# Perspectives on Highly Adaptive or Morphing Aircraft

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## *ABSTRACT*

*The ability to adapt to different flight conditions has been fundamental to aircraft design since the Wright Brothers' first flight. Over a hundred years later, unconventional aircraft adaptability, often called "aircraft morphing" has become a topic of considerable renewed interest. In the past two decades, this interest has been largely fuelled by advancements in multi-functional or smart materials and structures. However, highly adaptive or morphing aircraft is certainly a cross-discipline challenge that stimulates a wide range of design possibilities. This paper will review some of the history of morphing aircraft including recent research programs and discuss some common misconceptions and technical challenges of this work.*

## 1.0 INTRODUCTION

While definitions for "Aircraft Morphing" vary widely, in general, the vision for the capability that morphing may enable does not. This capability focuses on increasing the adaptability of the vehicle to enable optimized performance at more than one point in the flight envelope. Whereas conventional airplanes are generally optimized with a bias towards a single design point; morphing vehicles are optimized for multiple design points. Morphing vehicles tend to accommodate the missions of more than one conventional vehicle using the same vehicle. For example, a morphing vehicle may be able to fly fast *and* slow efficiently. For missions where there are conflicting or perhaps contradictory major performance requirements, such as supersonic cruise speed and short landing requirements, the morphing vehicle will employ unconventional transformation to achieve mission objectives at minimum penalty. Thus, a morphing vehicle may expand the flight envelope, resulting in increased conventional mission capability or it may enable new missions that are impractical without unconventional vehicle transformation. From a design perspective, a morphing aircraft behaves as if it were multiple different aircraft, and would likely have multiple v-n diagrams and performance curves to consider.

To provide the desired added performance capabilities, morphing aircraft will likely have new sub-systems that are more complex and heavier than the conventional sub-systems that they replace. For many simpler missions where flight conditions are not varying considerably or where requirements are not conflicting, the added sub-system complexity for morphing is not needed. For some missions (such as the design mission for the Grumman F-14 Tomcat), morphing concepts are actually the minimum penalty solutions. This paper will briefly summarize a few historical examples of missions where morphing concepts were used. It will also provide a summary of recent research on morphing aircraft and some challenges and lessons learned. Since the words "aircraft morphing" mean different things to different research groups, a discussion of the definition of morphing aircraft is also included.

### 1.1 Definition of Morphing

From the Merriam Webster dictionary, to "morph" means to undergo transformation, to change the form or character of something. In the parlance of aeronautics, there is not a formal definition for "Aircraft Morphing" that is universally agreed upon in the technical community. One of the reasons for this disagreement is because much of the discussion about the definition focuses on *how* the morphing is done, such as how large and in what way the transformation is accomplished. For example, many say aircraft morphing is large, seamless shape change. Others define categories such as micro (small) and macro (large) morphing or local and global morphing, etc. Some impose a requirement for the use of smart materials and structures while others exclude any conventional shape change such as flaps. Yet others focus exclusively on structural shape change and exclude virtual shape change from flow control approaches.

Unfortunately, concentration on the "how" of morphing is likely to persist in the technical community. This potentially enables artificial constraints that reduce innovation and limit the use of more optimal applications by restricting prospective solutions to those that fit the individual researcher's definition of morphing. Ironically, although the field of aircraft morphing seeks to expand the aircraft's capability through unconventional transformation, at times, the definitions of what is considered morphing appear to constrain and not expand opportunities. It is important to consider that there are many methods to transform or change the vehicle to achieve the same performance objective. The vehicle's mission determines the best method to use not the definition of terminology.

The authors suggest that broadening the concept of what morphing includes would be beneficial to the community by freeing up these artificial constraints. Instead of focusing on a novel approach being used, a better strategy would be to highlight the increased *capability* provided by a morphing vehicle and seek the best methods to enable it. This increased capability is driven by the unique class of mission of a morphing vehicle: the ability to effectively and efficiently adapt to different, even widely varying, mission requirements. The NATO Research and Technology Organization, Applied Vehicle Technology (AVT) Technical Team on Morphing Vehicles (AVT-168) developed the following definition for morphing: *Real-time Adaptation to Enable Multi-point Optimized Performance*. This includes morphing applied to air, land and sea vehicles.

This definition for morphing, as it applies to air vehicles, will be used in this paper since it points toward the desired capability for all morphing vehicles that is distinct from conventional vehicles. Morphing is more appropriately focused on the mission requirements for transformation than the method or degree of transformation. The former solely determines the latter.

## 2.0 HISTORICAL PERSPECTIVE

In the last decade, research on aircraft morphing has swelled to include many universities, government laboratories and industrial research programs across the world. The concept of morphing aircraft is, however, far from new. Since the beginning of flight, the desire for more has pulled aircraft in the direction of multi-point optimized performance.

Today, it is hard for us to fully appreciate how commonplace technologies that we have grown accustomed to were, in their day, equivalent to "morphing." Many decades ago, designers quickly exhausted the performance available with aircraft designs that were basically fixed. As the desire for ever higher performance pulled designers out of their comfort zones, innovations such as retractable landing gear and multi-element high-lift systems became commonplace. These technologies have proved so useful that today nearly all conventional aircraft have some transformation, or change, to fulfil their mission. It is also easy for us to think that these ubiquitous solutions were obviously going to work, and that a great many potential approaches had not been tried and failed. As we know, aircraft are such complicated machines, with such high performance demanded, that it is extremely difficult to predict a priori how well new approaches are likely to work. The previous examples of retractable landing gear and deployable high-lift systems were heavier, costlier, more difficult to maintain, and more vulnerable to failure than the sub-systems that they replaced. They were only adopted because the performance benefits of these approaches more than offset the penalties on their particular applications. Similarly, new morphing technologies should not be immediately dismissed merely because they are more challenging to adopt than the technologies they are replacing. What matters is the total improvement of the vehicle system, not the penalties of the sub-system.

A scan of the history of aircraft design will show numerous drawings of concepts for morphing aircraft such as those shown in Figure 1. Many of these drawings remained merely notional concepts. However several concepts did take flight. Even for successful designs, the time span between first concept and general acceptance was typically several decades. The successful designs also required a great deal of risk reduction, and often more than one design to get it right.

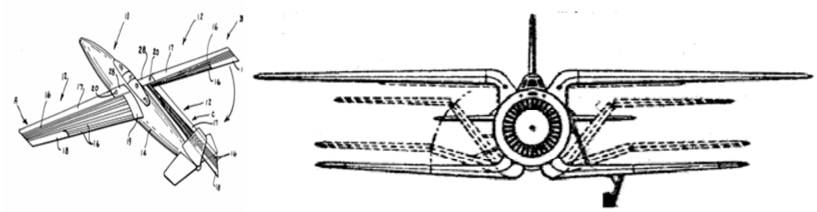

**Figure 1 Unconventional Morphing Concepts from History**

Although Messerschmitt incorporated ground-adjustable variable sweep in their P1101 design of 1945, it was not until 1951, that the Bell X-5 took flight, beginning the exploration of variable sweep concepts to increase aircraft adaptability. It took another 13 years before variable sweep became operational on the General Dynamics F-111. The controversy that followed the US Navy version of the F-111 meant that the question of the utility of variable sweep was still in doubt. Eventually, the US Navy embraced variable sweep on their Grumman F-14 Tomcat. Variable sweep subsequently became an accepted feature on other military aircraft, including the American B-1, the European Tornado, and the Russian MiG-23/27, Su-17/20/22 and TU-160. For many of these aircraft, sweep change is scheduled with Mach number, enabling more optimized aerodynamic performance over a range of mach numbers. While all of these implementations were of a symmetric, aft-swept design, a very small, slow, man-carrying demonstrator was built of the novel “oblique” wing. The “oblique” wing reduced many of the penalties associated with the now “conventional” variable sweep implementation, but introduced new complications that would need to be addressed to be successful. Several concepts for variable sweep are shown in Figure 2.[1,2]

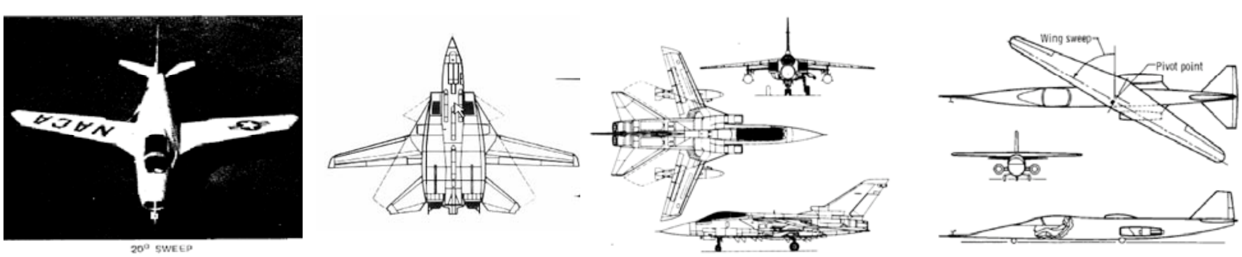


**Figure 2 Variable Wing Sweep Morphing Concepts from History**

Span change has also been a desired design feature, although much harder to effectively realize. Examples include the Fanasa Beach of 1969, the Akaflieg Stuttgart fs-29 sailplane of 1975, and the large, supersonic North American Aviation XB-70 Valkyrie of 1964 (see Figure 3).[3] The XB-70's wing tips drooped, providing many benefits. At supersonic conditions the drooped tips improved directional stability and drag through capturing compression lift, and also reduced pitch down. At subsonic conditions the larger span improved induced drag and provided greater roll power while not creating directional over stability.

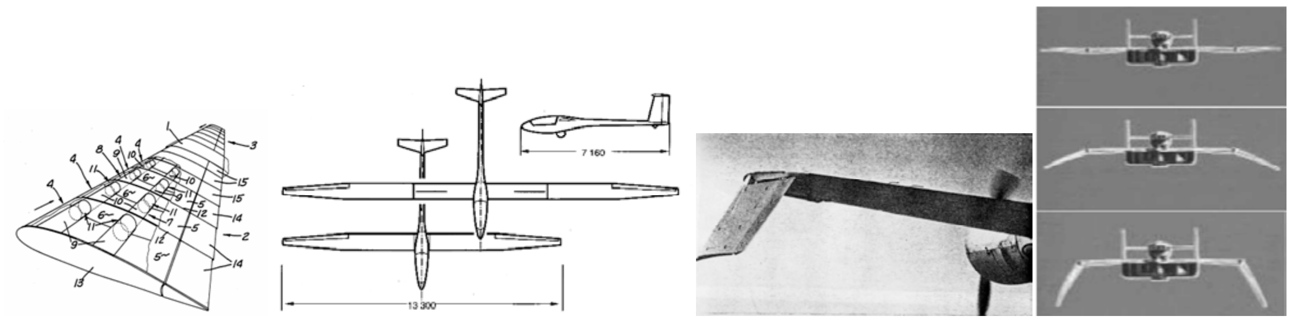


**Figure 3 Span Change Morphing Concepts from History**

There are many other examples of morphing aircraft in history. However, in the 1990's a renewed and more futuristic interest in morphing aircraft began to develop. Much of this interest was likely fuelled by the significant increase in research on smart materials and structures that offered new capabilities in actuators and sensors.

## 2.1 Impact of Smart Materials and Structures Research

In the late 1970's, through the 1980's and 1990's, there was significant growth in research of smart materials and structures around the world. The United States, Japan and Germany were some of the key initial locations of development. Although smart materials had actually been around for decades, or even centuries, the knowledge of how to exploit their unique capabilities as actuators to move and control structures began a new era of research in materials and structures. The ability to make structures adaptive and even smart when combined with active control systems and smart materials resulted in fundamental changes to engineering design for innumerable structures in civil, biomedical, industrial and other fields of engineering. In Germany, the term "Adaptronics" was created to refer to this new area of research and development. Adaptronics is said to be the adaptation of the elastic and mechanical structural properties by using optimally integrated sensors and actuators based on smart materials and combined with a control system and power electronics to enable the system to respond "self-sufficiently" to changing conditions.

Biologically-inspired research also swelled around this time as did nanotechnology research. The ability to make "designer" materials from the nano-level, and embed distributed sensors and actuators into new smart sub-systems fostered a plethora of new engineering concepts. In aerospace in particular, the newfound capabilities inspired visions of the "smart aircraft" of the future. These "smart aircraft" would have "smart wings" and other adaptive sub-components so that it could sense and adapt to its environment similar to biological systems. Some heralded the idea of the reconfigurable, or morphing, aircraft of the next century of flight. Others smirked at the bio-nano-smart-morphing "craze" as an over-hyped fad that would eventually quell when the realities of real application to real aircraft were recognized. Both perspectives have merit.

As with any burgeoning research area, the promises of the bio-nano-smart-morphing aircraft trend of the 1990's and early 2000's were likely optimistic. However, the positive impact of the surge in innovation, creative trial and error research and the resulting lessons learned should not go overlooked. Smart materials, adaptive structures, and nanotechnology, among others, have permanently changed engineering design. For example, smart materials are now ubiquitous in consumer and industrial products. In aerospace, countless research programs were launched around the world to explore the trade space of morphing aircraft and smart airplane systems. This research fostered many new concepts and technical discussions about alternative approaches in air vehicle design that provide the groundwork for future technology leaps. As with most disruptive technologies, the future direction of these technical leaps is difficult or impossible to predict.

## 3.0 AIRCRAFT MORPHING RESEARCH HISTORY SINCE THE 1990'S

Well supported by significant research on smart structures and biologically-inspired aeronautics concepts, the morphing aircraft research of the 1990's took on a decidedly biological flair: almost birdlike aircraft that could seamlessly transition from one configuration to the other, actively sensing flight conditions and adeptly reconfiguring to fly effectively in the changing conditions. The goal of seamless transition seemed to drive most research efforts. In the U.S. and in Europe many new projects were created to explore the trade space of morphing aircraft and rotorcraft and related technologies. In Europe these projects included the AWIATOR (Aircraft Wing with Advanced Technology Operations,) the 3AS (Active Aeroelastic Aircraft Structures) and many others. In particular, the German Aerospace Research Center (DLR) became a key leader in the field.

Adaptive propulsion system research was also initiated in several studies. A significant program on adaptive engines is the US Air Force's Adaptive Versatile Engine Technology (ADVENT) program. The goals of this program are to develop inlet, engine and exhaust technologies that optimize propulsion system performance over a broad range of altitude and speed.[4]

Also in the U.S., two government programs in particular became the focal points for much of the initial 21st century vision for morphing aircraft: NASA's Morphing Project with an animation of a futuristic morphing airplane and DARPA's well-referenced Morphing Aircraft Structures program with folding and stretching wings. A brief history of each of these research efforts is summarized in the next section.

### 3.1 NASA's Research

In the mid-1990's, NASA initiated a project called the "Aircraft Morphing" project – it later was simply called the "Morphing" project. The project was led from the NASA Langley Research Center (LaRC) in Virginia. It included fundamental research in smart materials, adaptive structures, micro flow control, optimization and controls. The objectives were to develop and assess advanced technologies and integrated component concepts to enable efficient, multi-point adaptability in air and space vehicles focusing on long-term, high-risk, high-pay-off technologies. The focus of the project was on exploring enabling technologies rather than on the development of a complete morphing vehicle.

As mentioned earlier, the words "aircraft morphing" have become synonymous with large structural shape change. Changing shape clearly has strong impact of many major performance variables; however, since this was just one of the approaches sought by NASA, "morphing" was defined differently for this project. Morphing was defined more in the context of a goal (adaptability) than in terms of one specific approach (large shape change). Thus, the following definition for morphing was used during the NASA project and for subsequent studies to more appropriately communicate the goal of the research: "efficient, multi-point adaptability". This definition included very small or large vehicle changes that were accomplished by structural or aerodynamic approaches. In defining "morphing" in this manner, "efficient" denoted lighter weight, and/or more energy efficient than conventional systems (at the vehicle level); "multi-point" denoted accommodating diverse, and sometimes contradictory, mission requirements (such as flying fast and slow); and "adaptability" denoted extensive versatility and resilience to varying conditions or problems.

In NASA's research, the focus was on increasing the efficient, multi-point adaptability of the airplane considering many different technical approaches. As such, virtual shape change through micro flow control was one of the key areas of research. The project research identified and tested several flow control concepts that effectively "morphed" the airflow such as separation control, circulation control and vehicle control using synthetic jets. Other morphing approaches examined included, nanotechnology and biologically-inspired technologies. Fundamental materials research formed the base of the project and technologies such as the LaRC Macro-Fiber-Composite™ were developed, patented and licensed. The innumerable tools and technologies developed in the project and the resulting lessons learned from successes and failures in the project provided much of the content for this paper. Figure 4 shows several examples from the project.

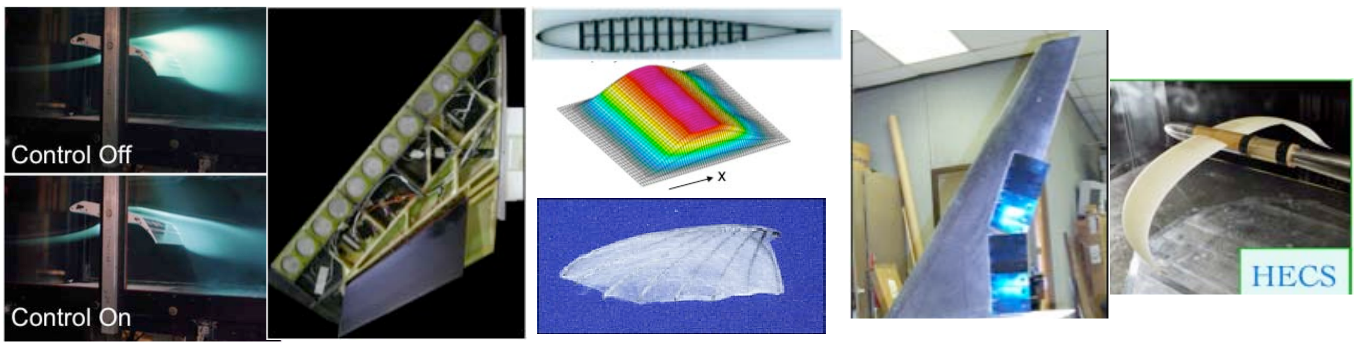


**Figure 4 Samples of Research Efforts from NASA's Morphing Project**

The size of NASA's Morphing Project varied year to year; however, generally it included 80-100 NASA researchers across many technical disciplines, several external partners at universities, industries and other government agencies. The full-cost budget of the NASA Morphing Project fluctuated around $20-35 million US dollars per year with a large portion of this budget used to fund university grants.

In 2001, NASA's image of a future morphing airplane concept caught the public eye (Figure 5). This image was created by a request from the then, NASA Administrator, Daniel Goldin. Administrator Goldin wanted a visionary animation of a future aircraft concept that morphed as a part of his testimony to the United States Congress. Though this was simply an artist's rendering of the visions of a handful of NASA engineers, this image has subsequently been used around the world to symbolize futuristic aircraft. This had both positive and negative effects. The animated morphing airplane concept did provide an inspiring vision of morphing to engineers, students, and innumerable non-technical airplane enthusiasts. However, the sophisticated icon also cemented the impression that morphing meant only dramatic continuous shape change. Some even erroneously assumed that the concept represented an actual vehicle.

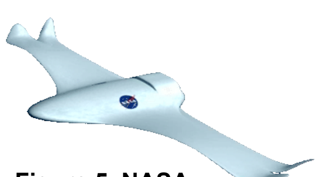

**Figure 5 NASA Image of a Morphing Airplane Concept**

NASA's Morphing project formally closed out in 2004; however, much of the research has continued in other programs, and collaborations with other government agencies and industry continue today. References 5 through 11 summarize some of the research efforts in the project through 2004.

Much other NASA research also greatly contributed to the study of adaptive technologies such as the Active Aeroelastic Wing (AAW) Program.

The AAW program was an extensive study on exploiting wing flexibility that began in the 1980's (originally called the Active Flexible Wing project). This joint NASA-Air Force Program culminated in a successful flight test program ending in 2003. Though typical aircraft design results in added wing stiffness and weight to address aeroelastic phenomena, the AAW program demonstrated that wing flexibility can be exploited instead of avoided in aircraft design, thus enabling lower weight vehicles. On the flight test vehicle, some structural components were removed, making the wings more flexible. While this normally would reduce operating envelope due to lower aileron reversal speeds or other aeroelastic challenges, the control system on the airplane was programmed to safely fly past reversal speed using leading and trailing edge control surfaces. This weight-efficient approach can enable improved manoeuvrability of high-performance aircraft at transonic and supersonic speeds.[12]

One of the many technical challenges identified in NASA's Morphing Project was the need for integrated design and optimization tools for morphing vehicles. In particular, the conceptual and preliminary design processes for aircraft with large shape changes are generally very difficult and time-consuming, and the processes are often customized for a specific shape change concept to streamline the vehicle design effort. Thus, when only one shape change concept or perturbations of that concept are being considered in design, existing tools can be used with some modification. However, if the designer seeks to compare very different shape change concepts using a consistent set of mission specifications, existing processes for conceptual design are not easily amenable.

NASA developed an integrated multidisciplinary analysis (MDA) method to enable conceptual design of morphing aircraft concepts. The approach enables an aircraft designer to assess several very different morphing concepts early in the design phase using consistent data and while obtaining second-order performance results so that design decisions can be made with better confidence.[13] The approach uses an efficient parametric model formulation that allows automatic model generation for systems undergoing radical shape changes as a function of aerodynamic parameters, geometry parameters, and shape change parameters. In contrast to other more self-contained approaches, NASA's integrated MDA utilizes off-the-shelf analysis modules to reduce development time and to make it accessible to many users. Because the analysis is loosely coupled, discipline modules, such as a multi-body code, can be easily swapped for other modules with similar capabilities. One of the advantages of this loosely coupled system is the ability to use the medium- to high-fidelity tools early in the design stages when the information can significantly influence and improve overall vehicle design. Data transfer among the analysis modules is based on an accurate and automated general-purpose data transfer tool. In general, setup time can be reduced from months to days. The integrated design approach is depicted in Figure 6.

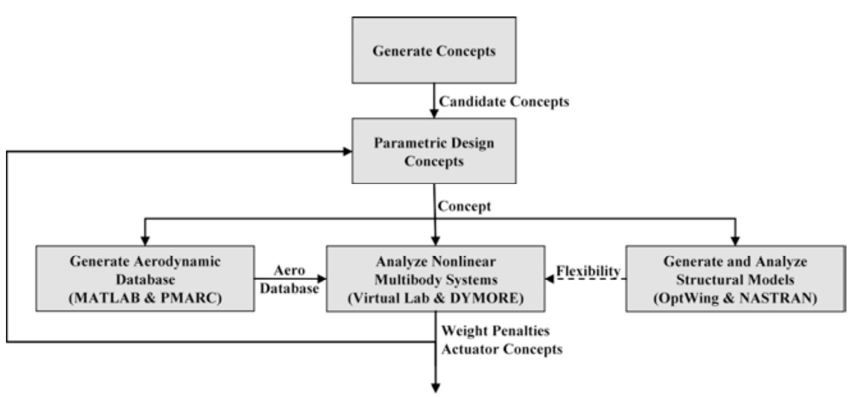


Figure 6 Overall integrated design process

### 3.2 DARPA's Research

The Defense Advanced Research Projects Agency (DARPA) initiated several innovative programs in the 1990's to develop smart materials and structures, Micro-Electrical Mechanical Systems (MEMS) and related technologies. Adaptive leading edge and hingeless control surface concepts were developed and wind-tunnel tested as a part of DARPA's programs. In 2002, DARPA initiated a program called "Morphing Aircraft Structures" (MAS). The program solicitation provides a good summary: "The overall goal of this new program is to create and advance enabling technologies and ultimately design, build, and demonstrate a seamless, aerodynamically efficient, aerial vehicle capable of radical shape change. Air vehicles are currently designed for single missions such as reconnaissance or attack. The levels of performance achieved by these structures for such specific missions are dictated to a significant degree by vehicle geometry. The ability to change the critical physical characteristics of the vehicle in flight would enable/allow a single vehicle to perform multiple mission profiles. The ability to morph would heavily influence system performance characteristics, such as: turning radius, endurance, payload, and maximum velocity, among others."[14]

For the first two phases of DARPA's MAS program, AFRL at Wright Patterson Air Force Base served as the agent to DARPA providing technical and contractual oversight to the program. The morphing designs, developed by contractors NextGen Aeronautics and Lockheed Martin, both offered considerable shape change including changes in span and wetted area. The morphing concepts focused on enabling a "hunter-killer" concept: low-speed loiter and high-speed attack on the same vehicle. NextGen's planar concept encompassed flexible skins to allow for changes in span, sweep and chord.[15] Lockheed Martin's folding wing approach incorporated flexible skins at two fold lines to allow the wings to "tuck" against the fuselage during high-speed conditions.[16] Both concepts underwent successful wind-tunnel testing at high subsonic speeds in the NASA Langley Transonic Dynamics Tunnel in 2005. The wind-tunnel tests were directed toward addressing structural integrity technical challenges of large shape change.

Phase III of DARPA's MAS program focused on flight-testing a low-speed, Remotely Piloted Vehicle (RPV) capable of large shape change to address the flight dynamics and controls challenges of future morphing air vehicles. For this phase, NASA Langley Research Center served as the agent to DARPA providing technical and contractual oversight. During this program, contractor NextGen Aeronautics designed and flight-tested an RPV with 40% change in wing area, 73% change in span and a 177% change in Aspect Ratio. This is one of the largest, repeatable changes in wetted area demonstrated in flight. Due to the flight regime of the RPV (low altitude and low subsonic speeds), the data is generally not scalable to full-scale aircraft. However, as a point of reference, previous examples of aircraft that change shape such as the F-14, B-1 and F-111 had little change in wetted area. Change in wetted area or aspect ratio has a considerable effect on many critical design variables. However, since it is very challenging structurally, it is typically not considered. One of the other technical challenges is the large variation in flight dynamic characteristics for the different configurations. Even with the considerable changes in flight dynamic characteristics, the NextGen morphing RPV successfully completed flight testing in 2007 including autonomous flight control while morphing (see Figure 7).

**Figure 7 Morphing RPV Developed by NextGen Aeronautics in the DARPA MAS III Program**

# 3.2 SOME LESSONS LEARNED FROM RESEARCH ON AIRCRAFT MORPHING

## 3.1 Are The Pay-Offs There?

Today, the term “morphing aircraft” has become somewhat of an overused buzzword that means different things to different people. The term has been used to make reference to a large body of research that in reality is not easily quantifiable or consistent. Though many are looking for simple answers as to the pay-offs of morphing, there is no simple answer. The pay-offs are relative only to the mission; and, the approach to vehicle adaptation varies considerably. As such, caution must be used in making over-arching conclusions based on the perceived successes or failures of any individual research effort. Each study addresses different goals, constraints, requirements, platforms and missions. For example, the Air Force’s F-111 Mission Adaptive Wing of the 1980’s successfully demonstrated the performance benefits of variable camber capability; however, some have criticized the weight of the structural mechanisms used. Developing weight efficient morphing mechanisms was not a goal of that program; and, this topic is a formidable research effort by itself. Two other examples are the NASA and DARPA programs on morphing mentioned above. The NASA Morphing Project focused on researching and developing a variety of enabling technologies including adaptive aerodynamics and biologically-inspired concepts to address morphing on different vehicles. The DARPA Morphing Aircraft Structures effort focused on large shape change for a specific mission scenario.

University efforts on morphing also have widely varying goals: span change; folding wings; flapping wings; design, build, fly in one or two semesters; explore morphing using one particular technology; etc. These efforts generally should not be compared to larger-scale morphing programs; because the purpose, funding and timeline of these efforts are quite different. Similarly, there are many morphing research efforts at laboratories in the government and industry that include research efforts of a somewhat academic nature. These are often done to explore or advance a new technical area (like embedded sensors, small actuators, material properties etc.) and, sometimes, to develop a new skill set within a research group. Although all of these efforts might be called morphing aircraft research, they must be taken in the context in which they were initiated; much of which is more technology push or sub-system design and not vehicle, or overall system, design. Unless the morphing technologies or sub-systems are accurately evaluated in an overall vehicle system it is often premature to try to make accurate claims about the real pay-offs.

From a vehicle design perspective, most operators deeply desire multi-point optimized aircraft. Several studies have identified the benefits of increased adaptability on a range of vehicles including micro-air vehicles, long-endurance aircraft, fighters, commercial aircraft, rotorcraft, engines, etc. The benefits of morphing are clear. The approach to morphing is still very much under research. As is noted in the section below, even though there is a wealth of research on morphing aircraft concepts, it is somewhat challenging to quantitatively compare and contrast different research efforts.

## 3.2 Conclusions from System Studies and Modern Morphing Myths

Since aircraft morphing research is used to describe a diverse body of research, two seemingly similar research efforts may actually be quite dissimilar. One researcher’s morphing concept for camber change to address acoustics issues for transport class aircraft may focus on gapless control surfaces while another researcher in a materials lab focuses on applying a new material concept to wing skins that effectively changes camber on a small generic airfoil. Even comparing vehicle-level systems design studies on morphing technologies can be challenging. Three general sources of misinterpretation are common, each perpetuating some myths about aircraft morphing.

The first source of misinterpretation often occurs when widely varying morphing approaches are lumped together as one overall approach category in a study and a blanket penalty or benefit is assigned to all morphing approaches collectively. For example, in some studies, concepts such as seamless control surfaces and variable span concepts are both generically called "morphing technologies" and considered as a single entity in a system design study and compared with other "non-morphing" concepts. The morphing technologies are given *one* generic penalty and benefit instead of separate penalties and benefits for each individual morphing technology. This generally over or under predicts the actual individual performance trade-offs, sometimes to a large extent. And, it is difficult to compare different morphing aircraft studies because the assumptions for the individual morphing approaches used are not always clear. For example, variable span technologies have high benefit but also very high "cost" to implement. Whereas seamless control surface technologies have quite a different performance benefit but may have lower "cost" to implement. Drawing the conclusion (and thus fostering the myth) that all morphing technologies have a very high "cost" to implement is inaccurate. Or, the opposite conclusion is also inaccurate: morphing technologies do not always pay-off. Each morphing approach should be delineated in design studies and considered by its individual benefit and "cost" to enable a true assessment of the technology.

Another myth has also circulated in the technical community: morphing technologies must weigh less and/or be less complicated than their conventional counterparts. In fact, the individual morphing technology (at the sub-system level) may weigh more and be more complex than the conventional approach. As long as the overall vehicle at the system level has a net benefit, the technology is appropriate. A familiar example of this is retractable landing gear. Retractable gear is enormously heavier and more complicated than fixed gear, representing as much as 10% of the empty take off weight and substantial mechanical complexity. However, when one considers high-speed flight and the larger propulsion system that would result from the aerodynamic inefficiencies of fixed gear, then it becomes obvious that retractable landing gear is key to having an efficient total system. Forcing morphing sub-system development to be consistently lower in weight, or less complex, than conventional sub-systems unnecessarily constraints the research. The dominant metric is at the system level not the sub-system level.

The second source of misinterpretation from the literature is present when one study assumes one approach to morphing, with specific assumptions (for vehicle mission, etc.), and another study has a very different approach and assumptions. For example, there are numerous ways to vary wing camber. Four different


**Figure 8 Four Different Camber Change Approaches**

approaches are shown in Figure 8: conformal trailing edge control surfaces (wind-tunnel tested during the DARPA Smart Wing program of the 1990s); spanwise blowing (from the F-4C flight test in 1984); seamless control surfaces augmented with active flow control (wind-tunnel tested by NASA in the Morphing Project); and comprehensive leading edge to trailing edge camber change (notional concept). The motivation for each approach is completely driven by the aircraft's mission. These results can only be compared in context with the specific mission specifications (speed, Reynold's number, etc.) and the trade-offs of each specific technical approach (weight, power, etc.). Thus, the benefits and trade-offs of variable camber morphing cannot be generalized to a single answer.

Another myth is that morphing must be accomplished by seamless structural shape change. This is understandable given that the genesis of modern day morphing aircraft had its roots in the adaptive structures community and the hope is that seamless structural shape change will yield very high benefit. However, as shown in Figure 8, the transformation required of a morphing aircraft is often to the *airflow*. This can be accomplished with flow control (a virtual shape change) or structural control or a combination of both. While not frequently considered in the morphing aircraft research community, active or passive flow control may provide an efficient and effective means of morphing. Certainly, the mission requirements and overall vehicle performance and efficiency determine the best solution. At present, advancements in flow control and structural control actuators and sensors and flexible skins are continuing at an unprecedented rate and may yield new opportunities in the near future.

The third source of misinterpretation is present when the morphing approach or sub-system (such as piezoelectrically-controlled vibration) is optimized instead of a vehicle (or system) level performance characteristic (such as gross weight). This may yield an optimized sub-system but a sub-optimized vehicle.

At the system level, it is clear that morphing is a multidiscipline challenge. At the sub-system level, each technical discipline often tries to solve the morphing challenge individually. For example, a structures expert may consider variable camber as solely a structural shape change problem. In reality, it's an adaptive aerodynamic, structures, materials and controls problem requiring the disciplines to integrate to find the best system solution. However, many studies on morphing are about optimizing a morphing sub-system or approach and not the vehicle system. Taken in the appropriate context, these studies are still a critical part of technology advancement. However, it is important to recognize that other multi-discipline approaches to morphing also exist and may offer even better solutions, either singly or in concert.

## 3.3 Technical Challenges

The renewed interest in morphing aircraft of the 1990's has reminded the technical community that morphing represents a fundamental shift in air vehicle design: from one main vehicle configuration, with small to medium perturbations about this point, to several configurations, with perturbations about each one. With a morphing aircraft, each configuration can effectively be a different vehicle with different moments of inertia, stability characteristics, aerodynamics, etc. The increased dimensionality of this multi-point design challenge substantially increases the analysis, characterization and validation required for design since each design maxima must be considered as well as transitions between them. It would be impossible to summarize the many technical challenges with developing a morphing aircraft because they vary dramatically depending on technical approach and mission as noted earlier. Only a few basic considerations are noted here.

**Figure 9 V-22 Osprey and F-35**

In the area of flight dynamics and control, each aircraft configuration has its own flight characteristics for which controls must be designed. The greater the diversity of flight characteristics, the greater the controls challenges. Recent examples of highly adaptive aircraft are the V-22 Osprey and the F-35 Lightning, shown in Figure 9. Both have required extensive control system design and testing not only for their various flight configurations but also for the transitions between those configurations. The NextGen Morphing RPV provides another example of a multiple configuration aircraft with a wide variation in flight characteristics.

Advances in control theory as well as flight dynamics testing and modelling techniques offer some relief to the increased complexity problem of morphing aircraft. Adaptive control approaches offer the potential to provide robust control with lower fidelity aircraft models. This could be particularly useful during the transition between modelled states or configurations.

In aircraft structural design, over the past 100 years, design has evolved to produce increasingly more rigid structures capable of carrying the ever increasing aerodynamic and g-force loading associated with modern fighter aircraft. Unfortunately this trend makes it relatively difficult to morph large sections of a modern aircraft structure. Early attempts to deflect modern wing-box structure using torque tubes and actuators resulted in aerodynamic benefits that did not outweigh the penalties associated with the additional hardware.

To realize the potential benefits of morphing, a paradigm shift needs to occur in the area of aircraft structural design. Rather than attempting to make the aircraft structure as rigid as possible, the aircraft structure must be designed to morph or reconfigure. This design approach is not without complex challenges. If the main load carrying components (such as the wing box) are more flexible then fairly sophisticated control schemes will likely be required to position the wing throughout the flight as well as control aeroelastic phenomena.

Another approach is to design the overall wing structure to include mechanisms permitting the required morphing motion without fighting inherent structural deflection forces. Retractable flaps and landing gear do not bend rigid structural members to achieve shape change. Rather, the structure includes pivots, linkages, and actuators to allow the surfaces or components to be moved to and locked into several different positions.

The NextGen Aeronautics morphing wing concept developed during the DARPA MAS program is an example of applying this approach to a wing structure. The primary structural members of the wing were configured into parallelograms that remained rigid in the out-of-plane direction to carry wing loads. The parallelogram-based design could make large area changes in the plane of the wing with relatively small actuators. Since structural elements were not being bent to hold any particular wing morph position, the actuators only had to be powered when a configuration change was made. To hold a particular configuration, the structure made use of worm gear mechanisms and/or other lockouts, without requiring the actuators to be continuously powered.

A further step in redefining the structural design paradigm will include the development of individual structural elements being capable of morphing in one or more directions. This may include the further development of specialty smart materials, or it may involve the development of microstructures with rigidity in some directions, but extreme flexibility in others. For example, unfaced unexpanded metal honeycomb is relatively rigid in several directions, but can be stretched to 5 or 10 times its original length in one particular direction. MEMS technology may eventually allow for the design of structural elements that are far more suited to morphing than the current homogenous metals or composites used in aircraft structures today. Reference 17 provides a good summary of many structural morphing concepts.

## 4.0 CONCLUDING REMARKS

Real-time adaptation to enable multi-point optimized performance in aircraft has been a challenging desire since the dawn of flight. Though the vision for morphing aircraft is not new, the potential enabling technologies from fields such as smart materials, nanotechnology and micro flow control have re-opened the door to a renewed interest in the subject in the last two decades. Innumerable studies on morphing technologies and aircraft have been conducted in many countries. Since the definition for morphing varies widely in the technical community, it is impossible to quantitatively compare results and make general conclusions as to the benefits or penalties of the broad suite of what is commonly called "aircraft morphing" technologies today. There are many methods to enable real-time adaptation in flight and each must be considered in context with the mission requirements. In some cases, a morphing concept may weigh more than an existing concept – but the added system functionality may lead to an overall system benefit that effectively outweighs the additional mass. That said, morphing does not always pay off, and careful and technology-specific trade studies must be done to quantify the specific benefit of any morphing concept.

In considering the next century of flight, performance demands will likely continue to increase and even diversify. One modern example is in addressing the increasing environmental concerns with air travel. Making substantial reductions in the environmental impact of air vehicles while maintaining or improving vehicle performance, or vehicle capabilities, often results in contradictory requirements. Adaptive or morphing technologies may be able to address some of these challenges with fewer penalties. It is conceivable that adaptive technologies will continue to find their way on future aircraft to address other common design challenges such as: expanding the flight envelope, solving lingering system and sub-system challenges such as noise and vibration, and in the dreams of many, enable a radical leap in aircraft capability. As with the dawn of powered flight, it may be the dream (and associated engineering curiosity) that propels the next leap.

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