Status and perspectives of laminar flow

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ABSTRACT

After identifying the ecological and economic drivers for use of laminar flow technology, we outline the mechanisms of laminar-turbulent boundary layer transition and review the status of natural laminar flow (NLF) and hybrid laminar flow control (HLFC). New ways to reduce the complexity of HLFC systems are presented, and the remaining steps to achieve technology readiness are discussed.

1.0 WHY LAMINAR FLOW

Planning for the expected increase in air traffic, the European Commission has issued the VISION 2020 document[1], requiring a reduction of the CO_2 emissions by 50% and of the NO_X emissions by 80%. Part of the reduction will be achieved by improved engines with higher bypass ratio, by the increased use of advanced materials, and by better cross-disciplinary optimisation. However, the expected benefits of these technologies will not be sufficient. In addition, drag reduction technologies are needed to achieve the VISION 2020 goals.

Another strong incentive to implement drag reduction technologies lies in increasing fuel prices. The average price for one US gallon of kerosene in Rotterdam over the period from mid 1986 to the end of 2001 was 59 US-cents. However, between 2002 and 2005, the price of kerosene rose to a level above 180 US cents. At 60 US cents/US gallon the fuel for a typical 6,000nm mission of a long-range aircraft costs about 17% of the DOC. Keeping the other parameters constant, the fuel share rises to 38% of the DOC for 180 US cents per gallon. Clearly, such high fuel prices provide compelling economic reasons for pursuing drag reduction.

To illustrate the order of the drag reduction potential by laminarity, we present a typical drag break-down of a transport aircraft in Fig. 1. Friction drag constitutes more than half of the total aircraft drag, with 18%, 4%, 3% and 3% for wing, horizontal tail plane, fin and nacelles, respectively. If the flow were laminar on 20%, 30% or 40% of the surfaces, the total drag of the aircraft would be reduced by 8%, 12% or 16%. Figure 1 also shows that the friction drag of the fuselage is about 22% of the total drag. Because of the very large Reynolds numbers, however, laminar flow cannot be achieved on the fuselage. Only turbulent friction drag reduction measures, such as riblets, can be applied.

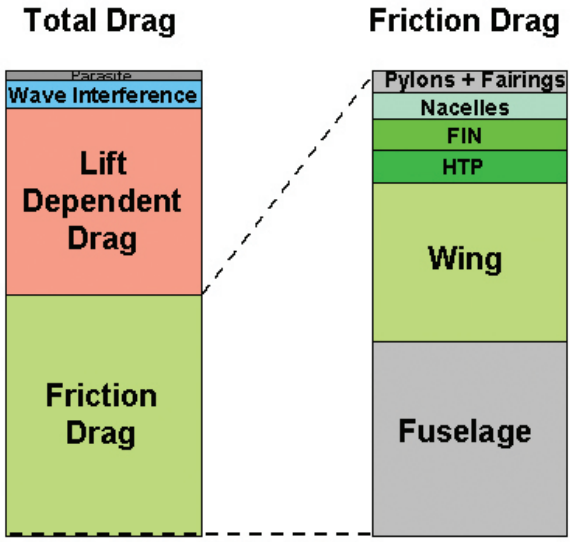


Figure 1. Typical drag breakdown of a transport aircraft.

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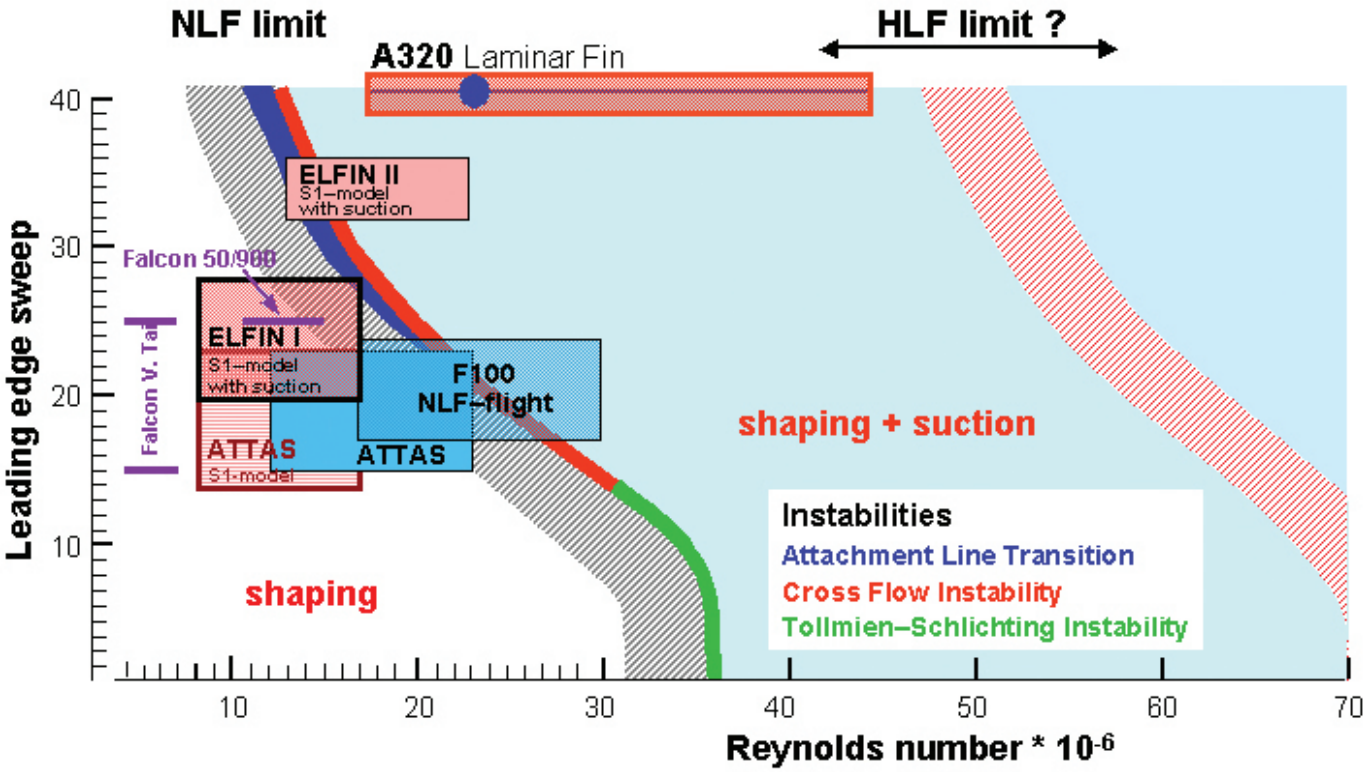


Figure 2. Reynolds number and sweep range of European laminar flow tests.

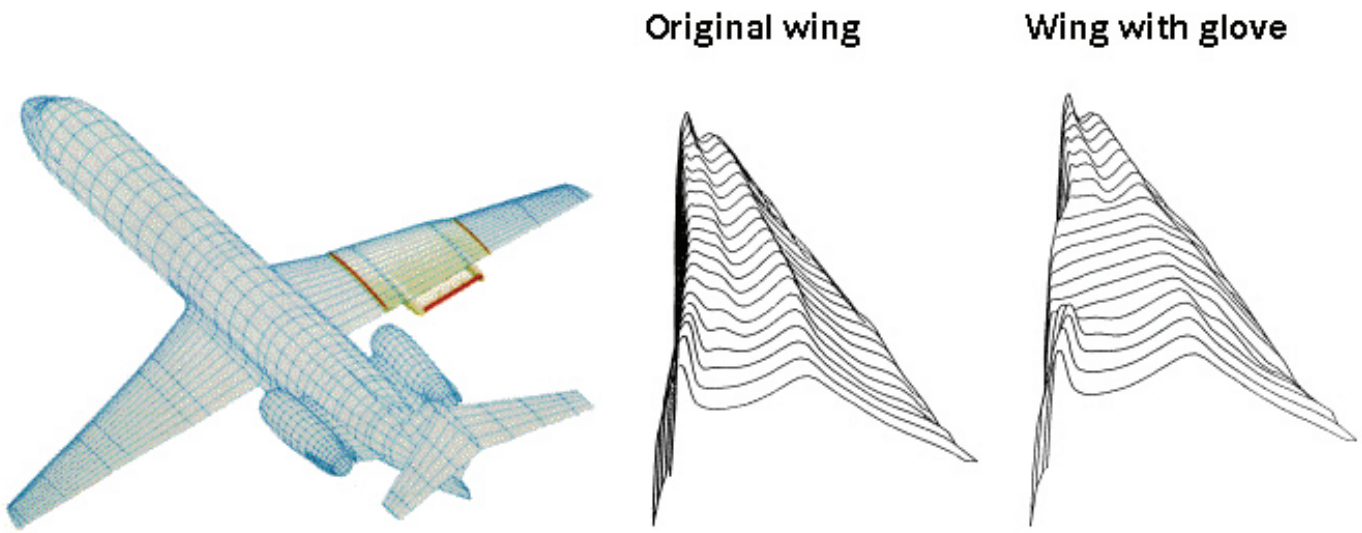


Figure 3. Fokker F100 NLF glove and pressure distributions.

2.0 LAMINAR-TURBULENT BOUNDARY LAYER TRANSITION

Some understanding of the phenomena causing a laminar boundary layer to become turbulent is necessary for the design of laminar surfaces. There are three phenomena to be considered. First, the attachment line can become turbulent on a swept leading edge if it is too blunt as found by Pfenninger during the laminar flow control flight tests with the X-21 aircraft[2]. Pfenninger observed that the attachment line stays laminar if the leading edge is sufficiently sharp. Furthermore, he formulated a criterion based on an attachment line Reynolds number ($R < 245$). The criterion was later confirmed by Poll[3] in wind tunnel experiments with swept cylinders. A verification using the flight test data of the Airbus A320 HLFC fin flight tests can be found in Ref. 4. The criterion constitutes a guide for choosing appropriate sweep and curvature of the leading edge.

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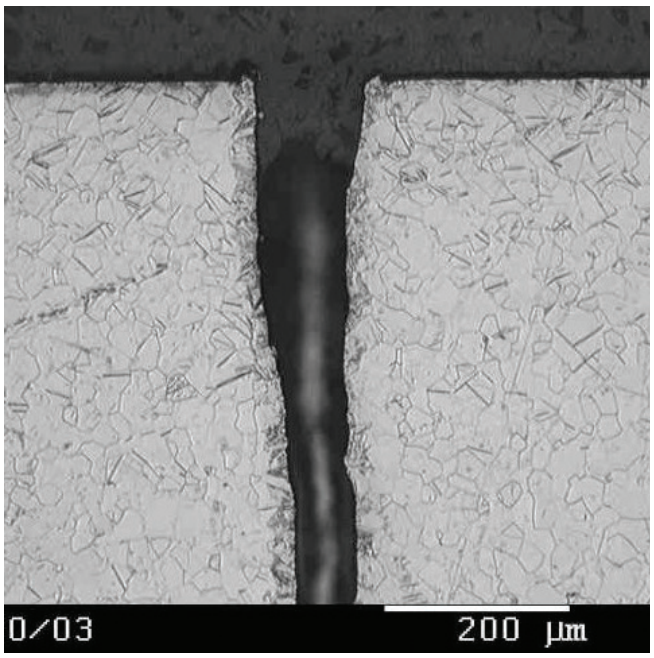


Figure 4. Suction hole in titanium.

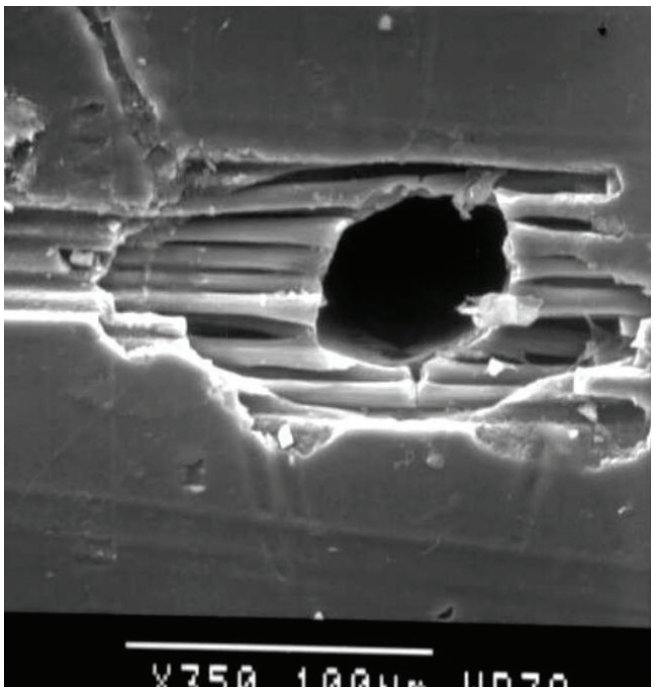


Figure 5. Rain erosion of CFK hole.

Furthermore, turbulence can be convected from the boundary layer of the fuselage to the leading edge of a back-swept wing. In order to avoid attachment line 'contamination', the turbulence might have to be diverted with the help of a 'Gaster bump'[5,6]. Such a device is obviously not necessary for a forward-swept wing.

Cross-flow instability is the second phenomenon causing laminar-turbulent transition. It was first observed as an unexpected early transition in a flight experiment with an F-86 fighter aircraft[7]. A few months later it was shown[8], that the transition was caused by an inviscid instability that arises if the cross-flow velocity profile of the boundary layer has an inflection point. This instability can occur very close to the attachment line of a swept wing. It does not occur in two-dimensional flow, in which the third phenomenon, the Tollmien-Schlichting instability, can provoke transition. This instability was theoretically predicted already in 1929[9], however, the first experimental evidence was discovered much later[10]. Both Tollmien-Schlichting and cross-flow instability can be described with linear stability theory[11], with which all tested laminar flow wings mentioned in this article were designed.

These instabilities can be weakened to delay transition by choosing an appropriate pressure gradient, by removing the slowest part of the boundary layer flow close to the surface with the help of suction through slots or small holes, or by cooling (in water: heating) the surface.

During the 1990s, a series of large-scale wind-tunnel experiments and flight tests were performed within Europe. They were evaluated with linear stability theory[12] to develop design guidelines for laminar flow surfaces. Reynolds numbers and sweep angles of the tests are given in Fig. 2. The tests showed that, by merely applying a suitable pressure gradient, i.e. by natural laminar flow (NLF), it was possible to achieve laminarity for

- leading edge sweep angles below 23°,
- Mach numbers up to 0·75, and
- Reynolds numbers up to 25m.

Under these conditions, natural laminar flow was obtained on a glove mounted on the wing of a Fokker F100 aircraft that was tested within the ELFIN programme.

The glove and the original as well as the modified pressure distribution are shown in Fig. 3.

As mentioned above, laminar–turbulent transition can be delayed with the help of suction through slots or small holes. Suction can be applied on the whole wing surface as with the X-21 aircraft (laminar flow control), or only before the front spar of the wing, in order to reserve the space in the wing box for the fuel tank. Behind the front spar, transition is delayed with the help of a favourable pressure gradient. The resulting flow acceleration leads to high Mach numbers making a careful design of the pressure recovery necessary in order to avoid an increase of wave drag due to strong shocks. Because both suction and shaping are applied, this technology is called 'hybrid laminar flow control'.

Even though boundary-layer suction has long been understood, the technology to produce very small holes was not available until about fifteen years ago. This impediment has now been removed. Small holes in metallic surfaces may now be made using laser or electron beams. An image of a suction hole drilled with a laser in a 0·8mm thick titanium sheet is shown in Fig. 4. The technology also allows the drilling of tiny holes in other materials such as aluminium or CFK. Aluminium is not currently being used as a material for suction surfaces because it is not sufficiently resistant to corrosion. Drilling holes in CFK destroys the carbon fibres within the material and it becomes vulnerable to rain erosion. Consequences for a surface that was exposed to only ten hours of rain can be seen in Fig. 5 taken from Ref. 13.

Using a laser-drilled titanium suction surface, Airbus explored the applicability of hybrid laminar flow control, by designing, manufacturing and testing an HLFC system for the fin of an A320[14]. The suction system had nine suction chambers and a compressor in the passenger cabin. It was oversized in order to be used at low altitudes for tests with high Reynolds numbers. Though this experimental system was much too heavy to obtain a net benefit, the flight tests (cf. Fig. 6) showed that laminar flow can be achieved for an Airbus-sized aircraft.

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Figure 6. A320 with HLFC fin in flight.

3.0 HLFC SYSTEMS WITH REDUCED COMPLEXITY

To make HLFC attractive, the suction system has to become simpler and lighter. A new approach with a simplified suction system for an A320 fin was developed within the ALTTA programme. This approach is based on three new ideas: The first one is a new production technology which was developed within the German RaWiD programme. In previous programmes, as ELFIN II and A320 HLFC fin programme, the inside of the suction system with the ducts, the chambers and the stringers that would carry the titanium suction surface, was built first. After the completion of the inner components, the perforated titanium sheet was attached to the supporting stringers in the last step by gluing or brazing. This 'outside last' approach made it difficult to check the connections between the stringers and the inside of the suction surface for structural integrity and air-tightness. Furthermore, it was difficult to guarantee the exact geometry of the outer shape and to avoid surface waviness. To overcome these difficulties, we reversed the process. Instead of attaching the perforated titanium sheet to the supporting stringers in the last step, it is done first, for example, by laser welding on a flat table. With this procedure, the welds can easily be inspected and reworked if necessary. After the stringers have been attached to the suction surface, it is bent to the desired shape and placed in a rig as seen on the left side in Fig. 8). Next, a second sheet is attached to the stringers to obtain a double sheet surface with the desired stiffness[15]. In the RaWiD programme, the inner sheet had large openings to allow the air to enter conventional suction chambers that were mounted on the inside of the inner sheet.

This production method allows the production of high-quality suction surfaces. A further advantage is that the outer surface is protected by the rig during manufacturing. However, it is restricted to developable surfaces, because the bending process can only be done perpendicular to the stringers.

The second new idea is to reduce the complexity of the suction system by making the suction chambers and most of the ducting unnecessary. In a conventional design, the suction chambers are used to control the pressure difference that drives the air through the porous outer surface. These chambers are connected with the compressor by ducts which may contain control valves to allow for a different pressure in each suction chamber. The new idea is to replace the large openings in the inner sheet used in RaWiD by suitably-sized orifices that control the pressure in the small compartments between two adjacent stringers. The whole space of the leading edge would serve as one large suction chamber with only one pressure level. This space could also house the compressor. The challenge of this design is that there is only one pressure level available and that the size of the inner orifices must be chosen such that they create the desired suction distribution, not only for the design case, but also for all off-design cases (cf. Fig. 5 in Ref. 16).

Within the ALTTA programme such a simplified system was designed for the A320 fin[16]. The elimination of the suction chambers and much of the ducting leads to considerable weight savings compared to a conventional system. In fact, with a careful design, the weight of the double sheet surface can be comparable to the weight of the existing leading edge box.

The fin of an aircraft was considered to be easy, because it has a symmetrical pressure distribution, even though off-design cases with sideslip and rudder deflection had to be considered. However, next, the design ideas were successfully applied to the horizontal tail plane of an A320, which has an asymmetric pressure distribution.

The third idea for simplification is to avoid a control system for the suction system. This leads to savings in both weight and maintenance. Such a system would be automatically switched on when a predefined altitude, such as, for example, 29,000ft, was reached. The further regulation of the air flow should be done by the compressor which has to be designed such that it automatically delivers the appropriate suction rate for the flight altitude. Such a self-regulating system was designed for the A320 fin within ALTTA[16].

With these new ideas, laminar flow has taken some large steps

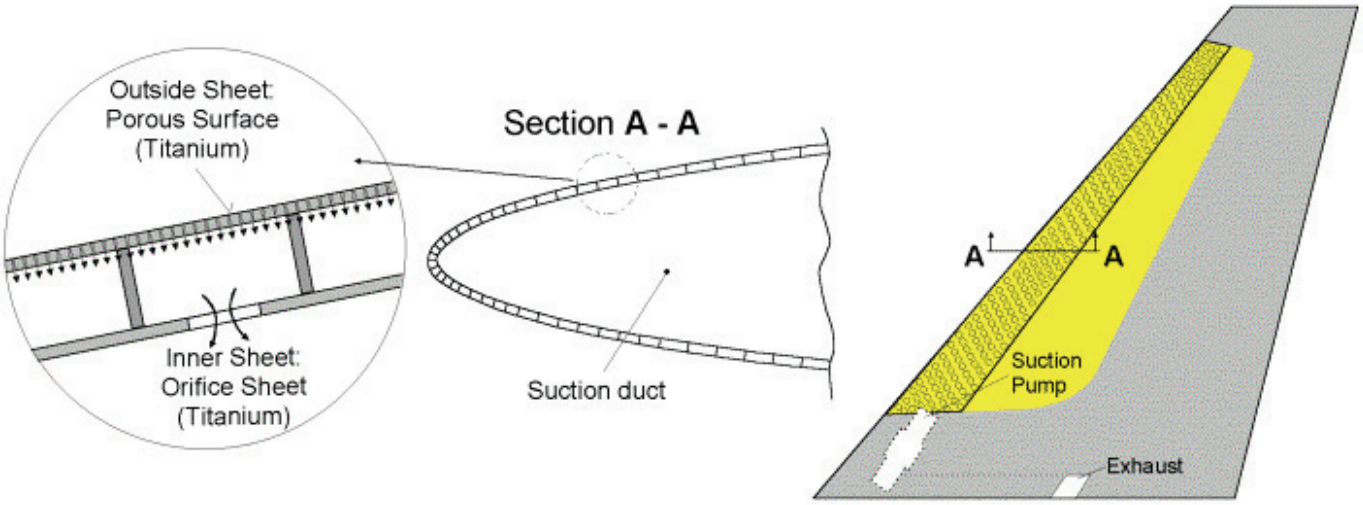


Figure 7. Sketch of a simplified HLFC system for a fin.

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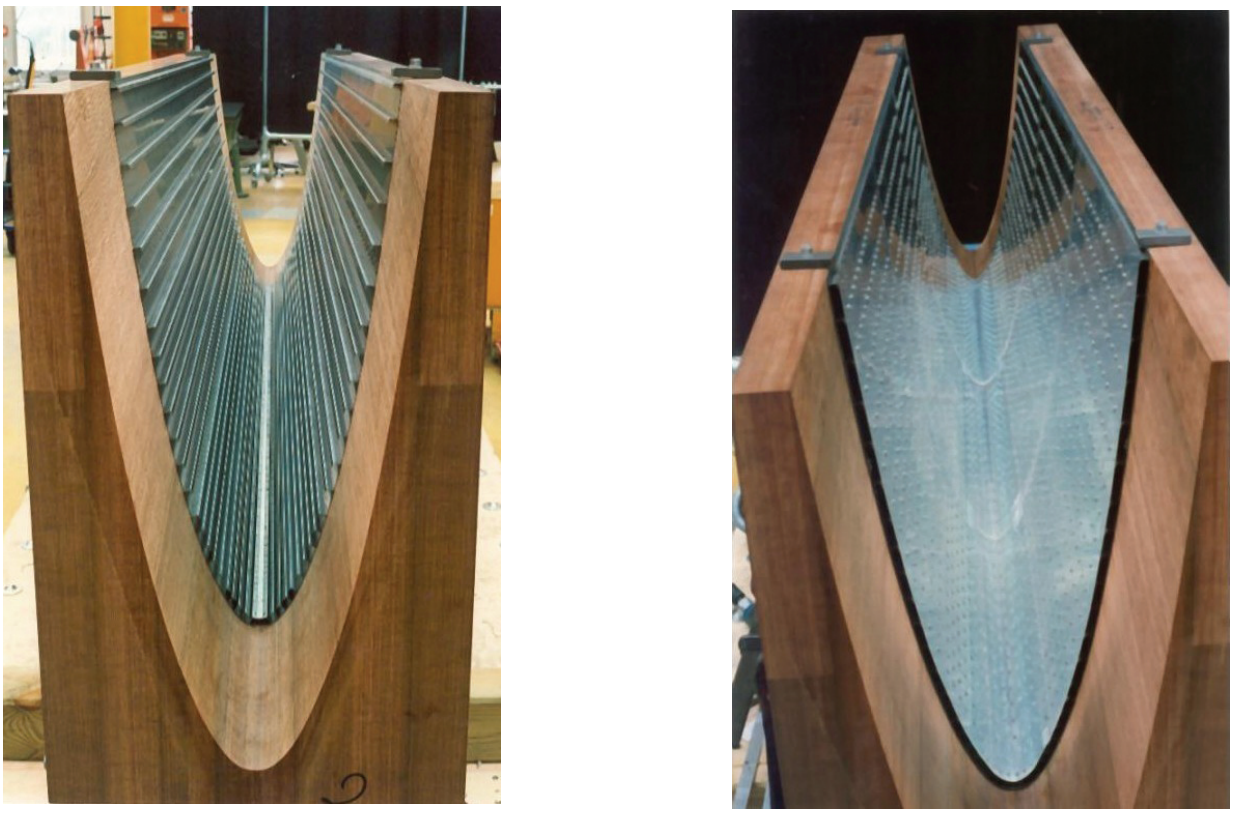


Figure 8. Perforated titanium plate with stringers in the rig before and after the attachment of the inner sheet.

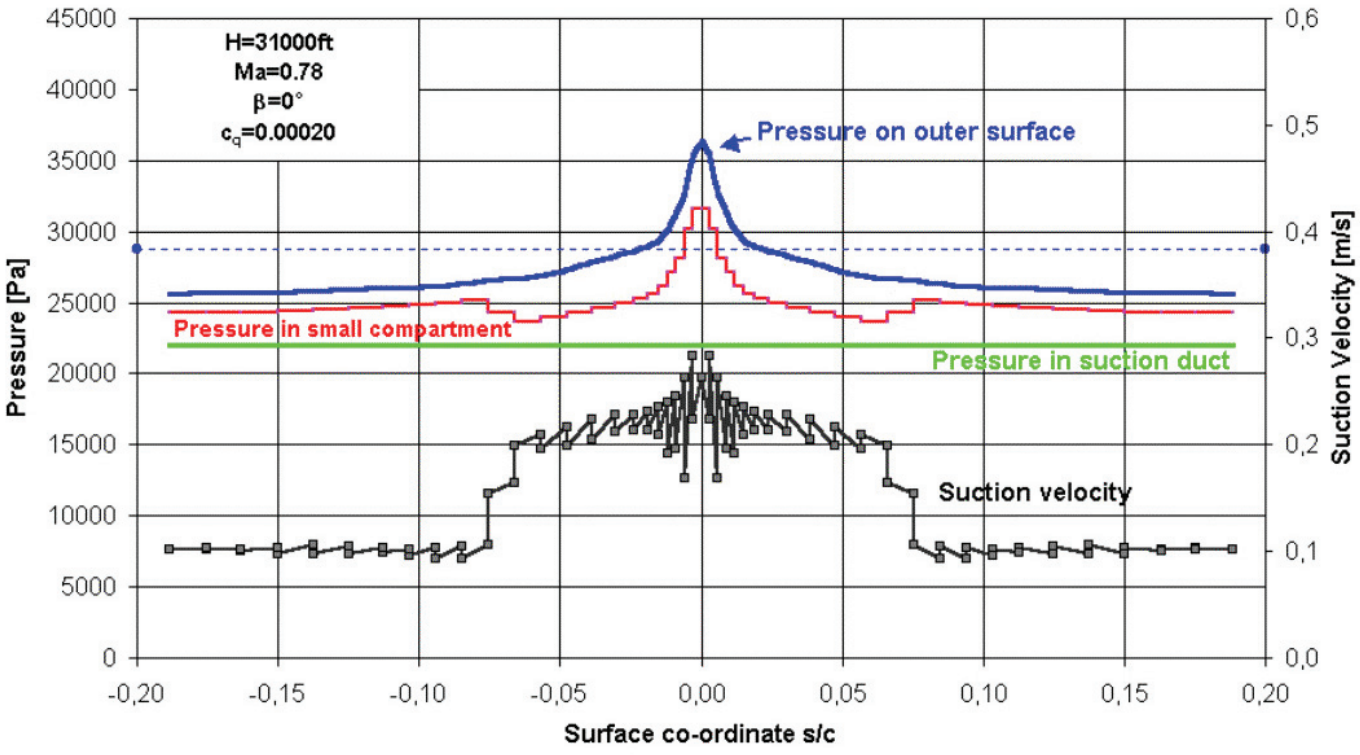


Figure 9. Chamber and surface pressures for the simplified design.

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towards practicability. There are, however, two more questions that need to be answered. Keeping the laminar surfaces clean and combining the HLFC system with an anti-/de-icing system. At this time, we have solutions for both, but they are not optimal. A cleaning/de-icing system based on pressing liquid or foam out through the suction holes was tested on a Dornier Do-228 aircraft within HYLTEC programme. Furthermore, a de-icing system working with bleed air was installed in the aircraft. Flight tests showed that these systems do work. However, the additional weight and the additional maintenance requirements, especially for liquid systems, would negate the benefit gained by the drag reduction.

In the author's opinion, the only way forward is to develop a self-cleaning coating for the suction surface. The coating would have to serve two purposes: to avoid dirt accretion (that would cause the boundary layer to become turbulent) and to make an anti-/de-icing system redundant. Such a coating could be used for hybrid as well as for natural laminar flow.

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