role in the flight mode modulation of MAV. Admittedly, the widely applied adjustable pitch angle mechanism achieved more or less that mission. However, the disadvantages of this mechanism, such as the corresponding weight weakness and the overall ruggedness degradation, cannot be denied; therefore, it is imperative that new concepts are proposed to overcome them.

The anisotropy of composite structures evidently offers the potential of morphing a rotor through careful choice of structural layout. In this concept, the passively adaptive flexible blades will be employed in order to improve horizontal flight performances for range and covertness issues, as well as hovering performances for endurance purpose. The proposed study will principally focus on exploring aerodynamic and structural performance of this flexible rotor experimentally, which is to be compared with the CFD/CSD numerical simulation.

As it is well known, insects and birds have flexible wings to adapt to their flight environment. They can deform their wings for a wide variety of flight modes. A considerable amount of research on flexible wing has been done in recent years. The research from Swartz [24] shows that the highly deforming bones of bats enable them to achieve an outstanding flight performance at either a positive attack angle or a negative attack angle. The wings of bats consist of membrane and arm bones and bats can flex their wings in minimal way to avoid structure failure and flutter and enlarge the wing camber during the downstroke. The corresponding wing kinematic data of bats have been measured by Tian [25]. It has been shown that the bats can decrease wing areas to increase the forward velocity through changing their wing spans. It sufficiently describes that the kinematics of bats is more complicated than the simple flapping motion of insects and birds. On contrast, obviously, birds and insects flex their wings in different manners. The birds flex their wings during upstroke to minimize the drag and still keep the wing surface smooth by slipping the features. The insects bend the wing chordwise to generate camber and prevent bend in the spanwise direction. Flexible fixed wings enable both natural and manmade flyers to improve stability and controllability, which can indeed provide a more consistent lift to drag ratio than a fixed rigid wing by adaptively adjusting the camber according to the instantaneous flow. Evidently, the passive camber results in delayed stall [26-27]. Both rigid and membrane wings show clearly similar lift performance under modest attack angles. However, stall of flexible wings occurs at higher angle of attack than the rigid wing. This characteristic is a crucial feature in enhancing the stability and manoeuvrability of MAVs. Most importantly, the flutter frequency of a membrane is higher than the vortex shedding. A main reason for this phenomenon is the coupling of aerodynamics and structural dynamics. The flexible fixed wing concept has been successfully incorporated in MAVs designed by Ifju [23]. Unidirectional carbon fibers were used for the leading-edge spar and chordwise battens. The extensible membrane, made of latex rubber, was chosen to allow significant flexible wing deformations even under very small loads. The MAVs designed with this concept have been proved to remarkably improve the aerodynamic performance. The University of Bath in UK is also interested in flexible membrane wing for MAV application as well. Many works achieved by wing tunnel test had been done and published [28-29].

Since flexible fixed wing scored a great success in MAVs performance improvement, a natural extension of the passively adapting concept is to expend it to the design of a combined propeller/rotor [30]. Currently, Ph.D. Student at ISAE is working on the design of flexible rotor for MAV. Experimental modal analysis of the rotor should be performed with different support stiffnesses in order to compare with the numerical result as well.

With rapid developments in aerodynamics, aeroelastics and materials, the flexible rotor represents an attractive design option to achieve better overall performance. Currently most flexible rotors operate under high Reynolds number conditions and the proposed work will contribute to transfer the passively adapting concept to fixed flexible wing and flexible rotor, for MAVs applications.

6. Aerodynamics-control interactions

In addition, the interest of multi-mission MAV is new challenge for designer. Both hovering and forward flight capacities are requested. Several concepts had been investigated [31]. Finally, the most attractive platform is a tilt-body platform [32]. The characteristics and efficiencies of control surface both in-ground and out-off ground effect must be investigated such presented by Ref.33. The aerodynamics of VTOL MAVs during transition between vertical and horizontal flight modes must be identified in order to well design control laws. At low speed and high AoA, local flow on MAV wing is strongly merging between incoming freestream flow and propulsive induced-flow. Local aerodynamic of wing and the control surface are modified. McCormick [34] had reported the calculation of this flow interaction but it is not accurate for very low Reynolds number. Flight path stability is very important for searching and identifying targets on the ground, especially for a camera platform MAV. A review of autopilot for MAV applications is given in Mueller et al., 2007 [7]. Although an advanced and efficient technique of flight path planning and control for UAV has been well summarized, an accurate and correct aerodynamic derivative coefficient is highly important for MAV control. Moreover, since the flying model is always not perfect as design for example from material, fabrication technique and process, and the detail element such junction and control linkage. The aerodynamic of flying model may change. The campaign of wind tunnel test for investigating of platform aerodynamics and control surface efficiency is normally set up at the end of design process both just before and during the flight test.

7. Conclusions: Testing as a validation tool

According to the sections above, aerodynamics of MAV is highly interaction problem which is induced by low aspect ratio low Reynolds number aerodynamics, aerodynamics-propulsion interactions, aerodynamics-control interactions and aerodynamics-structure interactions. Obtaining the aerodynamic characteristics of MAV is involved by many parameters. Therefore, design of a small air vehicle such MAV is very difficult comparing with other air vehicle in particular for unconventional configuration. Present numerical calculation may be applied for very roughly predict of early design process. Some effects of initial parameters can be more or less evaluated such wing aspect ratio [35], wing camber, wing thickness [36]. However, wind tunnel test is strongly required for the validation of concept and design of MAV.

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