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THE VERY FLEXIBLE AIRCRAFTS AND ALBATROSS FLIGHT

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Abstract

This paper presents an investigation to the characteristics and the aerodynamic performance of very flexible aircrafts (VFA), as well as provides several control strategies to change the shapes actively. Comparisons are made in terms of aerodynamic performance of different shapes of VFAs which are induced from albatross fight. The notion that to fly a VFA like an albatross is discussed based on the feasibility and deformation strategies.

1. Introduction

High-aspect-ratio aircrafts develop rapidly on the demand of military and civil utility, such as the "Helios" developed by Aero-Vironment and "Zephyr" developed by QinetiQ, as well as the "SolarImpulse" , those programs have achieved a lot of records and show a attractive perspective in intelligence, surveillance and reconnaissance missions. Moreover, Google and Facebook companies enter into this field actively by investing to the solar-powered high altitude and long endurance (HALE) aircrafts acting as the High Altitude Pseudo-Satellite. As shown in Fig 1, those are some HALE aircrafts or conceptions.

Aimed at the long endurance at high altitude, it needs to maximize the aerodynamic efficiency to keep the balance of the energy recycle which plays a crucial role in the HALE system, and these aircrafts tend to have high aspect ratio wings, allowing high lift-to-drag ratios. Besides, it has to keep the weight of structure fraction as small as possible to reduce the energy consumption and to keep a budget for the weight of other subsystem, such as rechargeable battery.

Fig. 1. Some HALE Aircrafts or Conceptions

A dominating character of those unconventional aircrafts is that they undergo large deformation during the flight as the stiff is much less than the traditional ones. In fact, wingtip deflections as high as 43% of the half span have noted.

Albatross, whose wing is about 12 feet for tip to tip, is one of the biggest birds in the world. Different from the others, albatross seldom flap its wing during flight. It glides in the wind for a long time only by changing the shape of its wing [1], it is an efficient approach to flight.

There is so much resemblance between very flexible aircrafts and albatrosses of the configurations and stiff. So, could the VFAs fly like the albatrosses by shifting their shapes actively and how to realize the change of shapes? Based on those question, this article presents an investigation to the characteristics of the very flexible aircrafts (VFA) and the aerodynamic performance, as well as provides several control strategies to change shapes actively. Lastly, the notion that to fly a VFA like an albatross is discussed based on the feasibility and control efficiency.

Here are some pictures of VFAs and albatrosses.

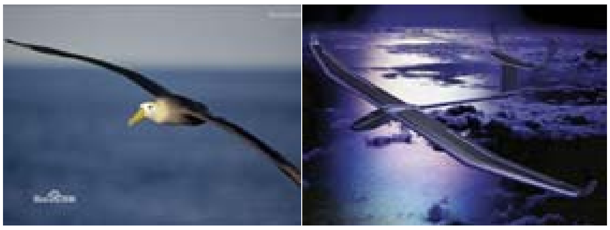

Fig. 2. Albatross and the First Model of Solar-Impulse

Fig. 3. Albatross and Zephyr UAV in Flight

2. Background

For the Very Flexible Aircrafts, the aspect ratio is much larger than the traditional ones and the weights are much lighter than the conventional aircrafts for the same size. For instance, the take-off-weight is only 2000kg (2 tons) of SolarImpluse whose wing is 63.4m which is two times longer than a Boeing 737 whose take-off-weight reaches to more than 30 tons. Massive composite material are adopted in manufacturing the structure of the VFAs, especially the carbon fiber and the honeycomb structure is widely used.

For those reasons, the VFAs would undergo a large deformation when flying in the wind, especially when the maneuver takes place. As a consequence, a serial of questions are derived by those flexible features. [2-6]

Firstly, when deformation occurring, both the aerodynamic performance and the load distribution changes heavily. It is a tough issue to handle the law between the deformation parameters (like frequency, torsion angle) and the dynamic performance. Unfortunately, the law plays a very important role in the control system designing. Another noticeable question should be taken into consideration is the control efficiency of aileron. To roll a plane, the aileron moves downwards to acquire the lift / moment, but a down-head moment would appear to decrease the locate attack angle of the wing, which means the control moment lose at a certain extent. As the elasticity keeps constant while the down-head moment is a square function to the airspeed, the aileron would lose its function at a certain velocity.

Then, the nonlinear characteristic of the structure caused by the large deformation is remarkable [7]. As a consequence of large deformation, the geometric-nonlinear effect should take into consideration, the structure characteristics is quite different from the traditional ones which could be solved based on the linear assumption. Several research group have been paid attention to this issue, and plenty pioneer work has been done. [8, 9]

Thirdly, the aeroelastic response shows strong nonlinear effect and highly sensitive to the turbulence [5, 10, 11]. As repeatedly mentioned in the Ref [12], one of the root causes is lacking of analysis methods led to an inaccurate risk assessment of the effect of configuration changes. The recommendations is to develop more advanced, multidisciplinary (structure, aeroelastic, aerodynamics, etc.)” time-domain” analysis methods appropriate to highly flexible, “morphing” vehicles. The traditional methods to analyze the aeroelastic are based on the linearization of the structure and aerodynamic models. However, the recent researches [13] have proved that the effects of flexibility may make the response of the vehicle very different from the rigid, which means that the methods based on linear models we employed are no longer feasible for the very flexible aircraft. Based on the theory of nonlinear beam theory and ONERA aerodynamic, the results acquiring by Tang and E.H. Dowell [14, 15] are in good agreement with experiment for static aeroelastic response and dynamic LCO amplitude and frequency. Another problem should be noted is that the aeroelastic response of this kind of vehicles is very sensitive to the turbulence like the gust of the wind, which can lead to a divergent consequence. Breaking down of the Helios HP03 when against in the turbulence is a convictive illustration of the issue. So it is crucial to understand the mechanism of the reaction between the nonlinear structure and nonlinear aerodynamics, as well as the response to different kinds of turbulence.

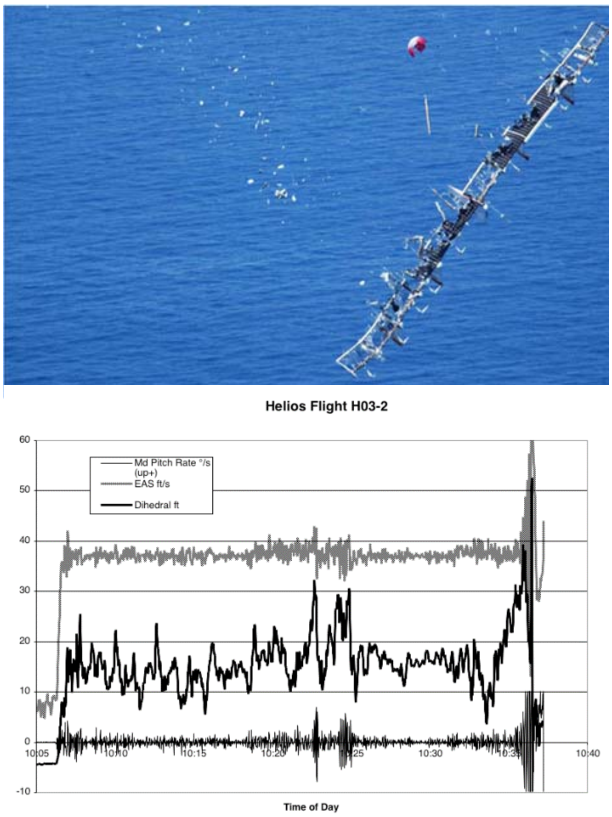

Fig. 4. The Crash of the HP03 and the Response before the Mishap [12]

Lastly, as the stiff of the VFA structure is much smaller than the traditional aerial vehicles, the frequency is very low and would couple with the control system. However, some parameters (for example, the static margin as shown in Fig. 5 and pitch inertia as shown in Fig 6) relating to the controller are not constant anymore but varied with time, which means the linear controller adopted by most rigid aircrafts are not suitable for this kind of vehicles. To analyze the performance and design the control system for the VFAs, lots of works have been done by several aeroelasticians. Especially, the Carlos E.S. Cesnik, Weihua Su, Christopher M. Shearer, as well as their teams [16, 17], have done remarked studies about nonlinear aeroelasticity. Based on the principle of virtual work, the governing differential equations of the flight dynamics/aeroelastic response of a very flexible aircraft are developed.

In all, we could say that a very flexible aircraft is an integrated system which the structure, aerodynamic, control, etc. are involved and some subjects relate and react each other, which means that they should be solved together. [18]

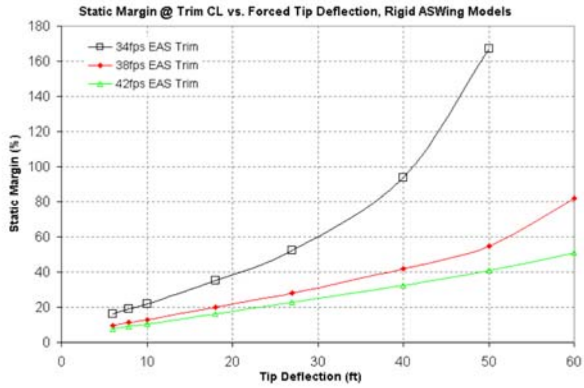

Fig. 5. Static Margin Versus Aircraft Stability with Increasing Airspeed[12]

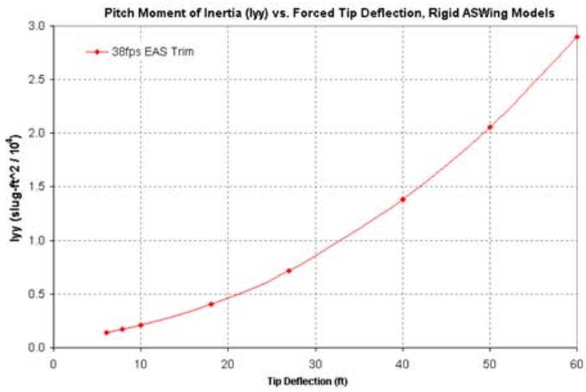

Fig. 6. Aircraft Pitch Inertia Versus Wing Dihedral at 38 ft./sec [12]

The dominant difference between the flexible aircrafts and the rigid is the deformation. Unlike the traditional method, which try to prevent the deformation, we can take advantage of it to control the vehicle like the albatross.

Albatross is one of the biggest birds in the world. Different from the others, albatross seldom flap its wing during flight. It glides in the wind for a long time only by changing the shape of its wings.

There are many advantages of changing the shape actively [19-21]. As the aerodynamic performance of rigid wings is constrained by its shape, it hardly suitable for different missions. However, for the VFA, especially those that work in different flight environments with variable tasks, the flight envelop would be enlarged obviously by changing its shape actively according to the conditions that measured by the sensors. Moreover, comparing to the conventional measures which produce the control lift/moment by aileron or elevator, the maneuverability and adaptability could be highly improved. For the response of aeroelasticity or even the flutter, which is a divergent behavior at a certain airspeed, can be also controlled or avoided by changing the wing actively.

3. The aerodynamic performance

In this part, comparisons are made in terms of aerodynamic performance of different shapes of VFA that are induced from albatross fight, as well as the control efficiency.

Since the stiff of VFA is in a certain range which the deformation is moderate rather than huge distortion as a handkerchief in the wind to lose its initial shape. Moreover, changing the shape of the wing is the easiest and most efficient way to improve the aerodynamic performance. And fortunately, for the VFA and albatross, wing is the most important component to provide lift to keep in the air. Therefore, this analysis assumes that only the main wing changes its shape, while the body and the tail is regarded as rigid.

To assess the aerodynamic performance, vortex lattice method is adopted to solve the load distribution. By distributing the vortices or doublet on the lift surfaces, the load can be determined with the combination of boundary condition. This method is widely employed to solving the aerodynamic in the aeroelastic issue. With disposing the Horseshoe vortices on surfaces and the source/doublet lines on bodies, AVL (Athena Vortex Lattice) is an efficient software originally written by Harold Youngren.

To compare the aerodynamic performance of different shapes, a model was established based on ref [22]. The details of the parameters are listed in Table 1. Several resemble configurations are induced from the albatross fight, and comparisons are made in terms of total lift and load distribution, as well as the control moment and efficiency.

3.1 The models

To compare the aerodynamic performance of different shapes, several configurations induced from the albatross are investigated. To simple the question, only the high-aspect-ratio wing and the tail is take into consideration as the body make a little contribution to the lift. The baseline of the shape is as blow and the initial attack angle set to 3 degree according to the balance of lift and gravity of the albatross.

Tab.1. The Parameters of Albatross Model [22]

Parameter	Value
Mass	8.5kg
Wing Area	$0.65m^2$
Span	3.306m
Aspect Ratio	16.81
Cd_0	0.033
$(L/D)_{max}$	20

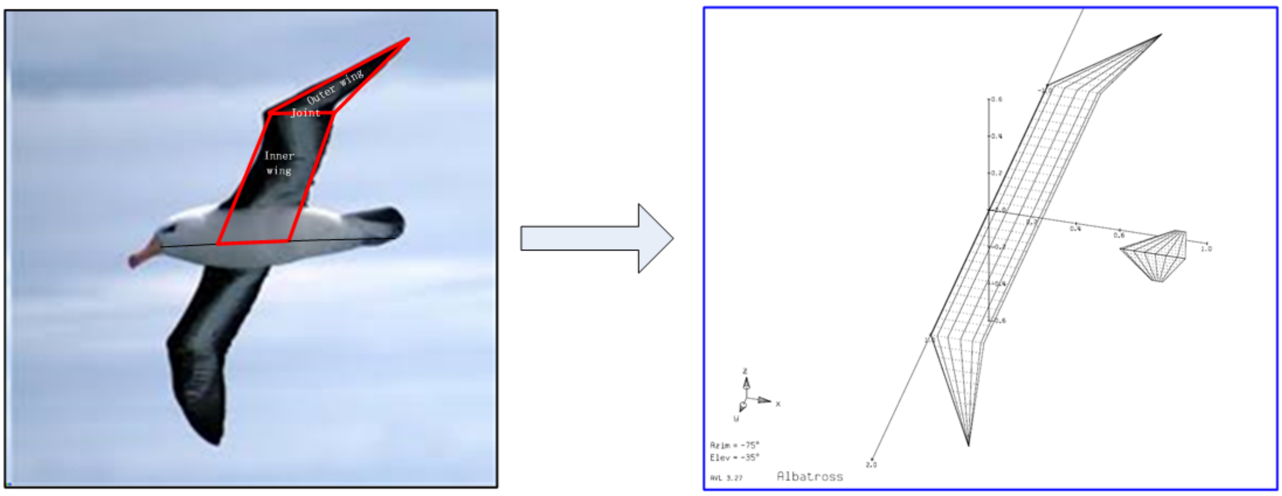

Fig. 7. The Albatross and the Aerodynamic Model

3.2 The aerodynamic performance and control efficiency

3.2.1 The dihedral angle

Firstly, the effect of the dihedral angle of the entire wing (including the outer and inner sections as Fig.7) is investigated. Fig. 8 shows three configurations of the dihedral angle of 30 degree, 0 degree and -30 degree in the front view, respectively. The distribution of lift coefficient is shown in Fig 9, the results indicates that the lift would be decrease as the presenting of the large dihedral angles of the entire wing. However, the different directions of dihedral angle lead a little difference at the root of the wing.

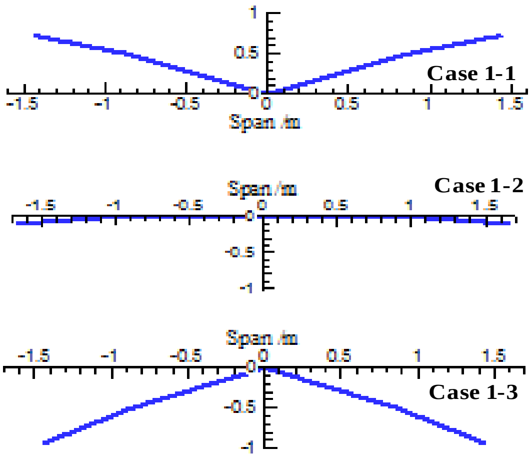

Fig 8. The Front View of Albatross Model of Different Dihedral Angles

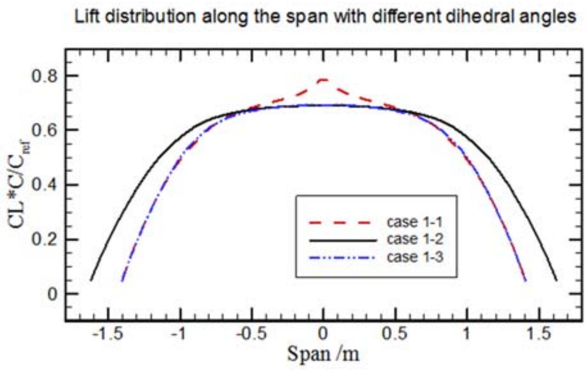

Fig. 9. The Lift Distribution along the Span of the Case in Fig. 8

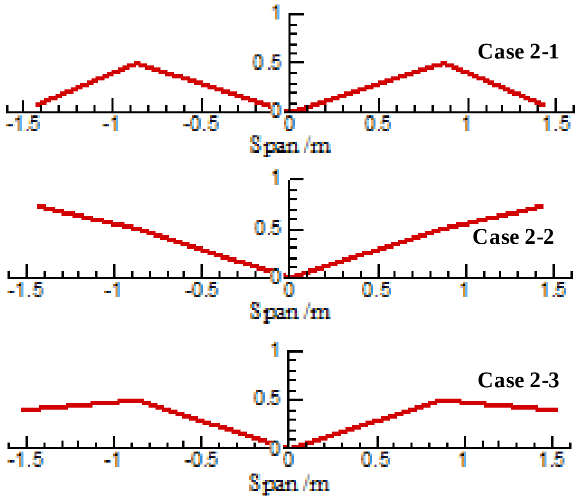

Fig. 10. The Front View of Albatross Model of Different Dihedral Angles

Similarly, different configurations of the dihedral angle of outer wing and the spanwise lift distribution is shown in Fig 10 and Fig 11, respectively. The results suggest that the influence of dihedral angles of the outer wing is very limited.

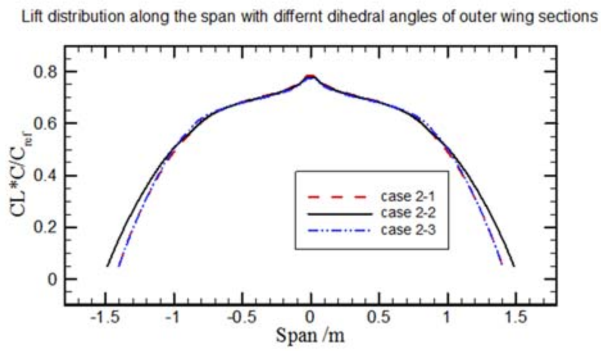

Fig 11. The Lift Distribution along the Span of the Case in Fig. 8

3.2.2 Torsion at the joint

Then the effect of torsion at the joint is studied based on the assumption that the distribution of the torsion angle is linear between the root and the joint, as well as between the joint and the wing tip. Keeping fixed of the root and tip of the wing, the issue is investigated by shifting the torsion angle at the joint, symmetrically and anti-symmetrically.

For the symmetric cases of the torsion, the lift distribution is symmetric, while the total lift increase with the augmentation of torsion angle at the joints, as shown in Fig 12 and Fig 13. However, when the torsion is anti-symmetric, the change of the total lift is quite limited while the rolling moment increases linearly to the torsion angle at the joint.

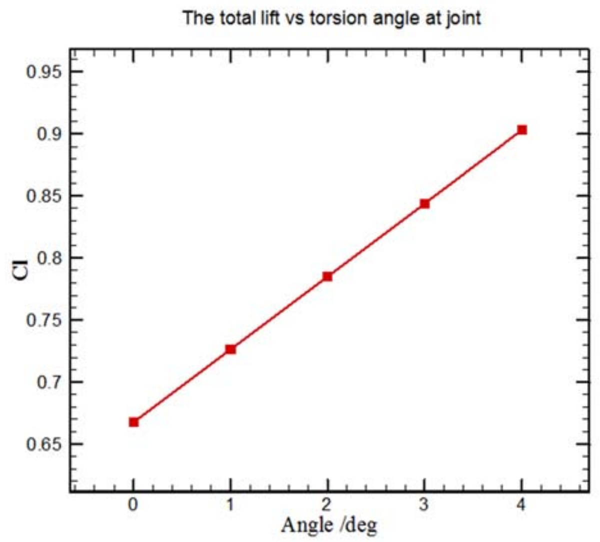

Fig. 12. The Total Lift Coefficient vs. Torsion Angle at Joints

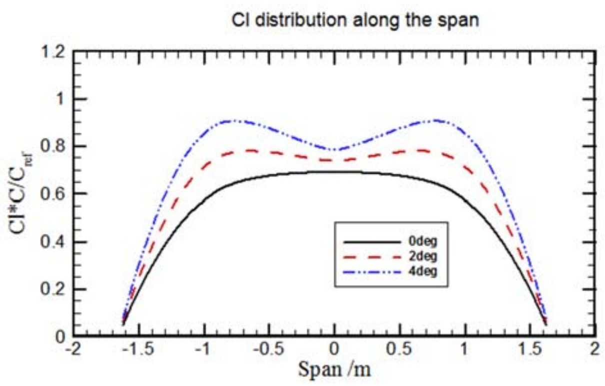

Fig. 13. The Lift Distribution along the Span with Different Torsion Angle at Joints

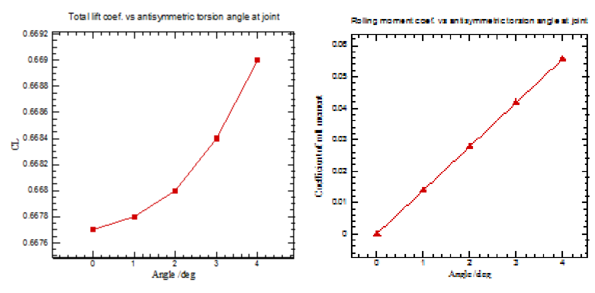

Fig. 14. - The Total Lift Coefficient and Rolling Moment Coefficient vs. Anti-Symmetric Torsion Angle at Joints

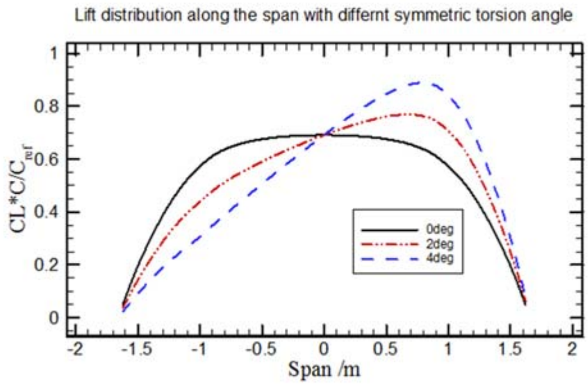

Fig. 15. The Lift Distribution along the Span with Different Anti-Symmetric Torsion Angle at Joints

In summary, the dihedral would cause the alternation of the total lift, while the change of distribution is quite limited. For the torsion of the wing, both the total lift and the distribution is impacted for the symmetric cases. However, the change of the total lift is quite limited while the rolling moment increase linearly to the torsion angle when the torsion is anti-symmetric. Base on the results, we can conclude that torsion of the wing is the effective way to change the lift distribution which plays a crucial role in control.

4. The deformation strategy

To fly like a bird is a long-cherished wish for the human beings, the most important step is shape alternation, much work has been done to realize the shape shifting and plentiful device patents and concepts have appeared.

So far, there are several approach to realize the deformation of the wing [20, 23]. That is, 1) traditional control surfaces; 2) smart material and devices; 3) multi-fractions configuration.

4.1 Traditional control surface

To change the shapes of the VFAs, the first notion coming into mind would be that to install a couple of control surfaces such as ailerons and leading-edges flap to aerodynamically induce the twist or deflection. By this approach, the flexibility of the wing are well used rather than a shortcoming as conventionally regarded.

The Active Aeroelastic Wing project is a two-phase flight research program that is investigating the potential of aerodynamically twisting flexible wings to improve roll maneuverability of high-performance aircraft at transonic and supersonic speeds. The test aircraft has been modified with additional actuators, a split leading edge flap actuation system and thinner wing skins that will allow the outer wing panels to twist up to five degrees. The traditional wing control surfaces—trailing edge ailerons and the leading and trailing edge flaps—are used to provide the aerodynamic force needed to twist or "warp" the wing.

Even through the F/A-18A Hornet, which is a fighter vehicle undergoing the transonic, are selected as the tested aircraft, this technology could also enable higher aspect-ratio wings (such as the HALE), which could result in reduce aerodynamic drag and weight economically. However, the mechanism that aerodynamic, structure and control system react each other is far from totally clear to take into practice.

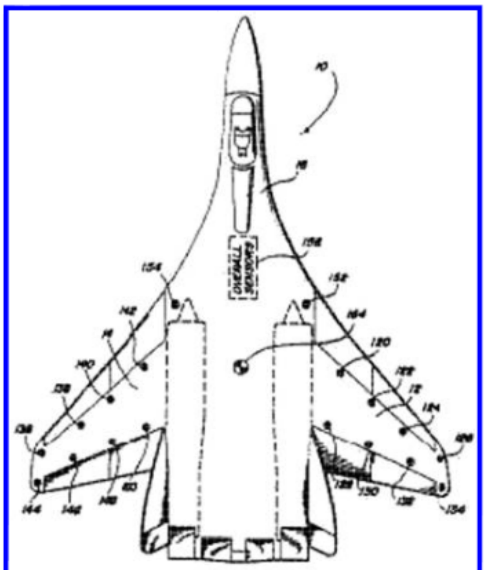

Fig. 16. AFW Patent Drawing Showing Control Surface Locations [24]

4.2 Smart material and device

Unlike the approach mentioned above, in which many large electric motors and flaps are involved, modern adaptive or smart structure system integrate shape memory alloys, magnetostrictive material, activated by electric fields, temperature or magnetic fields. This method is a truly concept that realize the shape change from integrating the smart material, actuators and sensors. The shape of the wing could automatically change its shape softly and continuously according to the flight condition by adopting the sensitive sensors.

From 1990s, the NASA Langley Research Center shows a strong interesting in the aircraft shape change, and the effort make a contribution to the concepts, flow controllers, as well as the adaptive materials. At the same time, Defense Advanced Research Projects Agency of U.S. conduct several smart material and smart structure programs (like Smart Rotor Program, Smart Wing Program, etc.) and Morphing Aircraft Structure (MAS) Program.[24]

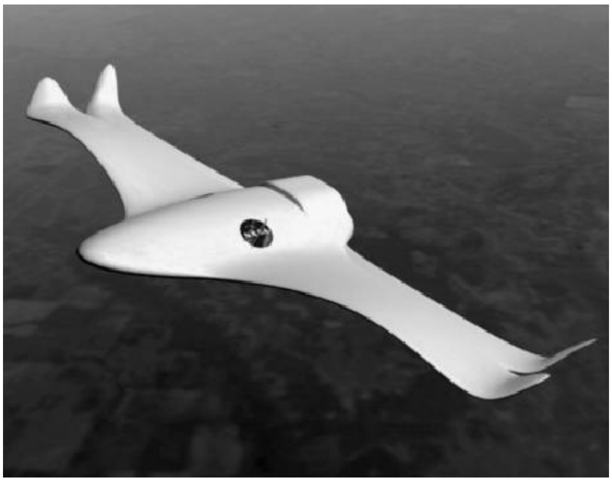

Fig 17. The NASA Langley Research Center Morphing Aircraft [24]

4.3 Multi-fractions configuration

The intent of Vulture program which is initiated by Defense Advanced Research Projects Agency (DARPA) is to provide an uninterrupted five years airborne payload-on-station system with the capacity of 450kg. During Vulture Phase I program, three companies join into the competition for the phase II compact by offering a convictive designing conception. Even though the Boeing win the agreement with DARPA to fly the SolarEagle unmanned aircraft for the Vulture II demonstration program, Aurora’s design named “Odysseus” is an innovation blue print for the VFAs to realize shape shifting.

Fig. 18. The “Odysseus” Concept [25]

Inspire by the “Odysseus”, a notion of VFAs, in which several fractions that are regarded as rigid ones connect hand in hand with joints, is put forward. Moreover, the joints between two frictions can turn in a certain angle, by which the fractions would change the attack angle, the dihedral, as well as the sweep angles. Directed by different circumstance and state, the performance of aerodynamic would highly improve by shifting shapes correspondingly.

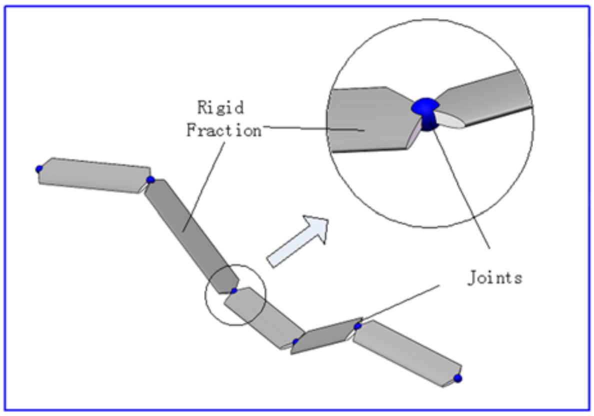

Fig. 19. The Concept of the Multi-Fraction Configuration

As mentioned above, the aeroelasticity is a crucial issue that may lead a divergent response when against the turbulence. However, this configuration could be an advisable option for solving this problem by disconnecting the fractions when the divergent consequence may happen. This is because that each fraction can be regarded as a rigid one which could handle the turbulence much easier. Then, the configuration can be established again in the peaceful wind.

Even through several approach are proposed to shift the shape and some attempts have been implemented, there are some factors, which directly contribution to make the choices, should be taken into consideration. That is the weight and maturity of the technique. The traditional control surfaces method may failed to keep the weight as some redundant flaps are needed, as well as the implement devices. For the smart material and devices approach, the realization is constrained by the maturity of the smart material. Nevertheless, this method shows a powerful perspective in the morphing vehicle. Another notion of multi-fractions configuration is a promising conception which is just on the drawing of the designer.

5. Conclusion

This paper has investigated the features of the very flexible aircrafts, especially those which own high aspect-ratio wings. There are several prominent characteristics which should be paid attention to. 1) Both the aerodynamic performance and the load distribution changes heavily due to the deformation of the wing; 2) the nonlinear effect of the structure caused by the large deformation is remarkable; 3) the aeroelastic response shows strong nonlinear effect and highly sensitive to the turbulence; 4) the frequency of the structure is quite low and may couple with the control system. So the VFA can be a system in which the structure, aerodynamic and control are involved, and those subsystem relate with each other tightly, which places restriction on general design, structure, aerodynamic performance, and controllers that are not likely to be met unless design in from the beginning and solve together.

Inspirited by the albatross, several configurations are proposed and comparison are made in terms of aerodynamic performance and control efficiency. The results suggest that the dihedral would cause the alternation of the total lift, while the change of lift distribution is quite limited. And, for the torsion of the wing, both the total lift and the distribution is impacted for the symmetric cases, the change of the total lift is quite limited while the rolling moment increase linearly to the torsion angle when the torsion is anti-symmetric.

Lastly, three notions about shape change strategies are discussed, there are 1) traditional control surfaces; 2) smart material and devices; 3) multi-fractions configuration. So far, the smart material and devices may be a good choice to realize shapes alternation for the VFAs.

Acknowledgments

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