AIRCRAFT CONCEPTUAL DESIGN WITH NATURAL LAMINAR FLOW

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Abstract

In this paper we describe a conceptual design process for aircraft with natural laminar flow. The wing pressure distribution is described by several parameters which are used as design variables in a multidisciplinary optimization. An existing conceptual design tool is enhanced to include the effects of the wing pressure distribution on structural weight, trim, high lift performance, and drag. Viscous drag is computed based on the wing pressure distribution using multiple runs of a quasi-three dimensional boundary layer code with a rapid transition prediction method that includes models for Tollmein-Schlichting, cross-flow, and attachment line transition modes. To demonstrate this design process, the method is used to design a narrowbody passenger transport. The design results indicate that when multidisciplinary tradeoffs are considered, natural laminar flow provides significant mission performance improvements.

1 Introduction

Rising fuel costs and greater sensitivity to the impact of emissions on the global atmosphere [1] increase the importance of fuel efficiency for future transport aircraft. Fuel consumption can be reduced by decreasing airframe weight or drag, improving the efficiency of the engines, and eliminating waste in the aircraft mission. An excellent overview of the physical phenomena associated with reduced fuel burn is given by Green in [2]. This paper presents a new conceptual design method that focuses on the multidisciplinary tradeoffs associated with aircraft designs using extensive regions of transonic natural laminar flow, one of the technologies that appears promising for reducing fuel consumption.

1.1 Laminar Flow Control

Laminar flow arises when the boundary layer of the flow is stabilized so as to significantly delay the transition from laminarity to turbulence. Three primary mechanisms trigger transition on aircraft wings: Tollmien-Schlichting (T-S) instabilities, crossflow instabilities, and attachment line instability [2]. Attachment line instability is well understood and can be controlled [3]. To control the T-S and crossflow boundary layer instabilities, one may apply several methods of active laminar flow control (LFC) such as suction or cooling [4]. Alternatively, the boundary layer can be passively stabilized by shaping the wing pressure distribution, giving rise to natural laminar flow (NLF).

1.2 Design for Natural Laminar Flow

Design for NLF is attractive because, unlike active LFC methods, it does not require additional systems to be integrated with the aircraft. Generally, a favorable pressure gradient such as that shown in Figure 1 will stabilize the boundary layer, delaying the transition to turbulence. However, shaping the wing to generate such a pressure distribution presents several challenges. Boundary layers become more difficult to stabilize as the Reynolds number and sweep increase. Also, a pressure distribution that yields

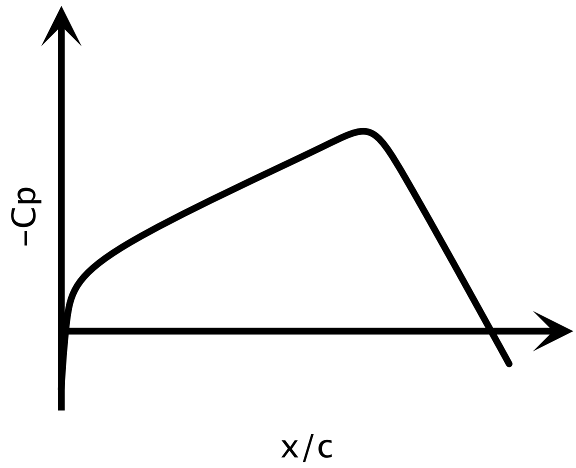

Fig. 1: Example of a favorable pressure gradient needed for NLF.

maximum laminar flow may require a wing geometry that is too heavy or develops too much compressibility drag.

Several previous studies have suggested that the net benefit in fuel burn for NLF is near 10% [5]. Achieving this improvement involves a complex tradeoff between the aerodynamic advantages of NLF and the penalties imposed on other disciplines. If the costs and benefits are not properly balanced, the resulting aircraft will have sub-optimal performance. For example, a previous study estimated that the lift to drag ratio of an aircraft with NLF could be increased by 20% to 30% [6]. The same study, however, showed that the overall performance of the notional aircraft would be worse than a turbulent reference aircraft due to the system costs of achieving NLF over the wing.

In aircraft conceptual design, a multidisciplinary optimization (MDO) method is used to compute rapidly the tradeoffs between aircraft systems [7]. Some researchers using MDO have included NLF through simple criteria, such as an empirical relationship between Reynolds number, sweep, and laminar-turbulent transition. This relationship is then coupled with empirical penalties applied to other systems [5], [8].

2 Methodology

This paper presents a physics-based method of including the effects of NLF in the conceptual design process. As discussed above, NLF arises when the pressure distribution on the wing is shaped in such a way that the wing boundary layer is naturally stabilized. However, the designer is not free to choose arbitrarily a pressure distribution shape. The selected pressures must be consistent with other aircraft features such as wing weight, viscous drag, compressibility drag, induced drag, $C_{L,max}$, and trim.

In the present method, the wing pressure distribution is described by several parameters which are used as design variables in an MDO process. Some of the possible pressure distributions are conducive to laminar flow, and some are not. The optimizer is free to choose which distribution is best. For certain design constraints, a laminar aircraft may be optimal, and for other constraints a turbulent aircraft will be optimal. This parameterization replaces some variables typical in a conceptual design optimization, such as wing thickness, and imposes many other constraints on the aircraft.

The results of the optimization include not only a wing planform description but also the target pressure distribution required for the predicted performance. These results can then serve as a starting point for higher-fidelity optimizations.

Wing thickness is no longer an independent design variable because a prescribed pressure distribution implies a certain wing geometry. The distribution of pressure on the wing is described by interpolation between pressures at several streamwise stations. A minimum of three sections, located inboard of the planform break, at the planform break, and on the outboard portion of the wing (Figure 2), describe the underlying wing geometry. Additional prescribed sections would increase the fidelity of the method but add complexity and computational cost.

The pressure distribution at each spanwise station is represented by five dimensionless pressure parameters and four dimensionless chordwise parameters, as shown in Figure 3. The parameters are chosen to allow a distribution with a rooftop pressure gradient that can be either favorable or adverse, while keeping the number of design variables to a minimum. Such a parameterization encompasses both NLF type airfoils and more conventional turbulent supercritical sections.

The upper surface design variables consist of four parameters: an initial rooftop pressure (*p1*, *x1*) and a final rooftop pressure (*p2*, *x2*) at the start of recovery. The lower surface design variables consist of five parameters: an initial rooftop pressure (*p3*, *x3*), a final rooftop pressure at the start of recovery (*p4*, *x4*), and an aft pressure point fixed at 50% of the distance between the final rooftop pressure location and the trailing edge (*p5*). To complete the section pressure distribution, the stagnation pressure is found based on the local leading edge sweep. A linear pressure rise is assumed from the stagnation point to the first rooftop pressure parameter. For the recovery region aft of the final rooftop pressure parameter, the pressure distribution has a concave parabolic shape. For three spanwise stations as in Figure 2, a total of 27 design variables represent the pressure distribution.

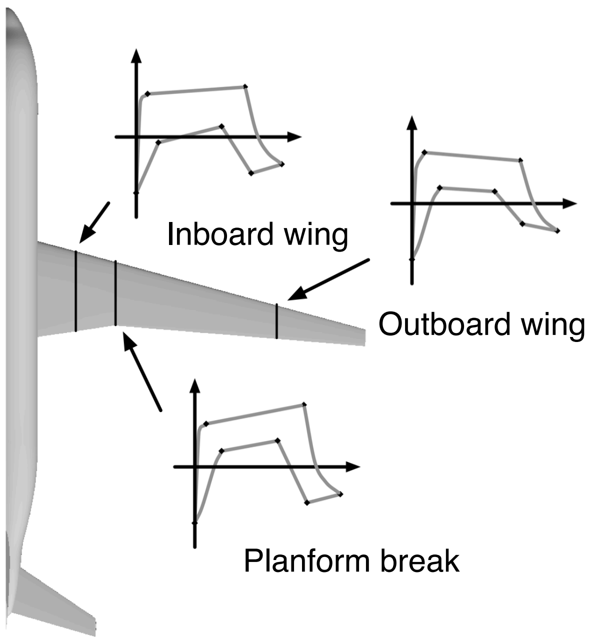

Fig. 2: Three notional chordwise pressure sections describe the pressure distribution over the wing using 27 parameters.

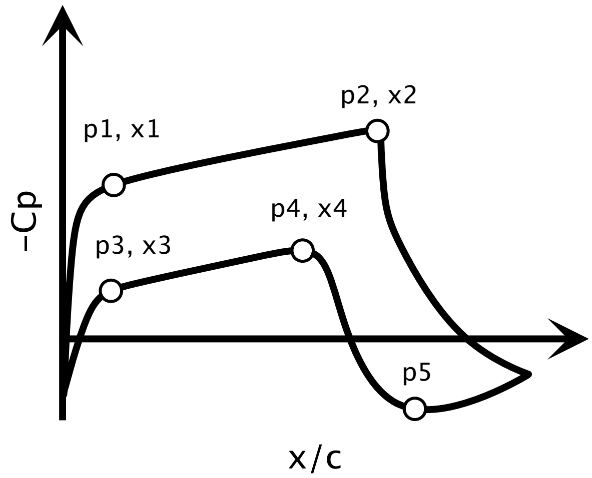

Fig. 3: Dimensionless pressure (*p*) and chordwise (*x*) parameters for a two-dimensional slice of the wing pressure distribution.

3 Implementation

For this study, a conceptual design tool developed by Desktop Aeronautics [9], the Program for Aircraft Synthesis Studies (PASS), was modified to use the parameterized pressure distribution described above. The induced drag, compressibility drag, viscous drag, $C_{L,max}$, trim, and wing weight modules included in PASS were altered to make use of the pressure parameters. Additionally, two new modules were added to PASS: a quasi-three dimensional boundary layer transition computation and a quasi-three dimensional airfoil inverse design computation.

3.1 Structural Weight

The primary weight models in PASS employ structural analyses augmented by corrections based on empirical data. For example, the wing weight is estimated by computing the required skin thickness to support bending moments at limit load and to maintain a minimum gauge. This is correlated with empirical data for transport aircraft to determine the actual weight. The parameterized pressure distribution implicitly defines the wing geometry, and this geometry must be computed so that its effect on wing weight is included.

The wing geometry is synthesized from the three prescribed pressure sections described above using equivalent two-dimensional distributions based on inverse Karmen-Tsien corrections, Lock's sweep-taper transformation [10], and an inverse panel code. The wing thickness distribution is used directly in the wing weight computation.

3.2 Drag

The parameterized pressure distribution affects all components of wing drag. The maximum normal Mach number on the upper and lower surfaces is computed for each of the three defining pressure cuts. It is limited to 1.15 on the upper surface and 0.98 on the lower, corresponding to a weak upper shock on a supercritical airfoil. Fifteen counts of compressibility drag are assumed to exist at this condition, and sweep theory is used to capture the variation with sweep [11].

A five term Fourier series describes the lift distribution over the wing. A linear constrained optimization problem is solved to find the set of coefficients that yield minimum induced drag with the desired total lift and the prescribed lift at the 3 defining sections.

The viscous drag computation is somewhat more complex. The three-dimensional pressure distribution is constructed from the pressure parameter design variables by linearly varying the pressures between the three defined slices. This pressure distribution is interpolated onto a set of boundary layer arcs on the upper and lower wing surfaces (Figure 4). On each arc, a sweep-taper boundary layer analysis with transition prediction is performed [12].

The results of the boundary layer computations are then used to compute the wing viscous drag using the method of Squire and Young [13]. The boundary layer code also predicts the location of any incipient separation, which is constrained by the optimizer.

The wing three-dimensional pressure distribution is integrated and used in trim computations for the cruise portion of the mission. Simplified trim routines provide tail load estimates during takeoff, climb, and landing, when the airplane is assumed to be fully turbulent.

Many additional routines available in PASS were used to solve the multidisciplinary optimization problem, with design variables and constraints listed in Tables 1 and 2. A nonlinear sequential quadratic programming algorithm from MATLAB was used to produce a feasible design that minimized an economic metric, required yield with a typical passenger load factor.

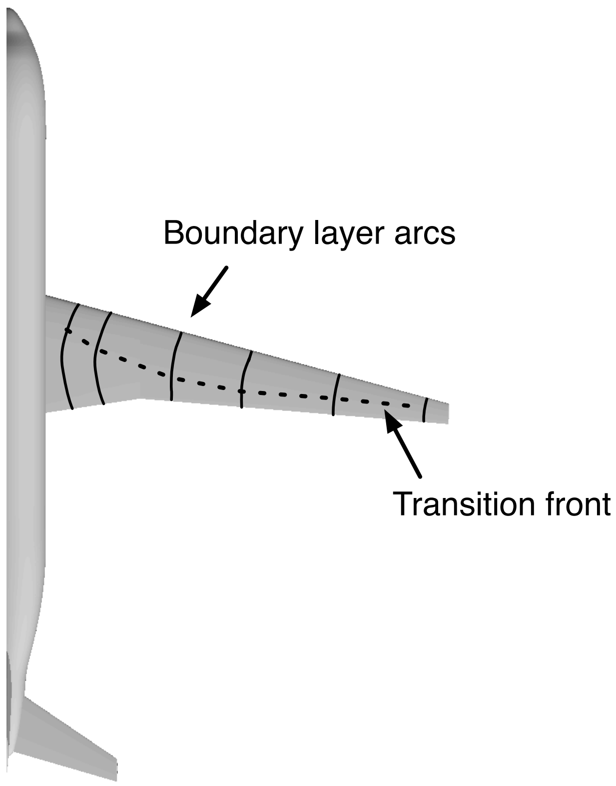

Figure 4: Notional boundary layer arcs and transition front on the wing.

4 Example Results

4.1 Laminar Design

The conceptual design methodology described above was used in the design of a medium-range narrow-body passenger aircraft. For this study, the target aircraft carries 150 passengers 3000 n. miles at a cruise Mach number of 0.75.

The engine used in all the studies is a parameterized version of a very high bypass ratio geared turbofan (GTF) study engine similar to those used in NASA Glenn studies [14]. The GTF engines were chosen to be representative of the types of engines likely to be available for future NLF aircraft. The engine is parameterized in such a way that its performance can be scaled by the sea-level static thrust. Due to the large diameter of the engines, and similar to other fuel-efficient airplane concepts [15], the engines were mounted on the rear fuselage.

Initial investigations showed that mounting the heavy GTF engines on the aft fuselage caused significant balance issues at zero payload conditions, especially with low sweep wings. The large C.G. range requires an oversized horizontal tail for trim, with increased weight and drag. Alternatively, a ballast tank could be employed, which would be filled with up to 7.5% of the maximum takeoff weight for flight with very light payloads.

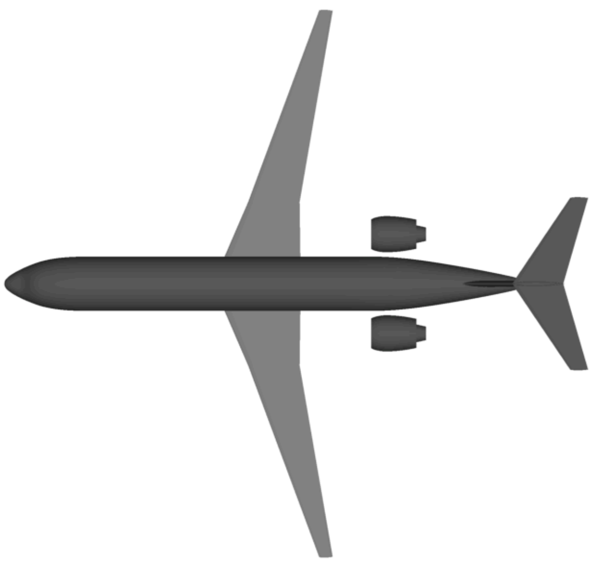

Fig. 5: Turbulent reference aircraft designed with new method.

Design Variable	Units	Value
27 pressure parameters		-
Maximum takeoff weight	lb (kg)	163270 (74058)
Wing aspect ratio		13.5
Wing quarter-chord sweep	deg	17.75
Wing reference area	ft^2 (m^2)	1259 (117.0)
Sea-level static thrust	lb (kN)	23231 (103.3)
Wing location along fuselage	%	0.4
Horizontal tail area (fraction of wing area)	%	0.27
Initial cruise altitude	ft (m)	33529 (10220)
Final cruise altitude	ft (m)	37201 (11339)
Wing taper ratio		0.2 (fixed)

Table 1: Design variables and values for the turbulent reference aircraft

4.1.1 Turbulent Reference

The first aircraft designed with the new method was a turbulent reference aircraft. The modified PASS conceptual design tool described above was used, but the flow was assumed to transition to turbulence at the leading edge of the wing. This allowed the design of an all-turbulent aircraft using the same set of analyses, engines, and technology level as the subsequent laminar designs. A planform view of the turbulent reference aircraft is shown in Figure 5. Table 1 lists the design variables and the values found by the optimizer in this case. The problem constraints are summarized in Table 2.

4.1.2 Laminar Sweep Study

Using the same design variables and constraints, a series of laminar designs were performed. The wing sweep was varied parametrically from

Constraints	Units	Value
Cruise range	n. miles	≥ 3000
Takeoff field length	ft (m)	≤ 7500 (≤ 2286)
Landing field length	ft (m)	≤ 6000 (≤ 1829)
Engine out climb gradient	-	≥ 0.024
Drag-to-thrust ratio	-	≤ 0.92
Stability margin	-	≥ 0.0
Wing cruise lift coeff. margin	-	≥ 0.0
Tail rotation lift coeff. margin	-	≥ 0.0
Tail cruise lift coeff. margin	-	≥ 0.0
Tail landing lift coeff. margin	-	≥ 0.0
Maximum normal Mach (upper)	-	≤ 1.15
Maximum normal Mach (lower)	-	≤ 0.98

Table 2: Constraints in example design optimizations

-10.0 degrees to 25.0 degrees, in increments of 5 degrees. At each sweep value, the airplane was re-optimized.

The solid curve in Figure 6 shows the variation of the fuel burn as a function of wing sweep. As the sweep increases, first the inner wing loses laminar flow, and then the outer wing loses laminar flow. This occurs in part because the inner wing has a larger chord, and thus a higher Reynolds number. Additionally, the wing weight is more sensitive to thickness at the root of the wing, and the optimizer trades laminar flow for additional thickness as sweep increases. The transition front was computed for each of the designs, and Figure 7 shows the optimized planform, the transition front, and a selected set of optimized design variables for a subset of designs from the parametric study.

In the region from -10 degrees of sweep to 5 degrees of sweep, the extent of laminar flow is constant. The improvement in fuel burn represents changes in the aircraft apart from laminar flow. The optimal design has a quarter chord sweep of 5 degrees, and presents a potential fuel savings of nearly 12% compared to the turbulent reference aircraft shown in Figure 5.

4.2 Turbulent-Constrained Laminar Design

The previous study assumed that standard fuel reserves could be carried by the aircraft. No consideration was given to loss of laminar flow during the mission. This presents a best-case scenario for improving fuel consumption.

If loss of laminar flow could be detected during the duration of the aircraft mission, the aircraft could switch to an alternate, all-turbulent design point to complete the mission. To implement this operational concept, PASS was modified to compute a secondary mission with fully turbulent flow at an alternate Mach number and cruise altitude. The range of this alternate mission is constrained to be the same as or greater than the range of the primary mission. This thus represents an extreme case where 100% of the laminar flow is lost at the onset of the mission.

The dashed curve in Figure 6 shows the results of a more limited parametric sweep study that includes the alternate turbulent mission. The design optimization was performed at

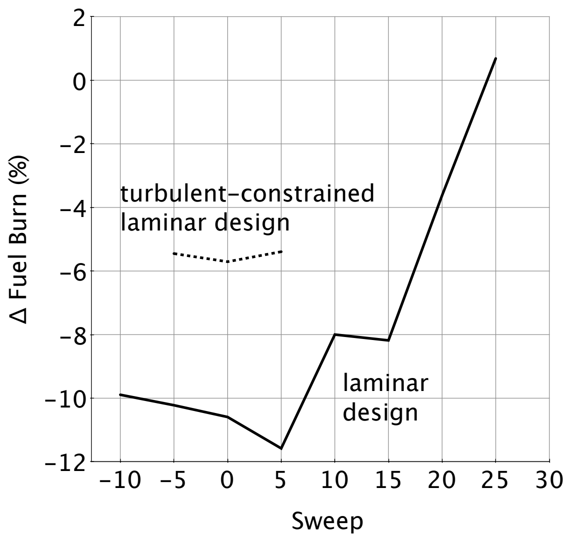

Fig. 6: Percent change in fuel burn from the turbulent reference aircraft shown in Figure 5.

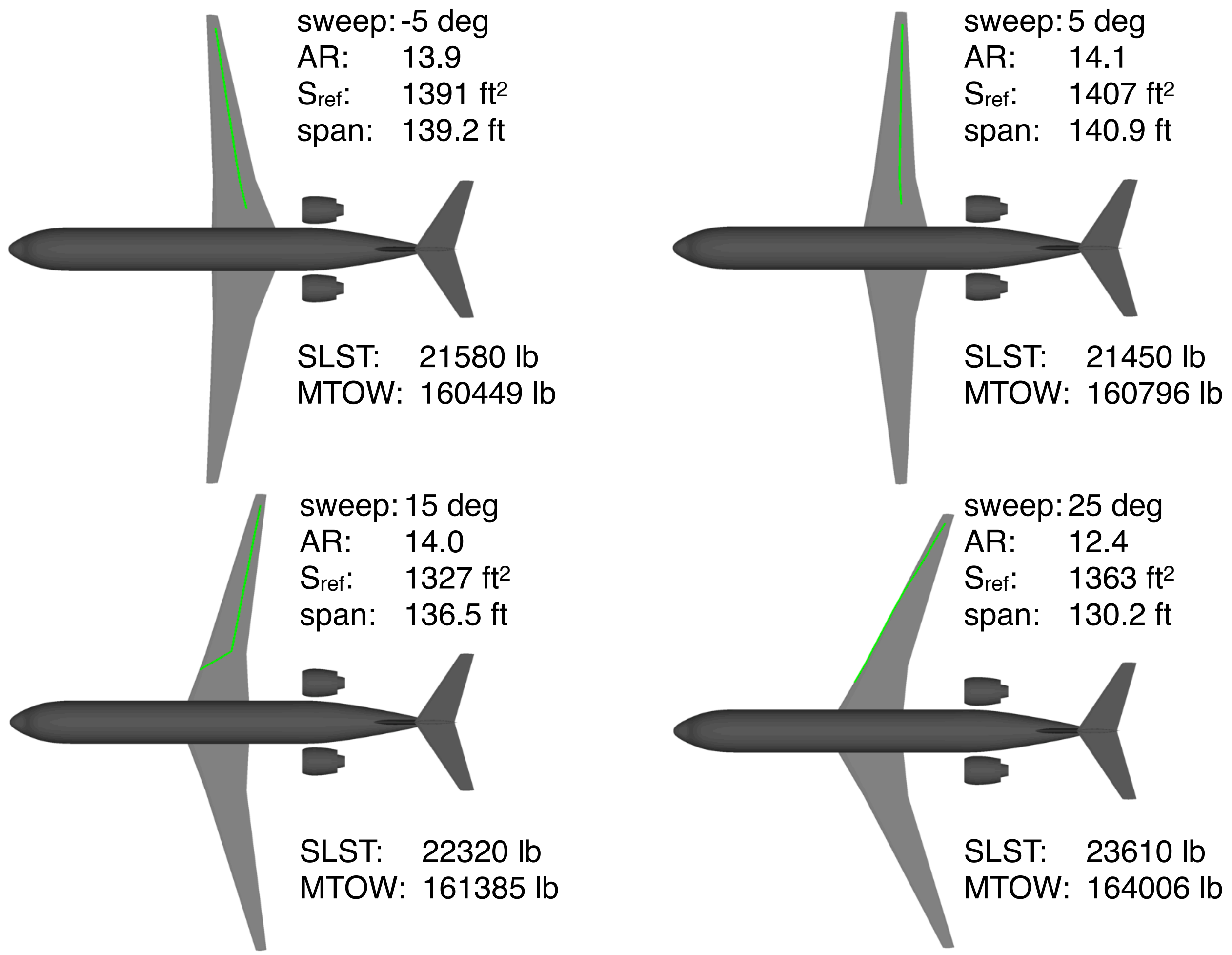

Fig. 7: Wing transition front, optimized planform, and selected optimization results for laminar designs with -5, 5, 15, and 25 degrees of wing sweep.

three sweep points: -5 deg., 0 deg., and 5 deg. of quarter-chord sweep. The results of these optimizations show that the optimal sweep has shifted to 0 deg. from the laminar-only design. Significantly, however, the results predict a fuel savings of nearly 6% relative to the turbulent reference aircraft, even with the alternate turbulent mission constraint. For the optimal design, the alternate mission Mach number is 0.67. Figure 8 shows a planform view of the optimal design along with the three pressure cuts that define the optimized wing pressure distribution. Figure 9 is a rendering of the aircraft.

5 Conclusions

A multidisciplinary optimization system, which uses a parameterized pressure distribution to capture the effects of laminar flow on the wing, permits efficient conceptual design of future aircraft. Example results indicate that a medium range transport aircraft designed to exploit natural laminar flow can reduce fuel consumption by 12% compared with a turbulent reference aircraft employing similar structures and propulsion system technologies.

Detecting the loss of laminar flow during flight could allow the airplane to fly an alternate mission. When simultaneously optimized to fly a primary (laminar) and alternate (turbulent) mission, an aircraft designed to exploit natural laminar flow still has improved fuel consumption of nearly 6% compared with a turbulent reference aircraft.

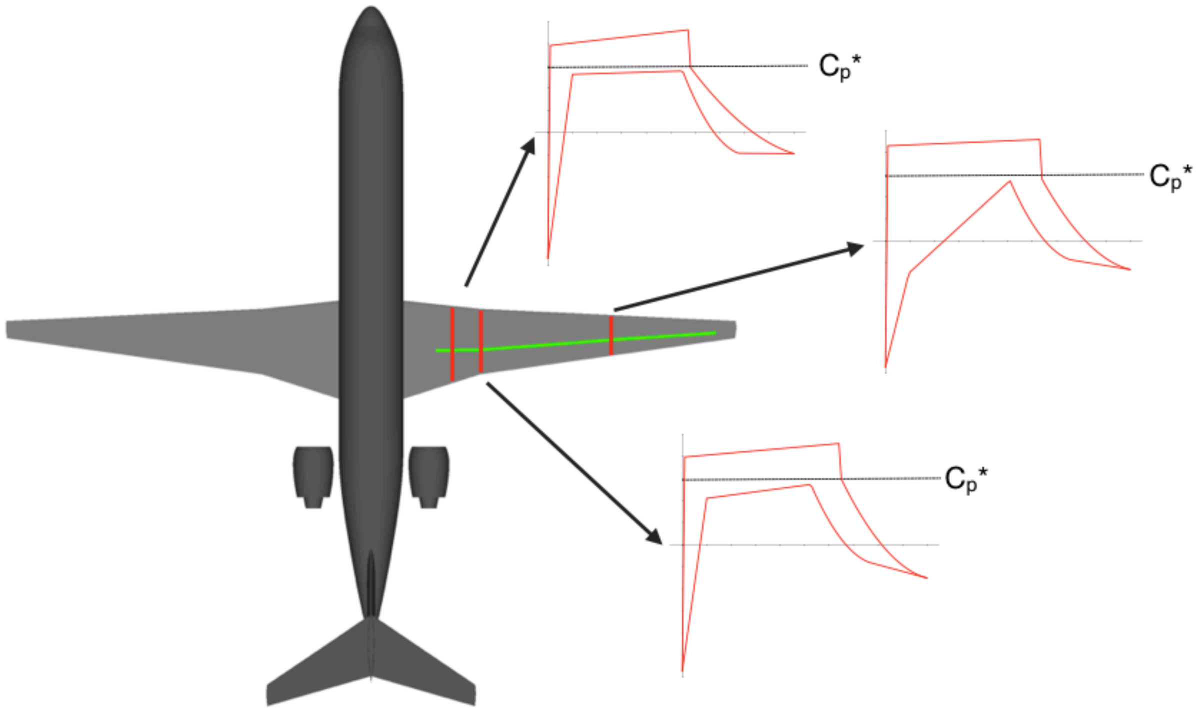

Fig. 8: Optimized planform and pressure distribution for the best turbulent-constrained design.

Fig. 9: Rendering of best turbulent-constrained laminar design.

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