Morphing Air Vehicle Concepts

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***Abstract*-This article summarizes the current level and trends in the emerging Morphing Air Vehicle Technology. The worldwide status of the research is introduced together with proposals related to the design and development of such vehicles from aerodynamics, flight mechanics, material sciences, and structures points of view. Part I introduces the morphing concept and its potential. Part II summarizes the present technological level, while Part III discusses technological challenges and solution proposals.**

I. Introduction

The term "Morphing Air Vehicle" refers to the airplanes with wings capable of significantly changing their planforms during flight as a result of a given input. Such ability has the potential of increasing fuel economy, mission capability, performance and flexibility.

Conventional fixed wing airplanes are designed such that their wing profiles and planforms are optimized for only one segment of their mission profiles or flight envelopes, i.e. cruise for transport airplanes, high-g maneuvering for fighters, loiter for reconnaissance and surveillance airplanes, etc. Each of these segments requires a particular wing planform shape as shown in Fig. 1 [1]. For all other segments in the mission, fixed wing airplanes show a compromised performance. On the other hand, morphing capability promises optimized wing shapes for all stages of the mission profile. Therefore, with morphing capability, mission performances of airplanes can be increased and/or missions requiring several aircraft types to accomplish may be performed with fewer types. The technology also has the potential of simplifying and even totally eliminating mechanically complex and heavy conventional control systems, reducing aerodynamic drag and noise.

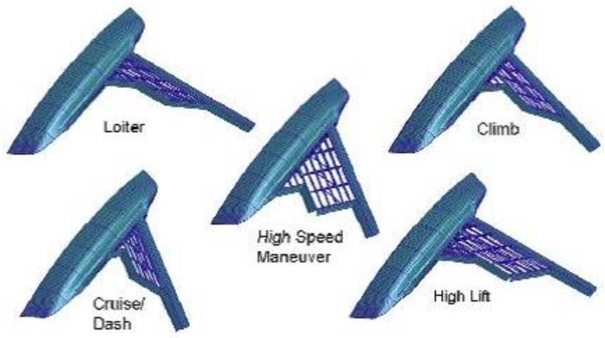

Fig. 1. Optimum wing planform shapes for different flight conditions [1].

Although there is no established definition of a morphing air vehicle, 200% change in wingspan, 50% change in wing area and 20^o change in wing sweep are mentioned and generally accepted in the literature [2]. Wings with unconventional control surfaces may also be defined as morphing.

A more formal definition of a morphing air vehicle is provided by DARPA (Defense Advanced Research Projects Agency). Accordingly, a morphing airplane is one that [3]:

- changes its state substantially to adapt to changing mission environments.
- provides superior system capability not possible without reconfiguration.
- uses a design that integrates innovative combinations of advanced materials, actuators, flow controllers, and mechanisms to achieve the state change.

Such a capability may be used in order to achieve the benefits listed below:

- Increase in the aerodynamic efficiency (lift/drag ratio),
- Elimination of the complex and heavy high lift devices and mechanisms,
- Elimination of complex conventional control surfaces,
- Reduction in the aerodynamic noise,
- Reduction in fuel consumption,
- Control of vibration and flutter,
- Achievement of higher mission flexibility.

Specific application determines the magnitude and frequency of shape change [4]. Large scale or full morphing is less frequent and employed only during transition from one flight condition to another like during transition to cruise flight following climb. On the other hand, control surface-like morphing is almost continuous.

II. PRESENT TECHNOLOGICAL LEVEL

A. Full Wing Concepts

Research activities on morphing airplanes have been going on in USA since 2003 under the Morphing Aircraft Structures (MAS) program supported by DARPA. The MAS program consists of three phases. In the first phase research groups were asked to design and manufacture wings capable of changing their wingspans by 150% and associated subsystems to be tested in a wind-tunnel. In the second phase, scaled wind-tunnel models of full-scale airplanes were considered [2].

As a result of the conducted research, two designs with substantially different approaches have been developed. The first one, developed by Lockheed-Martin is a “folding wing” concept. The concept allows variations in wing span and sweep angle during flight, Fig. 2 [5]. In this concept, the skin material is manufactured from a shape-memory polymer that softens and morphs within seconds after being heated. Heating is performed by small, flexible heaters embedded into the material in the form of layers. When the required shape change is achieved, heating is stopped, which fixes the wing shape. The wing surface thus developed is capable of maintaining smoothness under strains as high as 100% [6].

The second concept, which is developed by NextGen Aeronautics is a “variable sweep, variable chord concept”, Fig. 3. The flight vehicle is designed with a truss-like aluminum structure actuated with small hydraulic motors. The skin material is silicon reinforced by metal and produces morphing. Changes in area of 40% and span of 30%, with sweep varying from 15° to 35°, were achieved in flight at speeds of around 100kt (185km/h) [7].

Another full-wing concept is the active winglet concept for drag reduction, for which the wind tunnel model is shown in Fig. 4 [4]. Use of winglets in transport airplanes is common, which are especially useful for drag reduction during high-altitude cruise. The benefit of using winglets during take-off and climb is much less however, but with the concept shown, it is possible to employ the winglets as extensions to the wingtips allowing dual use of these devices.

Fig. 2. Lockheed-Martin's "folding-wing" concept [5].

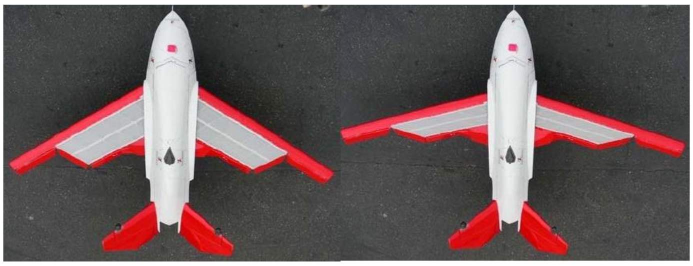

Fig. 3. NextGen's "variable-chord, variable-sweep" concept [8].

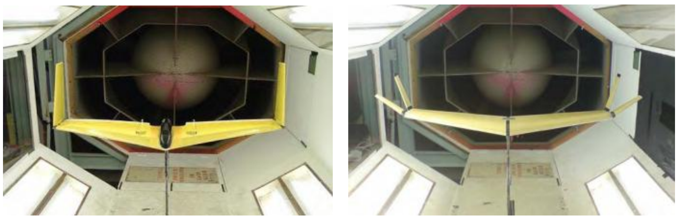

Fig. 4. Active winglet concept for drag reduction [4].

B. Trailing Edge Concepts

FlexSys Inc. has completed wind-tunnel and flight tests of a compliant wing with support from the Air Force Research Laboratory, Fig. 5. The wing span and chord are 50 in. and 30 in, respectively. The trailing edge of the wing can be deflected at a rate of 30^{o}/s, while the total deflection is $\pm 10^{o}$. Moreover, a twist of 1^{o}/ft could be achieved. Tests show that deforming the leading and trailing edges of the wings significantly improves the aerodynamic efficiency of wings and fuel savings in the order of 5-15% may be possible if morphing takes place automatically as a result of varying flight conditions [9].

Monner et al. [10] used a finger concept in order to obtain a variable camber trailing edge for a civil airliner wing. A metallic but flexible skin is used to achieve an aerodynamic profile. The inflexible ribs at the trailing edge were replaced with a few plate-like elements (fingers) that were joined together and could rotate relative to each other, Fig. 6. Although each element had a high stiffness, the combined structure was flexible and allowed chordwise and spanwise differential variable camber when actuated by electrical motors. The technology was implemented in a 3.2 x 0.9 x 0.6m (span x chord x thickness) demonstrator model to prove the concept. The elements were made out of metal and Carbon Fiber Reinforced Polymer (CFRP) [10].

In the rotating rib concept shown in Fig. 7, the classical connection between the skin and the ribs, traditionally based on rivets, is substituted by a discrete number of linear slides allowing the skin to glide over the rib contour. On TE of the airfoil, upper and lower skins are not rigidly connected to each other but they are able to glide into a linear slide bearing. The torque applied by the actuators is required to deform the skin panels and to gain friction forces inside the slide bearings (plus external loading) [12]. To demonstrate the reliability of the concept, a proof-of-concept wing section model has been designed and tested with the following characteristics:

- A wing section equipped with 4 rotating ribs, 1.4m span, 0.622m chord and a maximum rotation of 5.5^{o},
- Each rib is divided in two parts, each one 50% of total chord long: the front part is fixed and, together with main spar and leading edge, constitutes the structural box, while the rear part is rotating,
- The thickness of the skin is equal to 1mm.

At DLR an airfoil has been developed where the ribs have been removed and the number of spars increased. The orientation, i.e. angle, of the spars makes camber change possible due to low stiffness. The skin of the airfoil, which defines the shape, is essentially like a belt and the spars like spokes or ribs, hence the name belt-rib concept, Fig. 8. A 1:2 model (500mm wide) was manufactured based on A340 outboard flap from carbon fiber/epoxy resin composite with metallic hinges for the rib/belt connections. The concept could be actuated in the future with integrated solid-state actuators such as piezoceramic or SMA actuators. Test results showed a maximum deflection of 5° and an experimentally measured maximum strain of 0.099%. Stiffness requirements were also satisfied through experimental tests [11].

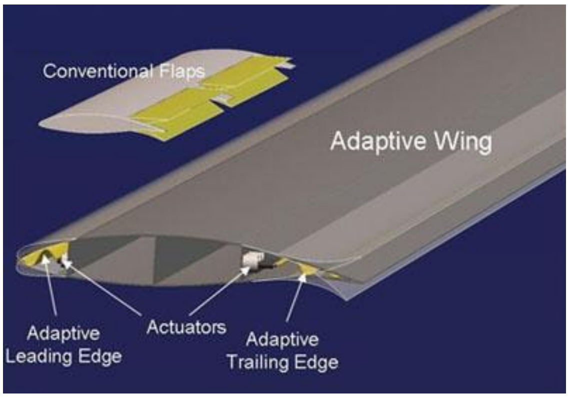

Fig. 5. FlexSys' "compliant wing concept" [9].

III. TECHNOLOGICAL CHALLENGES

Technical challenges towards designing, developing and manufacturing a successful morphing air vehicle are:

- Mechanisms (sensors and actuators providing shape change),
- Flexible skins (materials that supports the structure and shape change),
- Control laws (varying flight conditions and geometry).

Fig. 9 shows the complex mechanism employed by NextGen for their Morphing air vehicle, complete with structural elements, sensors and bar/slider assemblies.

A. Sensors and Actuators

- Lightweight, actively controlled system of sensors (nerves), actuators (muscles), and structures (skin and bones) that mimic the ability of animals to adapt to widely changing environments and threats,
- This requires new thinking (design paradigms), new analytical tools (computer codes), and extensive testing to arrive at efficient combinations to control the size of aerodynamic forces.

The related parameters to this end are:

- Force, displacement, frequency,
- Weight, volume,
- Power.

Alternatives [15]:

- Electro-magnetic motors. These have large power density but does not scale with size,
- Active materials; solid state but small power density,
- Active material motors. Their power density scales with size and present opportunities in small scale.

On the other hand, there are fundamental problems with active materials [15]:

- Piezoelectrics; displacement limitations (microns),
- Magnetostrictive; generating magnetic field,
- Shape memory; low operational bandwidth.

A promising new alternative lies in smaller scale systems in the form of active thin films [15]. Fig. 10 shows a smart material actuator employing this new technology and used by NextGen in its Morphing air vehicle.

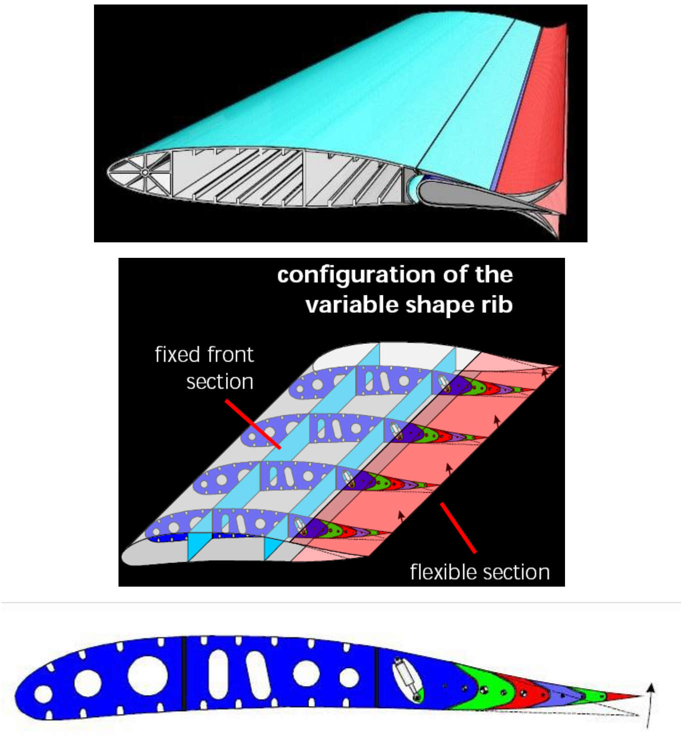

Fig. 6. DLR finger concept [12].

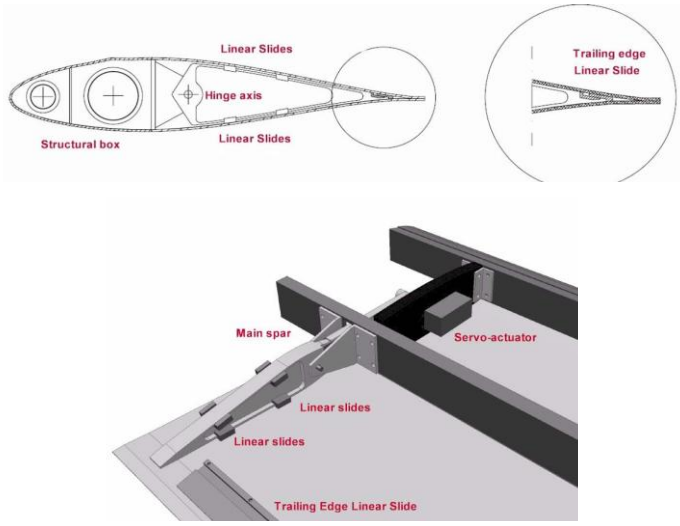

Fig. 7. Rotating rib concept of Politecnico di Milano [12].

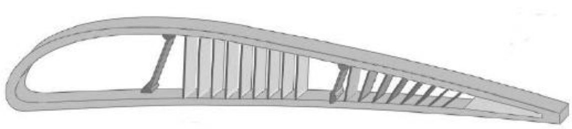

Fig. 8. DLR belt rib concept [13].

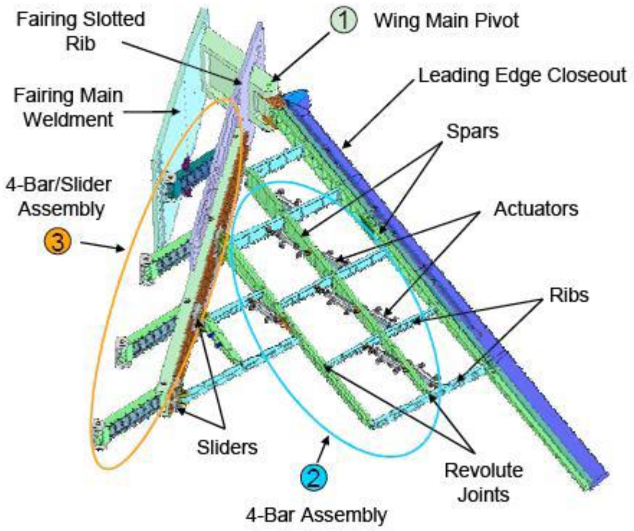

Fig. 9. Mechanism employed by NextGen in its "variable sweep, variable chord" concept [1].

Fig. 10. Smart material actuator [15].

B. Materials

For the envisaged shape changes, skin materials for morphing wings must have high recovery, strength and be flexible, elastic and resistant to the environmental conditions. Alternatives to this end are:

- Electroactive polymers (EAP),
- Shape memory alloys (SMA),
- Shape memory polymers (SMP),
- Nanocomposites.

EAPs are suitable for morphing wing applications due to their responsive and tunable properties. They can perform energy conversion between electrical and mechanical forms. Conductive polymers, ionic polymer metal composites, dielectric elastomers are examples of EAPs. Selection of these materials is generally based on actuation strain, speed, force, voltage and mechanical response entailed by application [16].

Conductive polymers actuate on the basis of reversible counter-ion uptake and expulsion that occurs during redox cycling. They make use ion interaction as the actuation driving force. Molecular driving forces such as, hydrogen bonds, twisting or polarization of a molecule and formation of reversible chemical bonds change the shape of polymer backbone. In the literature, there are studies on the actuation performances of polypyrrole and polyaniline [17]. These studies show that these polymers require low voltages for operation (1-10 V). However, their actuation strains (1-35%) and forces (max. 5 MPa) are relatively low. Also their actuation speed is low and they need an electrolyte solution for excitation. The mentioned drawbacks of conductive polymers might be overcome by incorporating conductive fillers such as carbon nanotubes (CNT) or carbon nanofibers into conductive polymers. It is expected that use of carbon nanotubes can enhance the stiffness of the conductive polymer and the actuation force. Furthermore, the presence of the carbon nanotubes may increase the actuation performances of conductive polymers [20].

Hybrid inorganic-organic nano-composite materials are of interest because of their multi-functionality, processability and potential for large-scale manufacturing. Inclusion of carbon nanostructures, metallic, magnetic and semi-conducting nanoparticles in polymer matrices has been investigated for a wide range of applications [21]. Control over dispersion of nanoparticle phase embedded in a polymer matrix is critical and often challenging. To achieve excellent dispersion, competition between polymer-polymer and polymer-particle interactions has to be balanced to avoid clustering of particles in polymer nanocomposites. The first uniform deposition of magnetic nanocomposite, Fe_3O_4, which has been synthesized using chemical co-precipitation route in poly(methyl methacrylate)/polypyrrole bi-layers from solution using spin-coating was performed to obtain superparamagnetic response [23]. Enhancement of electromechanical responses of electroactive polymers was obtained by highly uniform dispersion of inorganic dielectric nanoparticle fillers [24].

Shape memory polymers have attracted a great interest as promising morphing wing materials due to their shape recovery upon application of voltage. Therefore, they can be used as electroactive actuators. SMP can be thermoplastic or thermoset. These polymers consist of both hard and soft segments in their structure. The hard segments form physical or chemical crosslinks that is the main difference between these polymers. The ratio of the hard to soft segments and types of crosslinks determines the elastomeric nature of the polymer. Hard segments contribute crystallinity or crosslinking and give thermal and mechanical stability to the polymer and soft segments contributes toughness and elasticity. Fig. 11 shows a shape memory polymer in action, which is also known to be used in morphing air vehicle applications.

Combination of the superior properties of shape memory polymer (rubber, epoxy, thermoplastic elastomer, etc.) and nanofiller (carbon nanotube, zinc oxide, barium titanate, etc.) in composite structure are thought to be promising for the concept of morphing structure. In particular, reinforced shape memory polymers such as thermoplastic elastomer/carbon nanotube composites have been investigated in terms of their shape recovery effect and actuation performance [25]. The voltage stimulated response of the materials depends on the CNT content and degree of surface modification of the CNTs.

Fig. 11. A shape memory polymer used for morphing air vehicle applications [26].

C. Design, flight mechanics and control laws

Application of morphing wing technologies requires the concurrent development of design and optimization strategies to expedite overall development of these systems. Of major importance is the development of a robust morphing aircraft sizing algorithm to be used during conceptual design phase. The major drawback while developing such an algorithm is that accurate weight predictions are required for all major components including the morphing wing. A common approach used for fixed wing airplane weight predictions is based on the idea that a large database of wing weights, associated geometry and loading conditions already exist. By selecting a subset of these data with common futures like the aspect ratio and taper, various analytical methods can be used to predict wing weight as a function of the wing parameters. Direct application of the above approach is not possible for morphing wings because a sufficient number of operational airplanes do not exist. To overcome this problem, Skillen and Crossley [2] propose generating a surrogate wing weight database and developing a wing weight equation in the usual way. In order to define a set of morphing wings with various shapes, representative finite element models are developed for each wing in the database using Design of Experiments (DOE) method. Then, these are sized to give a corresponding weight estimate. Using these data, an appropriate basis equation is obtained using a least squares regression technique resulting in the morphing wing weight equation.

Unlike most conventional aircraft, morphing aircraft concepts require an aerodynamic analysis both for varying flight conditions and significantly varying geometric configurations. This requirement demands a preliminary analysis methodology that is fast, accurate and reconfigurable without having to remesh the flow field every time the geometry changes. A lifting-line approach is proposed by Wickenheiser and Garcia [27] as an aerodynamic modeling method as opposed to a CFD approach. This method breaks the 3-D wing into 2-D airfoils joined by their quarter-chord curve. The method is an extension to Weissinger's method for straight, swept wings. While in Weissinger's method, the downwash velocity at any spanwise location on the wing is related to the sum of downwash contributions of the vortex line attached to the quarter-chord line of the wing and the semi-infinite vortex sheet trailing behind it, the method proposed by Wickenheiser and Garcia does not consider the geometry of the wing cross sections or the non-planarity of the wake. The geometry of the wing is accounted for by introducing real airfoil data for each of the spanwise stations. The formulation leads to an integro-differential equation solved by sine-series representation of the circulation, which satisfies the boundary conditions of zero circulation at the wingtips. Gaussian Quadrature and the trapezoidal rule are then used to compute the integrals.

From the flight dynamics point of view, a major challenge is to control an airplane that morphs during flight because conventional flight laws assume rigid airframe. For this reason, it is probable that the linear theory and the assumption of a rigid airframe will not be sufficient so a nonlinear flight dynamics model for flexible airplanes should be developed similar to the one proposed by Shearer and Cesnik [28]. In this model, the six-degree of freedom equations of motion are coupled with the aeroelastic equations that govern the nonlinear structural response of the airplane. A low-order-strain-based nonlinear structural analysis coupled with an unsteady finite state potential flow aerodynamics form the basis of the low-order aeroelastic model. The equations of motion are integrated by an implicit Newmark method. The results reported by Shearer and Cesnik for a representative High Altitude Long Endurance (HALE) configuration indicate that although linear approach yields acceptable solutions for capturing aircraft dynamics for symmetric maneuvers, significant differences are observed for asymmetric flight, requiring nonlinear analysis approach.

IV. CONCLUDING REMARKS

As a results of the above discussion, it can be said that morphing air vehicles and associated technologies have the potential of introducing revolutionary developments to aviation. This technology will introduce important improvements in the control mechanisms, performance characteristics, fuel economies and weights of fixed wing airplanes. The mission flexibilities of civil and military airplanes will increase and missions normally requiring more than one airplane type to accomplish will be performed by much fewer or even with a single type.

In short term, the implementation of this technology will almost certainly be in fixed wing military Unmanned Aerial Vehicles. However, use of this technology in rotary wing airplanes and inhabited fixed wing airplanes is also envisaged in mid- and long-terms. The Cleansky Joint Technology Initiative launched by the European Commission in 2008 highly emphasizes the importance and potential of this technology.

However, it should not be forgotten that the morphing technology is still in its infancy. Materials and structures enabling large scale shape changes are still in identification and development stage. Yet, widespread and generally accepted tools for design, aerodynamic and flight mechanics analyses of such vehicles are also in development stage.

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