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Fuel Burn Reduction Through Wing Morphing

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Abstract Changing the shape of aircraft is beneficial because they operate in a wide range of flight conditions with conflicting requirements and the concomitant variations in aircraft performance. This chapter focuses on morphing systems that contribute to reducing fuel burn for commercial transport aircraft. We start with a summary of how morphing can reduce fuel burn from the system-level viewpoint, following which we analyze the three wing-morphing modes: planform, out of plane, and airfoil. For each of these, we review morphing mechanisms that are already in place, such as high-lift systems, and provide an outlook on how more advanced morphing technologies can further reduce fuel burn. The impact of any morphing system must be quantified by considering all the disciplines involved, and a clean-sheet design should be done to realize the full potential. The most promising type of morphing for the near future is variable trailing-edge camber, which can tailor the aerodynamic performance and more effectively alleviate maneuver load. Research on new materials and morphing mechanisms will make morphing systems lighter, more energy efficient, and more economical. It is just a question of time before we see aircraft wings that exhibit morphing capabilities that seem impossible today.

1 Introduction

The word "morphing" originates from the Greek word *metamorphosis*, which translates to "transformation." Morphing started being used as a term in computer graphics to mean a smooth transformation from one image into another. The application of the word morphing to aircraft started in the late 1990s [WHM+98] to mean a transformation of aircraft shape. Although there is no universal agreement between researchers on the type of shape change that constitutes morphing [Fri12], we adopt herein the broader definition that encompasses any type of shape change [Wei13].

Shape changes in aircraft are beneficial because aircraft operate in a wide range of flight conditions (e.g., takeoff, cruise with various payloads, and landing), each of which have conflicting requirements and performance metrics. For example, for efficient cruising, an aircraft wing should be as small as possible with moderate camber whereas, when landing, a large area and high camber are desirable for a low enough speed. This need has been addressed with conventional high-lift systems, which are morphing systems in their own right.

Morphing-aircraft research has centered on shape changes to the wing, which is the component that most impacts aircraft performance. There is, however, a notable exception in the retractable landing gear, which can be considered a type of shape morphing whose added complexity and weight pays for itself by drastically reducing the drag. Wing morphing can change the planform (sweep, span, chord), move the wing out of plane (twist, bending), or change airfoil shapes—which can also result in planform and out-of-plane morphing.

The focus of this chapter is on morphing systems that contribute to reducing fuel burn. This reduction may be achieved through a combination of better aerodynamic, structural, and propulsive efficiency enabled

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by shape changes. Because the vast majority of fuel is consumed by commercial transport aircraft, we restrict our discussion in this chapter to this class of aircraft. For a more general overview of aircraft morphing systems and their applications, including a historical perspective, see Weisshaar [Wei13]. For a comprehensive review of morphing technologies, including the underlying mechanisms and materials, see Barbarino et al. [BBA$^+$11].

2 Impact of Morphing on Fuel Burn

The impact of morphing on fuel burn arises when it helps the aircraft maintain high performance in spite of changing operating conditions and requirements. To quantify the impact of morphing on fuel burn, we must compute the performance over the complete mission (or even over several different missions), including takeoff, climb, descent, and landing. Figure 1 shows a typical mission profile for a long-range commercial transport aircraft. For such an aircraft, the fuel weight could represent as much as 40% of the takeoff weight and, therefore, as the fuel burns the aircraft lightens considerably. This changes the operating conditions: either the angle of attack is decreased, the speed is decreased, or the altitude is increased. Altitude is the preferred change because, if the altitude increases optimally, the aircraft can fly at its optimum point in the drag polar. However, this is not usually possible because of air-traffic-control restrictions, which constrain aircraft to operate at fixed altitudes. Thus, a long-range aircraft typically flies at constant-altitude segments and increases its altitude up to three times in 2000 ft increments during cruise, thus flying at operating points for which its performance is not optimal.

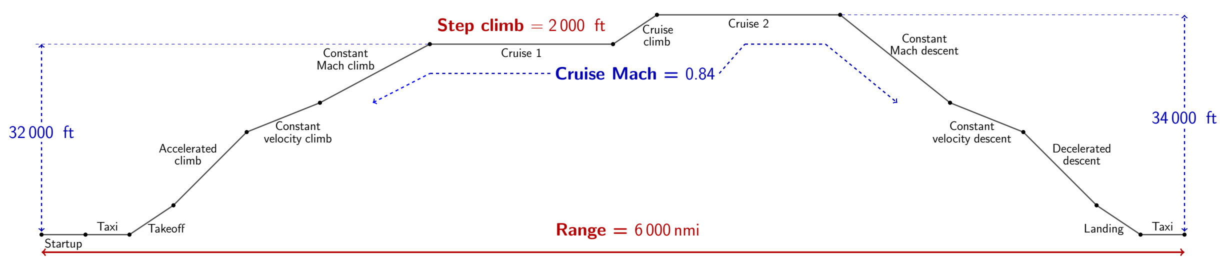

Figure 1: Typical mission profile for a long-range commercial transport aircraft.

The flight operating points for takeoff, climb, descent, and landing are even farther from the optimal operating point. Although the fuel-burn contributions from these segments are small relative to the cruise segment for long-range commercial transports, they become more significant for short-range missions.

Another factor that causes a deviation from the optimum operating conditions for a given aircraft is the weight, which is a function of the payload and the length of the mission (which dictates the amount of fuel). Although in theory it is possible to operate at the optimum point for a wide range of aircraft weights by varying the altitude to match the ideal lift coefficient, this is not always possible. In addition, many aircraft are stretched versions with increased takeoff weight whose wings are not ideally sized because they are inherited from a lower-weight version of the aircraft.

Given that commercial aircraft end up operating over a range of conditions, morphing their shape to obtain the best possible performance in each condition is a useful feature. The question is whether such a feature buys its way into the aircraft. For this to happen we require an increase in performance once we account for all the multidisciplinary trade-offs (drag, weight, and their ultimate effect on fuel burn). In addition, the increase in performance must be large enough to justify the potential added complexity and acquisition cost, which is ultimately a decision to be made by the airlines.

In its simplest form, we can quantify the fuel burn during cruise through the Breguet range equation:

$$W_f = W_0 \left\{ \exp\left[\frac{Rc}{V} \left(\frac{L}{D} \right)^{-1} \right] - 1 \right\}, \tag{1}$$

where W_0 is the aircraft weight at the end of cruise, R is the length of the cruise segment, c is the engine thrust specific fuel consumption, and V is the cruise speed. The fuel burn reduction depends on the aerodynamic performance (through the lift-to-drag ratio L/D), structural weight (embedded in W_0), and propulsion efficiency (through c/V).

What is not explicitly shown in this equation is that any change that improves one of these efficiencies generally affects the others. For example, increasing L/D by increasing the span (to reduce the induced drag) increases the structural weight and therefore increases W_0. Thus, morphing systems with potentially reduced fuel burn need to be evaluated by accounting for all these multidisciplinary trade-offs. In addition, "clean-sheet" designs should be considered, where all important variables are optimized through multidisciplinary design optimization (MDO) [ML13, KM14].

3 Planform Morphing

Morphing the planform shape of a wing includes varying the sweep, span, or chord (the latter two directly affect the planform area). Historically, morphing the planform has never been shown to buy its way in commercial transport, except for chord extension provided by high-lift systems—which is discussed in Sec. 5.

Sweep is desirable for lowering the wave drag but also decreases the overall lift coefficient, which needs to be compensated with baseline planform area, high-lift systems, or both. Hence, variable sweep would be desirable because it makes it possible to reduce the weight due to the high-lift system or wing size. Variable-sweep systems have been used in several supersonic military aircraft but never in commercial transports, which only need to operate optimally within a relatively narrow range of cruise conditions. The additional weight of variable-sweep systems and the structural reinforcement required in the wing-fuselage attachments negate the advantages stated above. In addition, the advent of sophisticated high-lift systems and supercritical airfoils that enable sweep reduction also contribute toward the choice of fixed-sweep wings.

Large spans are desirable for lowering induced drag, which constitutes about 30% of the total drag for a typical commercial transport aircraft in cruise. Although this percentage varies between the different phases of flight, there is no incentive to have a variable span during flight. The largest possible span determined by the multidisciplinary trade-offs is desirable in all flight conditions. A few successful designs of varying-span aircraft have been developed in the past, but the motivation for those was the associated variation in planform area to adapt to different flight conditions. An example of this is the Akaflieg Stuttgart FS-29 glider, which uses a telescoping wing to adapt to two different speeds: a low speed optimal for climbing in thermals, or a high speed to fly between thermals.

Although there is insufficient incentive for varying the span of a commercial transport in flight, there is a big incentive for reducing the span on the ground due to gate constraints. When the Boeing 777 program was launched in 1994, an option of folding wingtips was provided, but no airline selected this model. The folding wingtip was resurrected in the 777X program, which promises to provide folding tips that enable a span increase relative to the original 777, while maintaining compatibility with the gates that the 777 currently uses. The weight of the folding mechanism is claimed to be much lighter than the original mechanism.

4 Out-of-Plane Morphing

Out-of-plane morphing consists of any shape change that deforms the wing in the direction perpendicular to the planform plane and encompasses twist and spanwise bending. This does not include local airfoil-shape deformations, which are considered separately in the next section.

Wing twist was used in the very first successful powered aircraft, the Wright Flyer, where it was used for roll control. However, this form of control was quickly replaced by the aileron, which remains the preferred system today. Although twist morphing retains a smoother gap-free shape, which incurs less drag than a hinged control surface, it generally requires a more complex actuation system that uses more energy. In addition, twisting the wing without using excessive energy requires the wing to be more flexible, which could lead to undesirable aeroelastic phenomena within the flight envelope.

However, a better understanding of aeroelasticity and the development of composite materials have made twist morphing more feasible. Twist morphing can have multiple functions: it can increase the lift coefficient, control the aircraft, and alleviate aerodynamic loads. These functions can also be achieved with conventional trailing-edge surfaces or airfoil camber morphing (see Sec. 5).

The active flexible wing research program [Mil88] developed a morphing system that made relatively small shape changes in the leading and trailing edges to leverage the wing flexibility in twist to achieve larger control authority. This study concluded that the proposed approach could enable an aircraft to maintain roll authority beyond the aileron reversal speed of an equivalent conventional wing. This was subsequently demonstrated in the active aeroelastic wing program, which included test flights for an F/A-18 fighter with leading- and trailing-edge morphing surfaces [PBF+00]. Although such systems have not been used in commercial transport aircraft, the current trend has been to design longer spans and more flexible wings, where aileron reversal becomes more critical and such morphing systems might be a good solution.

In addition to enabling a lighter wing structure (or larger wing spans for similar weight) by maintaining the control authority of a more flexible wing, twist deformations can also be used for load alleviation, which decreases the wing structural weight.

There are two main types of load alleviation: gust load alleviation and maneuver load alleviation. Gust load alleviation is performed dynamically; as soon as a large acceleration is sensed on the wing, control surfaces act to decrease its effect on the structural loads. Maneuver load alleviation is less time dependent, and typically the total lift must be increased. In this case, control surfaces act to redistribute the load to be more concentrated towards the inboard of the wing to decrease the average bending moment for the same total lift, as illustrated in Fig. 2.

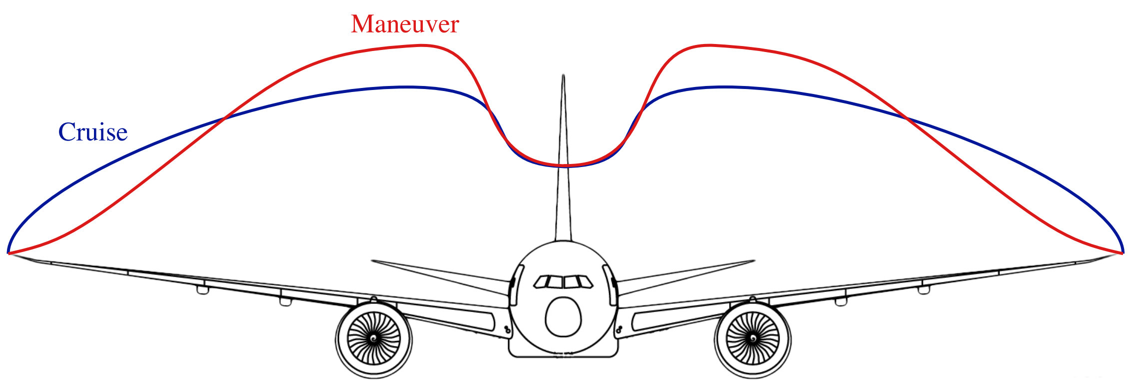

Figure 2: Twist morphing can shift the spanwise lift distribution inboard under critical load conditions to reduce wing structural weight.

Load alleviation does not necessarily need to be active; designing a wing with a coupling between bending and twisting deformations can passively reduce the bending load as the wing is subjected to increased lift by reducing the incidence of the outboard wing [HML12, XK14]. Swept wings naturally have some degree of bend-twist coupling, and this can be augmented by tailoring the stiffness. Composite materials, because they are anisotropic, are especially suited to this kind of aeroelastic tailoring. Passive load alleviation can also be enhanced by using raked wingtips, which, due to their higher sweep, have a lower lift-curve slope

[JPM10, KM14].

In addition to control and load alleviation, wing twist can reduce the induced drag by tailoring the spanwise lift distribution to be as elliptical as possible for any given flight condition. The spanwise lift distribution is a compromise between the desire to have a lift distribution that is close to elliptical at the cruise conditions, and the desire to have a more triangular lift distribution at the load conditions that size the structure. It is possible to achieve this by using passive tailoring. The right trade-off between these conditions depends on what the designer chooses to optimize and can be obtained through MDO, which includes both aerodynamics and structures and optimizes with respect to both aerodynamic shape and structural sizing [KM14].

With the active tailoring mentioned previously, it is possible to achieve higher performance than with passive tailoring. Furthermore, the larger the freedom in shape morphing, the larger the gains. Thus, in theory, morphing airfoils in the wing to any desired shape would be ideal. However, as previously mentioned, we must balance the energy, weight, and complexity of the morphing mechanism. The trailing edge is typically the most effective part to morph, so much research has gone into both modifying conventional ailerons and flaps, as well as using more sophisticated mechanisms to morph trailing edges, and adding camber to the wing. The spanwise variation of airfoil effectively changes the wing-twist distribution, but we reserve the discussion of this type of morphing until Sec. 5.

The other possible out-of-plane morphing is a change in dihedral. This includes the aeroelastic bending on the wing mentioned above but, unlike the changes in twist, this bending has little effect on aerodynamic performance other than a small reduction in the effective wing span and the lift. Morphing dihedral has been studied recently for unmanned aerial vehicles. Dihedral is present in commercial transport aircraft mainly for lateral stability. It also helps to maintain the clearance of the engine nacelles from the ground. Thus, morphing the dihedral is of little interest here. However, the folding wingtip of the Boeing 777X mentioned above in the context of morphing span can also be considered a change in dihedral.

5 Airfoil Morphing

There are a number of technologies used today in commercial transports that many people do not associate with morphing, such as conventional high-lift systems, which change aircraft shape to deal with the conflicting requirements for landing and takeoff (where higher lift coefficients are required), and for performance at cruise (where we want the smallest possible wing with a much lower lift coefficient). Leading-edge slats and Fowler flaps are a powerful combination that addresses this issue in an effective way. More recently, there has been progress in simplifying high-lift systems and packaging them more efficiently. This is seen in the Boeing 787 wing, where a single-slot flap is used with a compact mechanism. This results in smaller flap track fairings, which reduce both drag and weight.

There is currently no substitute envisioned for the combination of slats and Flower flaps. The reason is that, even if we could have a morphing mechanism that could change the airfoil smoothly to any shape, the high-lift coefficients required for landing cannot be achieved unless gaps are introduced or a blowing mechanism is used. Alternatively, the wing area could be increased, but this would incur a drag and weight penalty. However, ailerons with gaps or hinges could be replaced by smooth morphing surfaces with no loss in control authority, resulting in drag reduction.

Most research on airfoil morphing focuses on changing the camber (as opposed to the thickness), because camber is the primary parameter controlling the ideal lift coefficient. In addition, changes in the trailing edge are easier to integrate from the structural design point of view, because they do not interfere with the structural wing box. As mentioned in Sec. 4, these changes can be used to improve the spanwise lift distribution for induced drag reduction, load alleviation, or both.

Szodruch and Hilbig [SH98] provide an overview of several efforts to design variable-camber systems for transport aircraft and attempts to quantify the benefit of such systems. Figure 3 shows one of the most favorable results from that paper; it shows the result of a wind tunnel test on a variable-camber trailing-edge system, which exhibits improvements in L/D between 3% and 9%, together with an increase in the buffet onset C_L of 12%. Part of these gains were attributed to the fact that the variable-camber wing is more robust against manufacturing tolerances. For a fixed wing optimized for a single nominal condition, we expect the L/D curve for the variable-camber wing to show exactly the same performance at the nominal condition. However, realistic wings are designed to perform sufficiently well in other flight conditions, compromising the performance at the nominal condition. Therefore, a morphing wing still shows an improvement in this flight condition.

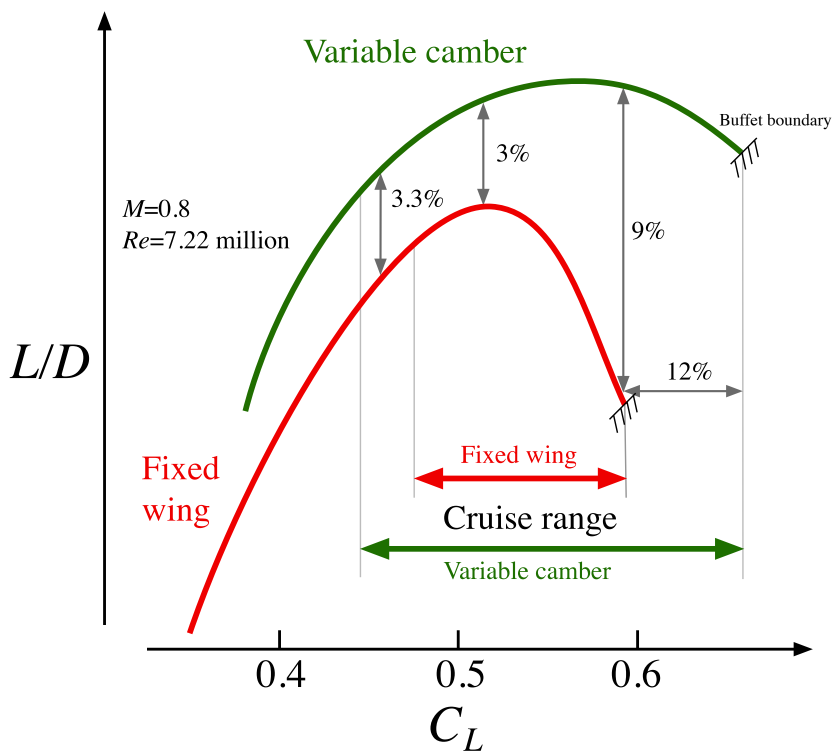

Figure 3: Variable-camber trailing edge increases the aerodynamic performance over a range of lift coefficients (adapted from Ref. [SH98]).

Ailerons have been used for maneuver load alleviation for decades but, in spite of several studies done in the 1980s [HW84, MSB] that showed the advantages of morphing for cruise aerodynamic performance, aircraft have been designed, until recently, to have a fixed wing geometry at cruise.

The Boeing 787 and the Airbus A350 are the first commercial transports to use a system that deflects the flaps and ailerons according to the cruise flight conditions to minimize fuel burn [Rec14]. Since modern transport aircraft already have movable surfaces along most of the trailing edge, as shown in Fig. 4, the adjustments are extensive. However, a smooth morphing system with no hinges along the entire trailing edge would be even better from an aerodynamic point of view and would also have more freedom in tailoring the spanwise variation of camber.

Given the fact that, to date, no substitute exists for the gaps in current high-lift systems, Hilbig et al. [HW84] proposed replacing the ailerons with a smooth system and integrating the system with Fowler flaps. Greff [Gre90] proposed a system that is presumably similar to that used in the Boeing 787 and Airbus A350, where conventional flaps are adjusted at cruise.

In addition to tailoring the spanwise lift distribution to reduce induced drag and optimizing the airfoil

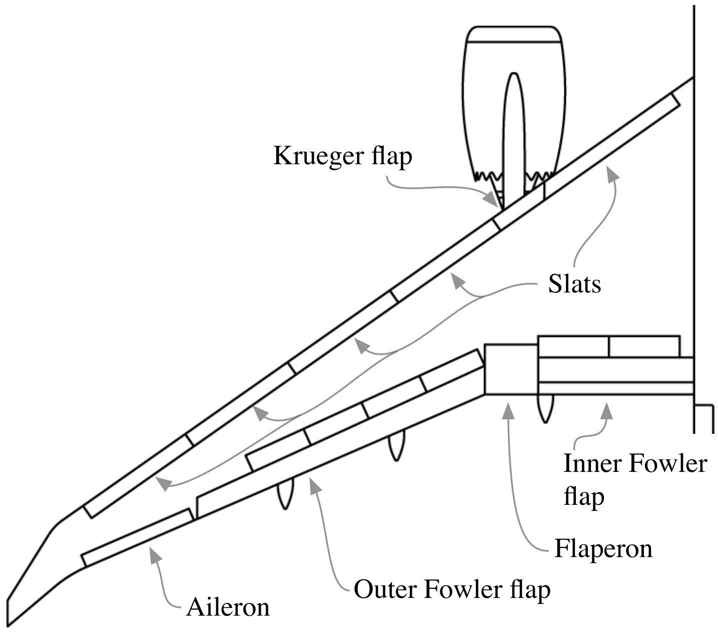

Figure 4: The trailing edge of a modern transport aircraft has either Fowler flaps or ailerons over most of its length.

camber for maximum aerodynamic performance at a given lift coefficient, there are a few other advantages of using this system. One advantage is the fact that changing the camber shifts the buffet boundary, which increases the operational flexibility. When this is considered in a clean-sheet design, it could also result in the sizing of a smaller wing and lower structural weight for a given mission [Gre90].

Another cited advantage is that the aircraft could fly at an angle of attack that is almost constant through the entire cruise segment, and thus the fuselage-wing fairing could be designed more effectively to minimize interference drag. The same advantage applies to the detailed shaping of the fuselage tail cone. Finally, less deviation in the angle of attack also gives designers more flexibility in meeting the 2° cabin-floor constraint, making it possible to lower the wing-root angle with respect to the fuselage. This reduces the pitching moment, the downwash, and the effective upsweep of the tail cone, resulting in an estimated additional drag reduction of 1.0%–1.5%. Greff's estimate of the combined drag reduction, which assumes rigid flap movement, is 5%[Gre90].

A downside of adjusting the trailing-edge camber is the increase in pitching moment, which adds trim drag. However, the penalty is estimated to be an order of magnitude less than the decrease in total drag [Gre90].

One of the important design insights that Greff [Gre90] provides is that the full potential of the variable-trailing-edge-camber concept can only be realized when the entire wing shape is specially designed with this concept in mind. The reason for this is that a conventional wing tends to have a chordwise pressure distribution that thickens the boundary layer to the point where it might not tolerate additional trailing-edge camber. The capability to perform high-fidelity aerodynamic shape optimization has since made this task much easier. Figure 5 shows an example of this design capability [LM15]. The wing on the left is a wing optimized by applying a Reynolds-averaged Navier–Stokes analysis together with an adjoint method and a gradient-based optimizer. The design optimization problem considers five different flight conditions. The result in red shows this wing analyzed for an off-design condition. The same wing with trailing-edge morphing is shown in blue. We can see that small changes in trailing-edge camber can reduce the shock by lowering the angle of attack required to maintain the target lift coefficient.

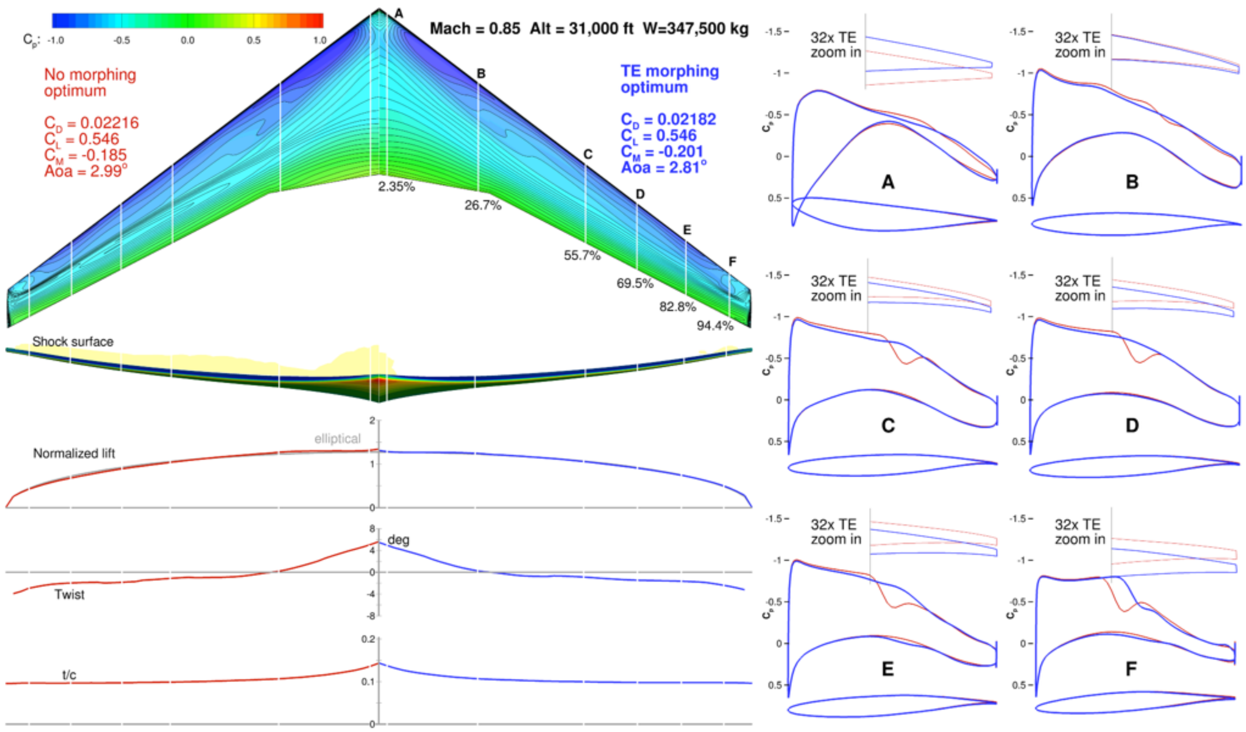

Figure 5: An optimized wing in an off-design condition (left, red), compared to the same wing with trailing-edge morphing (right, blue) [LM15].

Kota et al. [KOE+07, KHO06] designed, fabricated, and flight tested a lightweight low-power adaptive morphing trailing-edge wing. A scale model of the wing was installed under the fuselage of the Scaled Composites White Knight and flown at full-scale dynamic pressure and Mach number. From the experimental results, they estimated that equipping an aircraft with this mission adaptive compliant wing technology would increase the aircraft endurance by 15% or more. In addition to tailoring the drag polar for different flight conditions, Kota et al. also cite the benefit of morphing the wing to tailor the laminar bucket for natural laminar-flow airfoils [KOE+07].

6 Conclusions and Outlook

In this chapter, we provide an overview of all possible types of morphing but focus the discussion on morphing that enables a reduction of fuel burn for commercial transport aircraft. We discuss the types of shape changes and their impact on fuel burn rather than the mechanisms that enable those shape changes. Among the morphing mechanisms, we include the control surfaces and high-lift systems that we see in aircraft today.

The impact of any morphing mechanism must be quantified by considering all the disciplines involved in the aircraft, and a clean-sheet design should be done to realize the full potential of the system under consideration. Although many types of new morphing systems have been proposed, not all of them buy themselves into the aircraft in terms of overall performance once their weight, cost, required power, and maintainability are considered.

Although this outlook might seem bleak given the extensive research on exotic morphing mechanisms and the bold predictions in the literature, we know that, historically, it takes time for new technologies to make their way into commercial aircraft. As discussed in this chapter, the variable trailing-edge camber using conventional flaps, which began in the Boeing 787, was proposed three decades ago.

The more promising morphing systems for the near future seem to involve improvements in the variable-trailing-edge-camber technology by using morphing technologies that allow for smoother chord-wise shapes with no gaps, as well as more variation of the camber in the spanwise direction. Although adaptive trailing edges with conventional surfaces reduce the fuel burn for a typical transport mission by less than 1%, adaptive morphing trailing-edge technologies could reduce the fuel burn by 3% to 10%. Further gains are expected with improvements in the passive and active aeroelastic tailoring enabled by fine tuning the camber variation in the spanwise direction together with sophisticated real-time control systems. The higher degree of load alleviation afforded by such systems is likely to enable an increase in wing span to achieve further reductions in fuel burn because of lower induced drag.

Current research and development of new materials, the invention of new morphing mechanisms, and the continual improvement of design processes will eventually make the more exotic morphing systems lighter, more energy efficient, and economical. It is just a question of time until we see aircraft wings that exhibit morphing capabilities that seem impossible today. For example, airfoil shapes could be fully morphing and would continuously adapt to produce shock-free flow in any transonic conditions. Another possibility would be that we find a way to significantly change the wing area such that the slots associated with high-lift system are not required, and the aircraft can fly at cruise with the absolute minimum-area wing required, drastically reducing parasitic drag.

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