Study of a Flexible Wing Applied to LSFWB MAV

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Abstract
Low-speed fixed-wing biplane micro air vehicle (LSFWB MAV) has been developed for a few years at the department of aerodynamic, SUPAERO. The protoype TYTO-30 was performed successfully. The wind tunnel and flight test illustrated the performance of biplane concept for flying at low to high speed. However due to its very small mass, MAV is very sensible for wind gust and flow perturbation. A flexible wing concept was experimentally applied to the TYTO's forewing. The tested was carried out in the low-speed wind tunnel with the gust generator. The results show an advantage of flexible wing concept in term of force variation reducing.

1. Introduction
Micro Air Vehicles (MAVs), which has a dimension limited with in 15 to 20cm, have been interested since 1996. Many MAV was developed and participated in an International MAVs Competition. Due to its very small size, MAVs are usually designed with very low aspect ratio (LAR) monoplane wing concepts that resulting in very high induced-drag. *Laboratiore de l'Aérodynamique et de la Propulsion* of SUPAERO in Toulouse, France, proposed a biplane concept to correct this high induced drag problem [Ref.1]. Biplane MAV is interested if it has high load and fly at a low speed [Ref.2]. A low speed fixed wing biplane MAVs was successfully tested in 2006 with a dimension 50cm [Ref.3] and in 2007 with a dimension of 30cm (called TYTO-30). In Sept 2007, TYTO-30 will participate in 3rd US-Euro MAV competition. Although TYTO-30 can be operated at high speed range from 4 to 18 m/s, it is still been developing to improve aerodynamic performance and stability.

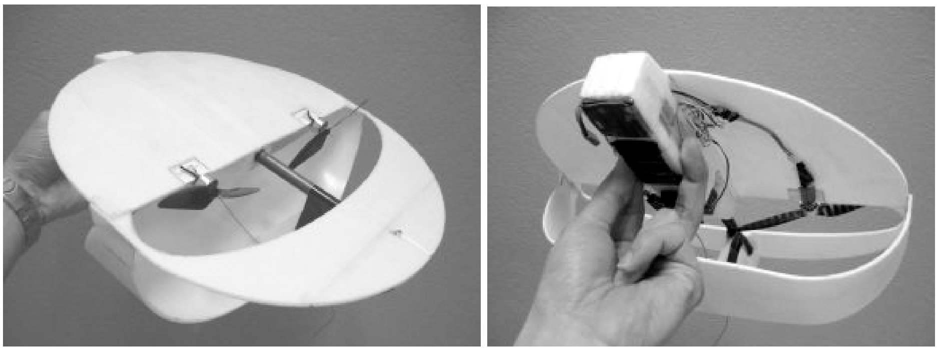


Figure 1: TYTO-30, low speed biplane pusher fixed-wing MAVs

1.1 Why?
There are 3 objectives for using active morphing wing to TYTO concept as the priority following.

1. MAV's Reynolds number, size and mass are very small compared with other air vehicle [Ref.4]. The aerodynamic forces produced by MAVs are very small. Drag force can be just only a few grams lift force is order of 100 g. MAVs is very sensitive to wind variation due to its very low mass inertia. Study of Simon [Ref.5] shows that the variation and turbulence are importance although MAVs are operated at low altitude. In addition, wind variation is becomes more importante in low speed flight [Ref.6]. In table 1 illustrates the characteristics of different air vehicles. During cruise, airplanes are in equilibrium (Eq.1) and then head wing of gust 5 m/s is applied (Eq.2). From Newton's law and aerodynamic force equation, acceleration which is a function of wing surface over mass is shown in the last column.

$$L = W = 0.5\rho V^2 S C_L \quad (1)$$

$$\Delta F = 0.5\rho S C_L \left[(V+v)^2 - V^2\right] = ma \quad (2)$$

To improve stability, MAV should have a static margin more than a bigger air vehicle that means the CG must be placed more close to the wing leading edged. This will result again a problem in weight balancing and component arrangement. For this, the first objective is to damping longitudinal wind gust response of TYTO.

Table 1: Force variation and acceleration perturbed by gust 5 m/s

	Mass	Span	Wing area	AR	Cruise speed	Force Variation	acceleration
Cessna 180	1185 kg	11 m	16 m^2	7.5	70 m/s	6844	5.78
K 100 (CAC system)	25 kg	2.6 m	0.9 m^2	7.5	~50 m/s	279	11.15
Dragon Eye	6 kg	1.1 m	0.33 m^2	3.6	18 m/s	40	6.65
Black Widow	0.08 kg	0.15 m	0.023 m^2	1	13 m/s	2.1	26.29
6" MAV (UF)	0.06 kg	0.15 m	~0.015 m^2	~1.5	25 m/s	2.4	40.56

2. TYTO concept was designed to minimize drag force particularly for very low speed flight but it must also travel at very high speed to arrive the target zone in a short time. So TYTO has very large operation speed. The study of U. of Arizona [Ref.7] and our experiment [Ref.8] shows that wing camber highly affects to minimum and induced drag. Low camber wing has small parasite drag but low lift coefficient and produces high induced drag. It is more adapted for high speed. In opposite way, high camber wing should be applied for a low speed flight.

3. In low speed mission, TYTO is operated at very high angle of attack where a pitching moment coefficient is very high and very far from an equilibrium design point. Since again MAV's dimension is very limited and tail moment arm is very short so the elevator must highly deflect and horizontal tail produces high negative lift. So TYTO need some device to reduce or correct this problem.

1.2 How?

A morphing wing concept was used in many aircrafts to improve their performance for operating at difference mission. A flexible wing was firstly applied to MAV by U. of Florida in 1990s [Ref.4]. Several morphing MAV concepts are also realized and used for control instead of conventional control surface [Ref.9-10].

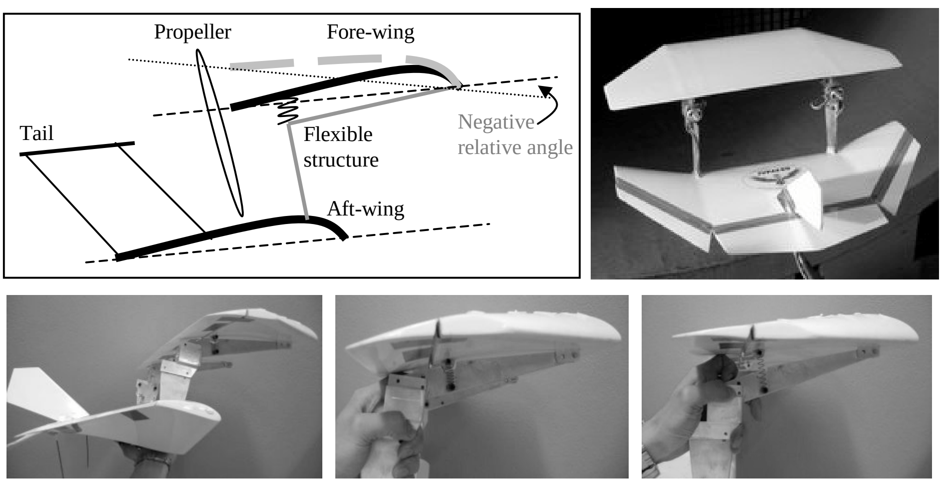


Figure 2: flexible biplane structure concept and Avilent model

Flexible biplane structure concept

Since the relative angle between two wings in positive stagger biplane can modify wing's pitching moment and lift coefficient, biplane MAV has more damping property if this relative angle can be well automatically adjusted with the incoming free-stream (Fig.2a). However the wing camber and profile are always the same, so an induced drag factor of biplane will not be much modified. Biplane is early stall when having high relative angle (relative angle is positive if the fore-wing's AoA is higher than that of aft-wing). More and more, even biplane's stall angle is changed but the maximum lift coefficient always approximately the same. This concept seems to not very satisfy the second objective. The flexible structure concept was also already realized in a large wind tunnel test section 2x3m^2 with the model Avilent as in Fig.2b. The results are not very satisfied due to the spring used.

Flexible fore-wing biplane concept

Another solution is applying a flexible wing to the fore-wing as shown in Fig.3. Changing of lift and moment on the fore-wing will modify and automatically damp longitudinal gust response. The flexibility of wing is also easier to adapt wing's camber, which highly modify an induced drag coefficient. The study of U. of Florida shows that the optimized flexible wing structures can also enhance the maximum lift force coefficient of wing. This result is very attractive for very low speed MAV. If the wing is can be optimized, TYTO should have more capacity for low speed.

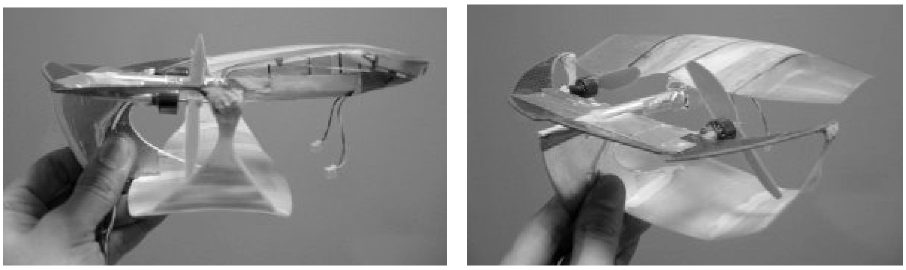


Figure 3: Flexible forewing concept

2. Model and Experiment

The numerical study on flexible wing concept was first done by using TORNADO and SAMCEF. The interface between two calculators was coded to transfer the result of each code. Tornado code is a vortex lattice calculation developed by KHT [Ref.11]. The viscous effect was considered and added into the code. Finite element method code SAMCEF was used to determine wing deformation after applied aerodynamic force and moment obtained by TORNADO. Tornado then uses new wing deformed profile to solve the new aerodynamic coefficients. The calculation is performed looping until the deformation convergent. The simulation gives the tendencies of deformation and the effect of structure on flexible wing. However, the result, which not presented here, when compare with experimental data is not acceptable because of lack of material property in calculation and also low precision and low experience in fabrication process.

In this paper study was done experimentally in low speed wing tunnel at SUPAERO. The aerodynamic characteristics were measured by high precision micro-balance developed by Aerodynamic and Propulsion Laboratory (LAP) in 2004 [Ref.2]. The wind tunnel provided at LAP is standard close loop type, test section 45cm by 45cm. Velocity is controlled by the power of motor and need long period to stabilize flow in test section. The wing gust can not be generated, so a new system was installed on this wind tunnel. This section explains the facilities and wing model.

2.1 Gust generation system

Gust generator system in wind tunnel test has been use by many universities. The principal is based on a perturbation method and most of them install gust generators in the convergence section just before test section [Ref.12-13] and they generate both longitudinal and vertical gust. This concept is usually used because it can be applied even in open loop wind tunnel. In order to generate longitudinal variation, many perturbation devices must be applied. Turbulence from these devices is also very high and reduces a quality of freestream. So new gust generation system was designed and tested by installing two rectangular plates in the convergence section. A rotation of these plates (Fig.4a), controlled by high torque motor, and creates a solid blockage in the wind tunnel resulting in a variation of flow in test section. The system is very simple as show in Fig.4 on the right. The variation of freestream depends on the initial flow velocity, the rotational speed of motor or plates, the size of plates and the rotational angle of plates.

$$U \approx fn(U_i, \varpi_p, S_p, \beta_p) \quad \textbf{(3)}$$

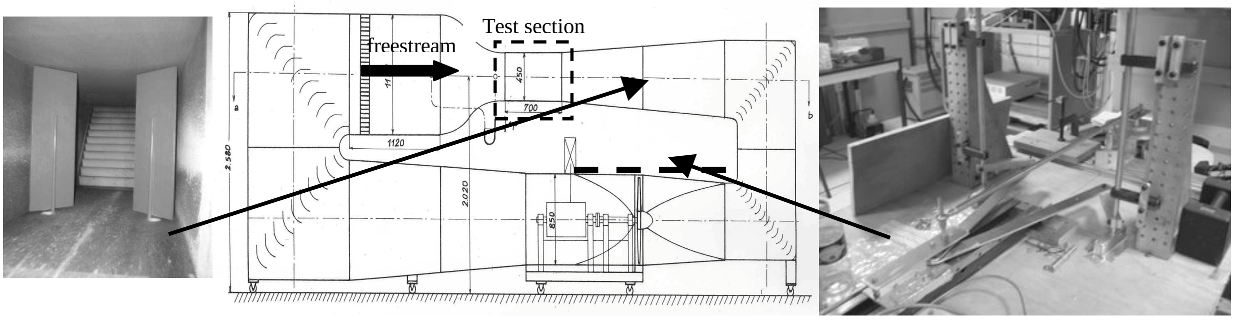


Figure 4: Longitudinal gust generator and low speed wind tunnel

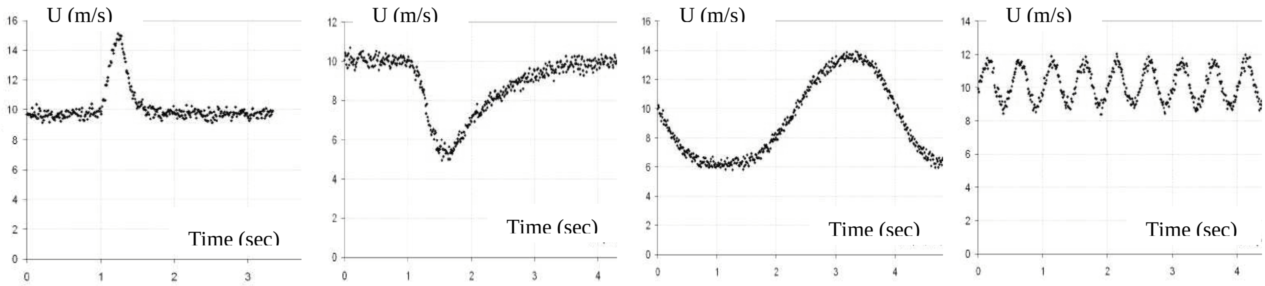
The system is highly repeatable because a commendable high torque motor was use. After installed two plates in the wind tunnel, turbulence intensity in test section was observed by LDV method, and it found that turbulence increasing is very low by this system, as illustrated in table 2. Mean velocity interested in this study is equal to 10 m/s which is the average speed between that of corresponding maximum L/D and of minimum power required [Ref.2]. Totally, 4 forms of flow velocity performed are presented in Fig.5; head wing gust, tail wind gust, low frequency variation speed and high frequency variation speed. The velocity in the test section was measured by hotwire anemometer TSI Model 8450.

Table 2: Mean velocity and turbulence intensity in test section

Position of plates (β)	Mean velocity (m/s)	Turbulence intensity (%)
No Plates	10	0.9
0° (parallel to freestream)	10	0.9
45°	7.3	0.9
90° (normal to freestream)	3.2	1.6

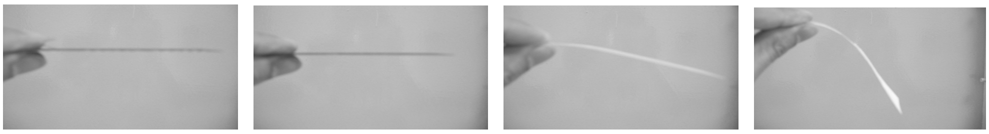
2.2 Materials and Wing models

The University of Florida uses extensible material in their flexible wing and successfully tested and proved in flight by many monoplane MAVs. In SUPAERO, we can not find latex or any extensible material to fabricate a flexible wing. Then our flexible forewing was made of composite material; carbon, fiber-glass and resin which have difference stiffness illustrated in Fig. 6a. The lowest fiber in Composite center of SUPAERO is type 25g/m^2. Many flexible wings were tested in wind tunnel but several will be presented in this paper as shown in Fig. 6b. Profiles or airfoils used are based on mean camber line of NACA 44xx and 84xx series.Another parameter in this study is effect of fabrication process or wing profile form. The first one called Non-developed profile wing is one that has difference wing profile along span-wise. The designed wing profile is applied only at root chord (44 for NACA 4400 and 84 for NACA8400) that differs from the second one, the developed profile wing (44D, 84D for NACA 4400 and 8400 respectively). All section along span-wise of developed profile wing has the same wing profile, the relative camber is always constant. The difference fabrication methods are shown in Fig.7.

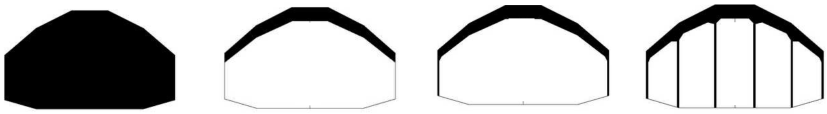


a) head wind gust b) tail wind gust c) low frequency gust d) high frequency gust

Figure 5: Gust and variation speed used in study

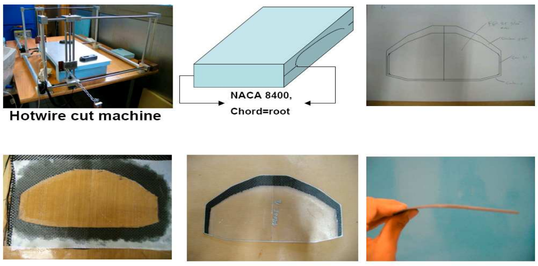


a. Rigidity of difference material applied to flexible wing
(from left to right : Carbon + resin, Carbon&fiber-glass + resin, 2 layers fiber-glass + resin and 1 layer fiber-glass + resin)

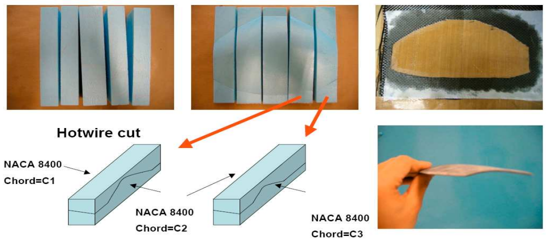


b. Wing structure (Black color – carbon&fiber-glass + resin and in white color – 1 layer of fiber-glass + resin)
(from left to right : Rigid wing, Flexible f1, Flexible f2 and Flexible f3)

Figure 6: Rigidity of difference material applied to flexible wing



a) Non-Developed profile wing



b) Developed profile wing

Figure 7: Fabrication process and Wing form

The fixation method or wing support was also included in the study. In fixation ‘A’, all root chord section is attached to the 3-cm larger fuselage so both camber and angle of attack at wing root are fixed. In fixation ‘B’, only first 50% of root chord fixes to the same fuselage, both camber and AoA can be adapted. Lastly, in fixation ‘C’, special mechanism was applied, this support fixes wing’s angle of attack while the camber can be changed. At the leading edge, pivot point, which arrows rotational in y-axis, is used while a slot support is applied at the trailing edge. All fixation support is presented in Fig.8.

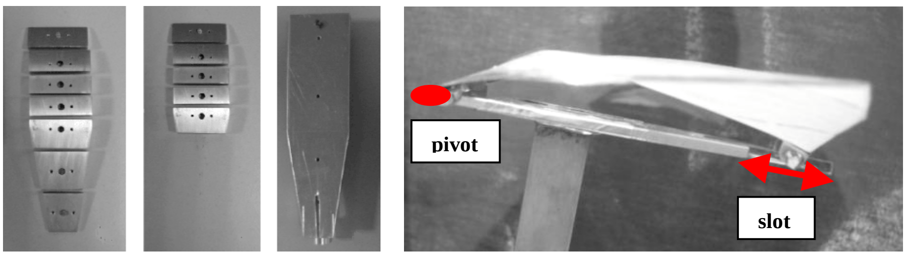


Figure 8: Fixation support (1st -type ‘A’, 2nd -type ‘B’ and 3rd and 4th -type ‘C’)

3. Results and Discussion

The tests were carried out first with a constant incoming freestream to observe wing characteristics of both rigid and flexible wings. Angle of attack was varied from –5° to 30°. Longitudinal aerodynamic characteristics were determined. Secondary, wings were test again at fixed angle of attack where lifts produced are identical (L=50g.) but the velocity in the section was varied.

3.1 Velocity effect and Wing structure

The result found is logically and it is similar to that of University of Florida [Ref.6]. Wing’s deformation highly depends on wing structure and applied force. The deformation of wing is in the way of both camber and angle of attack reducing when more force is applied. Wing that has more structures or battens is more rigid and more difficult to deform so that aerodynamic coefficient smaller decreased. Same as in low speed 5m/s, wing camber, angle of attack and aerodynamic coefficient are lower changed.

3.2 Wing form: effect from fabrication method

Aerodynamic characteristics are very sensitive to wing fabrication process. Even Developed profile wing has less battens structure than Non-developed profile wing, the lift coefficient of 84D-f1 is not lower than 84-f2. This due to the moment of inertia of developed profile wing is higher than that of non-developed wing (as see in the last photo of Fig.7a & 7b). The batten structure applied has very low effect to deformation (in undercamber direction) of Developed profile wing. Developed profile wing is very difficult to undercamber by itself. Table 3 shows an approximated wing deformation in term of equivalent wing camber.

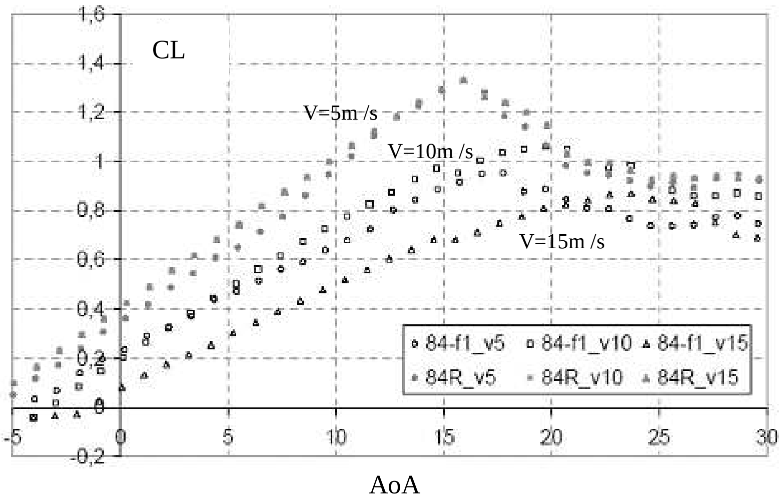


Figure 8: Effect of velocity on lift coefficient (V=5, 10 and 15m/s)

3.3 Fixation method

Fixation or support highly affects to wing deformation as well as wing aerodynamic characteristics. Absolutely, very high deformation was found in the wing fixation ‘B’ that has less constrains. The minimum drag of wing in fixation ‘B’ is lowest in all case because it can adapt itself to the freestream flow more than fixation ‘A’. However, it highly deforms even in high angle of attack so the maximum lift is very low.

In the case of fixation ‘C’ which originally expected for the second objective as explained in an introduction. Wing camber passively modified itself correspond to an angle of attack and freestream speed means that at high speed and low AoA, wing should have low camber to minimized parasite drag. And on contrary, at high AoA where operated in low speed flight, high wing camber is preferred to reduce an induced drag. The experimental result was not as expected, wing is overcamber in both case at 10 and 5 m/s. The calculation was also performed on wing NACA4400 and aerodynamic characteristics of wing were determined by formula given by Torres [Ref.14]. Normal and tangential force, produced by wing at difference AoA and speed correspond to the constant lift force condition, were determined and used to find the moment apply on wing structure. Normal force was applied at 40%C and tangential force was applied at half of maximum camber and the moment was calculated at leading edge. It was found that in both cases, wings have tendency to overcamber itself but the tendency of at high speed-low AoA is more than another situation. So the passive morphing wing concept is difficult to optimized and applied. Even additional mass of servo is added, the active control must be applied to success the 2^{nd} objective and it will be explained in section 4.

Table 3: Approximated wing camber deformation

	84D-R	84-R	84D-f1	84D-f3	84-f1	84-f3
Δ%camber at AoA=10°	0%	0%	3.2%	3.2%	5.6%	3.2%
Stall angle	22	16	22	24	20	20
C_L (max)	1.45	1.33	1.37	1.38	1.06	1.28

The deformation was determined by using the result on rigid wing NACA 0000, 4400 and 8400

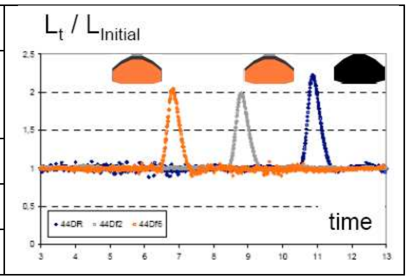
3.4 Dynamic response

The result presented here is in the term percentage of force and moment variation which calculated by the equation :

$$\%F_t = \frac{F_t}{F_{initial}} \times 100 \qquad \textbf{(4)}$$

The variation of aerodynamic forces and moment of flexible wing is smaller than that of rigid wing. This due to the variation of velocity compensates with changing in aerodynamic coefficient by deformation of structure. For example in head wing gust, that initial velocity is 10 m/s and suddenly increased to 15 m/s, from equation of lift, variation of lift should be increased up to 225% and this is exactly as experimentally found in rigid wing. Another side, this variation is equal to 200% in flexible wing model. Other results are resumed in table 4. It must be remarked that the variation of fiber-resin flexible wing is still high. This due to the material used is not extensible as used by University of Florida. However, it gives a tendency and advantage of flexible wing.

Table 4: Variation of force and moment

	Rigid	Flexible	Rigid	Flexible	
Gust form and [theoretical variation]	Head wing (10 → 15 m/s) [225%]		Low freq. (10 ± 3.6 m/s) [185%]		
Variation of Lift	225%	200%	185%	170%	
Variation of Drag	225%	180%	180%	170%	
Variation of Pitch	230%	215%	180%	170%	

4. Active Flexible Forewing

Increasing camber enhances minimum drag but reduces induce drag. The result found on a rigid wing camber 0, 4 and 8% shows that camber 4% gives highest L/D because it is optimizing between minimum and induced drag [Ref.8]. In practical use, each wing camber is suitable for difference flight speed. Study of University of Arizona recommends high wing camber for low speed mission and low camber for high forward flight to arrive the target quickly as possible with lowest energy. They had applied adaptive flexible wing concept to monoplane MAVs [Ref.15]. The same concept is applied to biplane MAVs. Two servo motors were installed at leading edge, the wing camber and AoA are controllable by the linkage as shown in Fig.9. This was used for both pitch control and roll control. However only pitch results are interested in this paper. The tests were done at velocity 5 and 10 m/s. The result found high camber wing produces more lift and lower induced drag. For C_L less than 0.5, low camber wing position 'C1' (camber at static point is 4%C) has higher L/D and should be used at 10 m/s while high camber position 'C2' (camber at static point equals to 8%C) is more appropriated for low speed mission.

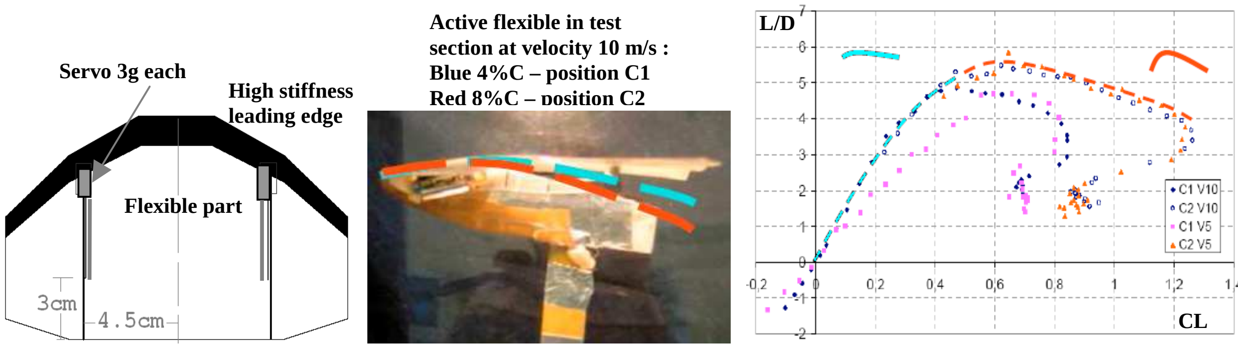


Figure 9: Active flexible wing controlled by servo-motors and L/D

5. Application

The active flexible forewing then was installed into the LSFWB MAV's model as shown in Fig.3. Two brushless motors LRK and propeller GWS 3030 were used. The flexible biplane tends to been less perturbed and more stable in gust condition than rigid biplane configuration. For example in head wind gust, un-powered model, variations of force are 238% and 213% for rigid and flexible configurations respectively. Same as in power model, variations of force are 207% and 182% for rigid and flexible configurations respectively. Induced drag factor reduces from 0.32 (rigid forewing camber 4%) to 0.27 when applying high camber C2 position. In addition, pitching moment coefficient at aerodynamic center is moved from -0.02 to + 0.06 by using high camber forewing. This arrows biplane MAV is easier to balance at low speed and high angle of attack. The maximum lift, in powered model identical energy, also increased from 2.5 to 3.0. The result in detail can not be presented because space limited. Finally, 6 grams of the additional mass from two servo motors is less than the addition lift force, 13.5 grams at 5m/s, benefited by active camber wing. In practical, one servo motor is enough for camber pitch control. Finally MAV gains 10 grams lift.

6. Conclusion

The flexible concept was applied to the forewing of biplane MAVs in order mainly to reduce or damp longitudinal gust that is very important for a small air vehicle. The gust generator was installed in low speed wind tunnel at SUPAERO. Gust generated is highly repeatable so comparison test had been performed. The experimental result shows that flexible wing characteristics are highly depend on velocity, structure, wing profile form and fixation method. The test result shows an advantage of biplane flexible concept although the efficiency of fiber-resin flexible wing is not very good as expect and found by U. of Florida. Active flexible biplane MAV reduces variation of force perturbed by longitudinal wing gust, and also improves aerodynamic performance and balancing as the objectives. In the future, an extensible material and optimized form and structure should be applied in the real application.

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