Nationaal Lucht- en Ruimtevaartlaboratorium
National Aerospace Laboratory NLR

NLR-TP-2002-376

Subsonic transport aircraft - New challenges and oppurtunities for aerodynamic research
The 36th Lanchester lecture

J.W. Slooff

Nationaal Lucht- en Ruimtevaartlaboratorium
National Aerospace Laboratory NLR

NLR-TP-2002-376

Subsonic transport aircraft - New challenges and oppurtunities for aerodynamic research

The 36th Lanchester lecture

J.W. Slooff

This report is based on a presentation held in May 1996 at the Royal Aeronautical Society in London, UK.
It represents the full written version, with some retrospective remarks, of the 36th Lanchester lecture.

Customer:	National Aerospace Laboratory NLR
Owner:	National Aerospace Laboratory NLR
Division:	Fluid Dynamics
Distribution:	Unlimited
Classification title:	Unclassified
	July 2002

Summary

This report contains the written version of the 36th Lanchester lecture which was presented at the Royal Aeronautical Society in London in May 1996.
Due to circumstances beyond his control the author was not in a position to produce a written version at or shortly after the time of the lecture. The written version presented here (six years late!) is offered with some retrospective remarks added.

The lecture addresses requirements for aerodynamic research for subsonic transport aircraft from the point of view that ‘market pull’ is, and should be, the driving factor in aerodynamic research and that new technological developments that the aerodynamics and associated communities have to offer (‘technology push’) should be assessed against the requirements of ‘the market’. After a description of market pull factors and of current (i.e. 1996) developments in aerodynamic and related technologies a list is offered of topics for aerodynamic research that have the best prospect for contributing to the market position of subsonic transport aircraft in the next, say twenty (or fifteen) years.

Contents

(24 pages in total)

The 36th Lanchester lecture (1996)

Subsonic Transport Aircraft –
new challenges and opportunities for aerodynamic research

J.W.Slooff
Head, Fluid Dynamics Division
National Aerospace Laboratory (NLR)
Amsterdam, The Netherlands

1 INTRODUCTION

Mister chairman, ladies and gentlemen,

We are, like Lanchester, living in an era of relatively rapid change in the pace of and conditions for aeronautical research in general and aerodynamic research in particular. That, however, is about as far as the comparison between Lanchester's and our present time goes: there are probably more differences than similarities. In order to illustrate this let us look at the following picture.
The evolution in time of things like aerodynamic technology usually follows an S-shaped curve like that in figure 1.

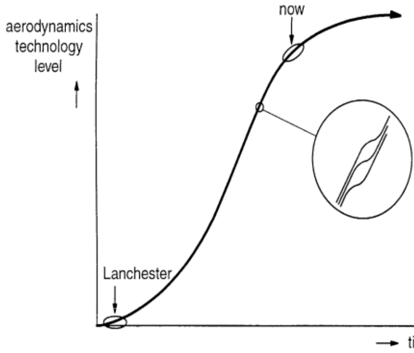


Figure 1. Typical “S”-curve, illustrating the evolution of technology in time

F.W. Lanchester, engineer, designer, inventor, scientist, poet and (vocal) musician (1), (2) worked in the lower left corner of figure 1, at the "Dawn of Aerodynamics" (3). Knowledge about aerodynamics was virtually non-existent at that point in time but was growing rapidly. Not, I believe, as a result of government initiatives and support, but because of the spiritual contributions of individuals like Lanchester himself.
The middle part of the S-curve represents the time period of rapid expansion of aerodynamic technology. This period started around, say, the end of the first world war and is characterized, in all countries, by strong government support and involvement.

We have now arrived, it seems, in the upper part of the S-curve where progress slows down and budgets shrink.
If we would look at the S-curve in a little more detail we would find, of course, that in reality it is not a single solid line but rather the envelope of a number of elementary 'S-curves', each representing the development cycle of individual elements of aerodynamic technology or knowledge. The picture then reminds us of that used in the 21st Lanchester Lecture(4) (1981) by Dr. E.W.E. Rogers, Deputy Director of RAE at the time (see Fig. 2).

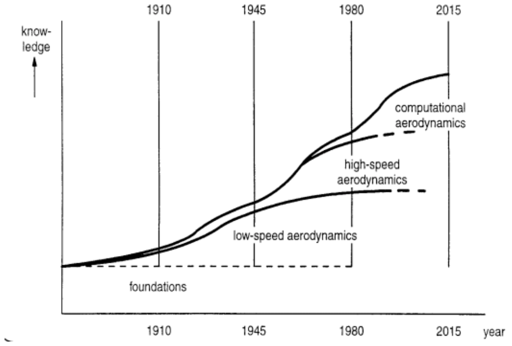


Figure 2. “The cycle of inheritance”
(E.W.E. Rogers, 1981)

Aerodynamics technology as a whole is now generally supposed to have reached the age of maturity. The glamorous days of new concepts and inventions are behind us. *Market pull* and not *technology push* is now the driving factor in research and development. Improved efficiency through 'rationalisation' and collaboration in and between *centres of excellence*, *business units*, if not *profit centres*, currently seems to be our prime if not only objective.
These winds of change have been blowing for some time already. In the UK perhaps longer than in any other European country. So, I run the risk of boring you with things that you are already well aware of. If that is going to be the case I apologize beforehand. I do hope, however, that you will find some interest in identifying,

with me, some of the new challenges and opportunities in aerodynamic research and development that we are posed with today.

For this purpose I will first quickly distinguish different types of subsonic, commercial transport aircraft; in particular those types of which we are, likely, going to see new specimen in the coming 10 to 15 years. Next I will summarize the requirements that are being put forward for such aircraft (*market pull*). This in terms of both general trends as well as specific, type-related characteristics. We will also try to translate the different *market pull* factors into requirements with respect to aerodynamic characteristics and related areas like aero-acoustics and aero-elastics.

The other, i.e. the *technology push* side of the picture is formed by emerging, new concepts, technologies and techniques. I have tried to identify and will discuss in some detail those with potential for application to subsonic transport aircraft or with potential for improving the process(es) of aerodynamic design and simulation.

In conclusion I will try, by balancing *technology push* with *market pull*, to identify those areas in aerodynamic research that have the best prospects for a good 'match' between the two.

2 SUBSONIC TRANSPORTS; MARKET PULL

2.1 General trends

If we want to identify challenges and opportunities for aerodynamic research we must first of all realize that it usually takes 10 to 15 years before a new piece of technology is actually incorporated in commercial aircraft design. As an example we can take supercritical wing technology. Although research on supercritical airfoils started in the early 1960's, it was not until the late seventies or early eighties that commercial transport aircraft with full-supercritical wings went into production. Such a time span is, of course, quite long and there is every reason to try to shorten it. Nevertheless it is clear that the aerodynamic research that we are doing now, or intend to start in the near future, should aim at a market that extends at least 10 to 15 years into the future.

In these next 10 to 15 years we are probably going to see new aircraft projects in Europe in the following categories:

- Regio Liner or Regional Jet (70 - 130 pax)
- Airbus family derivative(s)
- Advanced Turboprop(s) (40 - 70 pax)

and, possibly,

- Ultra-High Capacity Aircraft (A3XX, > 500 pax)

In addition, of course, research is going on for a possible next generation supersonic transport. However we will, for the sake of time and conciseness, not consider this in any further detail. The interested reader is referred to reference (5) for a fairly recent survey.

Having identified the "market" we can look at the requirements of that market. In doing so it is useful to

	RL	AT	UHCA
• **Cost reduction**			
- cost of ownership[1]	√√	√√	√√
- fuel[2]	√	√	√√
• **Tightening environmental constraints**			
- noise	√	√	√√
- emissions	√	√	√
• **Productivity improvement**			
- reliability/maintenance			
- operational flexibility	√	√	√
- speed		√	
• **Passenger comfort improvement**			
- cabin noise/vibrations	√	(√)√	√
• **Commonality/family concept**	√	√	√
• **(Design) risk reduction/elimination**	√	√	√
• **Safety**			

[1] 30-40% DOC

[2] 10-35% DOC

RL **Regioliner**
AT **Advanced Turboprop**
UHCA **Ultra High Capacity Aircraft**

Chart 1 Market pull factor general trends for subsonic transport aircraft

distinguish between the general trends in the airline and aircraft industry and more specific, aircraft-type related requirements.

Chart 1 summarizes the general trends that we are all aware of. The table is not extensive in the sense that it concentrates on the factors that are, directly or indirectly, influenced by aerodynamic technology.

As I have tried to indicate roughly through the number of 'tick marks' in the columns representing the different aircraft types (RL for Regio Liner, AT for Advanced Turboprop, UHCA for Ultra-High Capacity Aircraft), the relative importance of some factors varies between the types of aircraft considered. Airbus derivatives have been left out of table 1 on purpose because the possibilities for aerodynamic improvements are, of course, rather limited for derivative aircraft.

A number of remarks should be made here to further clarify Chart 1.

First of all it is important to note that (apart from safety) economics and **not** technology is the determining driving factor and that *cost of ownership* is the prime economic quantity. This is the case for all three categories of aircraft considered here. However, the relative importance will, ofcourse, vary between one category and another(6),(7),(8).

At present[§], cost of ownership constitutes 30-40% of the total *Direct Operating Cost* (DOC). For the purpose of further discussions, later in this lecture, it is useful to distinguish

- *design/development cost*

and

- *production cost*

as two main contributors to cost of ownership.

Fuel is, as yet, the next important cost factor. At the current[§] fuel price levels its contribution to DOC ranges from 10-15% for a short range aircraft to 35% for a long range, high capacity aircraft. These percentages are, ofcourse, quite sensitive to fuel prices.

Environmental constraints are tightening rapidly; not only in the sense of regulatory measures and operational restrictions ('community noise') but also in the sense of looming 'eco tax' measures (both noise and emissions). The latter would, ofcourse, affect the DOC picture as well.

Improvement of productivity and *passenger comfort* continue to be important design objectives. It appears, that some of the aspects involved tend to increase in relative importance for certain categories of aircraft.

For example, Air Traffic (congestion) Management (ATM) requires a higher operational flexibility, both 'en route' as well as in the proximity of the airfield. The first ('en route') would benefit from a wider range of economic cruise-C_L and –Mach numbers(9). This seems to be of particular importance for the 'Regio-Liner' category of aircraft and, possibly, the 'Advanced Turboprop' as well. For the 'Ultra-High Capacity Aircraft' the airfield performance characteristics in terms of trailing vortex wake and community noise are developing into primary design objectives. For the last category of aircraft the sheer (structural) weight, the associated inertia and stiffness of the structure pose additional challenges (stability and control).

For the 'Advanced Turboprop' higher cruise speeds would be required for improved productivity and operational flexibility. This would have to be obtained without, significantly, affecting other characteristics like DOC and noise levels. Whether this is possible or not seems, as yet[§], an open question; in the absence of a clear answer the current[§] trend seems to be 'turbofan rather than turboprop'[†].

There are two further general trends that we, as aerodynamicists, should be aware of.

The first is *commonality and the 'family concept'*. Commonality (of structural parts and systems) between derivatives and 'family members' is important for cost of ownership as well as for other cost factors such as maintenance, crew training, etc.. The family concept is also important for customer relations and 'manufacturer's appeal'. Commonality, like improved operational flexibility, implies, in principle, design for a wider range of operating conditions.

The other further general trend that we should be aware of is *design risk reduction/elimination*. While there is no need to explain the importance of this, it may be useful to address, at this point, some of its implications.

(Design) risk is associated with the notion of *'Quality'* of a product. We can define the *'Total Quality'* of a product (aircraft) as some weighted combination of the various factors discussed above. The *'Total Quality'* as such of an aircraft is determined to a very large

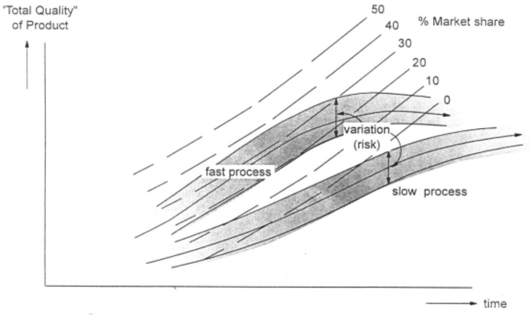


Figure 3. Illustrating the importance of *'variation'* and *'speed'* of the design and development process for the *'quality'* and market share of a product.

[§] Spring 1996

[§] Spring 1996

[†] This trend is still persistent in 2001

extent by the characteristics of the design and production processes and their control(10). The most important process characteristics are the *'variation'* (amount of uncertainty in product quality/ technical and commercial risk) and the *'speed'* of the process. Figure 3(10) illustrates, qualitatively, the importance of both.

Assuming that

1. the quality of a product must increase with (calendar) time in order to maintain a constant market share,

and that,

2. for a given process the attainable quality approaches asymptotically a maximum (after absorbing the 'learning curve' effects),

the figure attempts to illustrate that a fast process with small 'variation' reduces the risk of an insufficiently small market share. This applies to (aerodynamic) design and development as well as to production.

It is also important to note that the impact on product cost of design decisions taken in the early stages of the design/development process, when money spending is relatively low, is far greater than of decisions taken at later stages. This points to the (widely recognized) need for accurate (multi-disciplinary) information and tools in the early design stages.

2.2 Implications for aerodynamics

Having established the general trends and market pull factors we can think about their implication for the aerodynamic design of civil subsonic transport aircraft. In the following we will try to do so for each of the *market pull* factors listed in Chart 1 and discussed in the preceding (sub)section. While doing so it is important to recognize that some, if not all, of these market pull factors are interrelated. This in the sense that measures to improve the situation for a particular factor may also have consequences (positive or negative) for other cost factors. Where possible and appropriate we will try to identify such dependencies.

Cost of ownership

As indicated in Chart 2 aerodynamic design influences cost of ownership in two different ways: through design/development cost (non-recurring) and through production cost (recurring).

The effect on *design/development cost* is of a direct nature: a more efficient (cheaper, faster) aerodynamic design process contributes directly to reducing design and development cost. For a given set of design objectives and accuracy levels this requires increased productivity in wind tunnel testing, including model manufacturing, and CFD (Computational Fluid Dynamics) applications. It also implies a design process that makes 'optimum' use of both disciplines with the objective to minimize cost.

The effect of aerodynamics on *production cost* is of a more indirect nature but not necessarily less important. The aerodynamicist can help to reduce production cost by coming-up with simple(r) shapes with less complex curvatures and simpler high-lift and other aerodynamic systems *('design for manufacture').*

o **Cost of Ownership**
  - **Design/development cost**
    → *more efficient aerodynamic design process*,
    increased productivity of
      * **Wind tunnel testing**
      * **CFD application**
  - **Production cost**
    → simple(r) aerodynamic shapes *('design for manufacture')*
      * **wing, tail surfaces, pylons, nacelles**
      * **high-lift systems** **→ *increase*** C_{Lmax}

o **Cost of fuel**
    → *improve engine efficiency (installed)*
    → *drag reduction*
      * **boundary layer/friction**
        - **wetted area reduction** **→ *increase*** C_{Lmax}
        - **laminar flow**
        - **separation and turbulence management**
      * **vortex/induced (trimmed)**
      * **(shock) waves**
    (→ *reduction of structural weight)*

  improve configuration/propulsion-airframe integration ◀

Chart 2. Implications for aerodynamics of cost reduction

This, ofcourse, under the provision that the reduction of production cost is not nullified by other DOC components as a result of an excessive loss of aerodynamic performance.

Fuel cost are, as we all know, determined by engine efficiency and aircraft drag. Concentrating on *drag reduction* it is useful to distinguish between

- boundary layer or 'friction' drag
- induced or vortex drag
- shock wave drag

In an idealized design situation these three basic phenomena can be addressed separately:
Boundary layer drag can be reduced through

- reduction of wetted area
- application of laminar flow technology
- boundary layer 'management' (separation and turbulence)

Induced or vortex drag should be minimized for the complete, non-planar, trimmed configuration.
Shock wave drag can be minimized or even eliminated through 'supercritical wing' technology.
In practice there is a (sometimes strong) interaction between the drag components themselves as well as with other ('off-design') aerodynamic requirements and with non-aerodynamic requirements and other cost factors. One example is that a reduction in wetted (wing) area requires, in general, a higher C_{Lmax} at low speed, which is in conflict, in principle, with a reduction of cost of ownership through simpler high-lift devices. Another example is that a wing plus tail configuration designed for minimum induced drag may not represent an overall 'optimum' because of the effects of span loading and associated wing (root) bending moment on structural weight. These examples illustrate, again, the need for adequate multi-disciplinary design tools.

The implications for aerodynamics of the tightening *environmental constraints* and improved *passenger comfort* are summarized in Chart 3.
Engine noise reduction implies that we should work on source (fan, propeller, jet) noise reduction as well as on absorption (acoustic liners) and noise shielding effects. Possibilities for the latter are directly determined by the general lay-out of the aircraft configuration, in particular the position of the engines relative to the lifting surfaces.
For the reduction of *airframe noise* we should concentrate on the main sources, i.e. landing gear, flaps and slats.
Emission is determined by the level of thrust (= drag!) and engine efficiency. It is appropriate to note that drag reduction is good for, both, emission reduction and noise reduction, in addition to economy (fuel cost).
Improvement of *passenger comfort* through aero(-structural-)dynamic and aero-acoustic means calls for research on noise and vibration. We can distinguish between reduction at the source (engine, propeller) and

* **Environmental constraints**
- **Noise**
  - ♦ **propulsion**
    - → ***source noise***
      - **fan noise**
      - **jet noise**
      - **propeller noise**
      - **drag reduction**
    - → ***absorption (liners)***
    - → ***shielding (configuration)***
  - ♦ **airframe**
    - → ***landing gear, wheel bays***
    - → ***high-lift devices (flaps, slats)***
- **Emission**
  - → ***engine efficiency***
  - → ***drag reduction***

* **Passenger comfort**
- **Cabin noise/vibration**
  - → ***reduction at source (engine, propeller)***
  - → ***improved damping characteristics of cabin wall panels***
  - → ***active noise and vibration control***

Chart 3. Implications for aerodynamics of environmental constraints and passenger comfort

reduction inside the cabin. For both we can distinguish further between passive and active means, i.e. between improved acoustic liner materials and constructions and active noise and vibration control[§].

Chart 4 identifies three topic areas in aerodynamic research that may serve to improve *aircraft productivity*.

* **Aircraft productivity improvement**

→ ***supercritical wing technology for low wave drag over a range of cruise-C_L and –Mach numbers*** *(Regioliner)*

→ ***transonic propeller/slipstream – supercritical wing interaction*** *(Advanced Turboprop)*

→ ***concepts and means for rapid wake vortex decay*** *(Ultra-High Capacity Aircraft)*

Chart 4. Implications for aerodynamics of aircraft productivity improvement

The ATM-driven requirement for a wider range of economic cruise-C_L and -Mach numbers for Regio-liners asks for research on supercritical wing technology for a (wider) range of flow conditions. The requirement of higher cruise speeds for the Advanced Turboprop type of aircraft asks for research on transonic propeller slipstream – supercritical wing interaction. The requirement to reduce take-off and landing separation distances points towards concepts and means for the reduction of wake vortex intensity. The latter is, ofcourse, also good for safety.[†]

The requirement to (further) reduce *design risk* (Chart 5), in the sense of avoiding an 'underscore' (or 'over'score) of performance and possibly associated costly modifications in the later design or, even worse, early production stages, calls for more accurate design and simulation tools and facilities.

We conclude the discussion on the implications for aerodynamics of the various market pull factors by recalling that *commonality*, like increased operational flexibility, implies, in principle, aerodynamic design for a wider range of operating conditions in terms of C_L and Mach number. The classical example is that of a common wing for two different size aircraft of one family: by sacrificing some (but preferably as little as possible) aerodynamic efficiency for each of the individual designs, the total economics may be improved through a reduction of development and production costs. The optimization problem at hand is by no means a simple one and calls (also) for accurate multi-disciplinary design and optimization tools.

* **Design risk reduction**

→ ***more accurate design and simulation tools***
- **Wind tunnel**
    - **high(er) Reynolds numbers**
    - **wall & support interference**
    - **flow quality**
    - **improved diagnostic means**
- **CFD**
    - **grid (in)dependency**
    - **turbulence models**
    - **drag and C_{Lmax}**
- **multi-disciplinary simulation**

Chart 5. Implications for aerodynamics of design risk reduction

---

[§] Retrospective remark: possibly to be added to 'reduction at source': fuselage boundary layer noise reduction

[†] In the(spring of 2001 Boeing launched the concept of the 'Sonic Cruiser'. While there is no doubt that the .95 cruise Mach number will be good for productivity it remains to be seen whether this will outweigh the suspected increase in fuel cost.

3 TECHNOLOGY PUSH

Having established the market pull factors and their general implications for the directions of aerodynamic research and development we will now look at what the aerodynamics (and associated) communities can offer in terms of new technological developments. In doing so we will distinguish between

- concepts for improved (applied) aerodynamics of aircraft

and

- new or improved aerodynamic 'tools', i.e.
  - wind tunnel testing technology
  - Computational Fluid Dynamics (CFD)

We will also indicate, at least qualitatively, the potential for improvements towards the market pull factors identified in chapter 2.

3.1 Concepts for improved (applied) aerodynamics

The prospect (or is it an illusion?) of realizing *laminar flow* under normal, that is day-to-day operating conditions has probably fascinated the aerodynamics community more than anything else. This is not without reason ofcourse; the drag reduction potential being 15-20% of the total aircraft drag.
It has also been well established and demonstrated (see, e.g., reference (11)), that with the provision of a sufficiently smooth surface, *natural laminar flow* can be realized at Reynolds numbers below about $20*10^6$ and leading edge sweep angles not in exces of about 20 degrees. Hence, it is, in principle, an option for the smaller category of aircraft (Regio-liner, Advanced Turboprop), provided the cruise Mach number is not so high that shock waves trigger early boundary layer transition. For large, fast aircraft, such as the UHCA, natural laminar flow is out of the question. A *'hybrid'* solution involving distributed suction over a substantial (forward) part of the wing is then the only potential possibility. The added complexity is, however, enormous (see fig. 4, from reference (6), for a summary of the main aspects that are involved).
It is, nevertheless clear from, e.g. a number of Brite Euram (EU) projects and it has been demonstrated by the NASA/Boeing 757 hybrid laminar flow demonstrator aircraft that hybrid laminar flow is technically feasible.
Whether it is also economically feasible is another matter. Chart 6 summarizes the 'pro's and cons'.

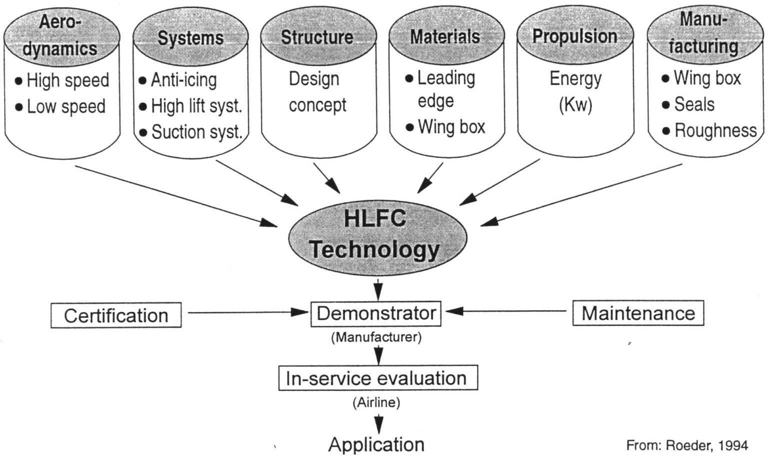
	DOC/Fuel			**Maintenance (Vulnerability)**	**Cost of Ownership**
	C_D 1)	**C_{Lmax}**	**t/c**		
Natural	**++**	**-?**	**-?**	**-**	**-**
Hybrid	**++**	**-?**	**-?**	**- (-?)**	**- -**

1) reduction potential 15-20%

**Can be done (wing, tail, nacelles), but:
Cost effective?**

Chart 6. Applied aerodynamic concepts (1): laminar flow control

In terms of fuel economy the (large) drag reduction potential is probably partly offset by a somewhat larger wing area and increased wing structural weight. The former because laminar flow wing sections tend to have smaller nose radii and, as a consequence a lower C_{Lmax}. The latter because laminar flow airfoils, at least for high speed, tend to have a lower thickness/chord ratio (t/c). Suction systems would also increase structural weight. Cost-of-Ownership is also affected in the negative sense. This because of high surface smoothness requirements, but in particular, in the case of hybrid laminar flow, through the added complexity of distributed suction. Because of increased vulnerability the same applies to cost of maintenance. For the hybrid laminar flow case even safety aspects are involved: anticipating a possible mal-functioning of the suction system halfway the Atlantic or the Pacific; how to deal with reserve fuel?



From: Roeder, 1994

Figure 4 Multi-disciplinary aspects of hybrid laminar flow technology

Insect contamination, erosion and surface damage (scratches and dents) due to ground handling, in particular in the wing leading-edge area, is another problem; probably more so for natural than for hybrid laminar flow. However there are indications(12) that, with leading-edge cleaning in-between flights, a time- and surface-averaged 'laminar efficiency of some 50% might be realized.

It is this author's impression that the conditions under which natural or hybrid laminar flow can be established are (fairly) well known and that there is little left to do for the aerodynamics community. It is up to the aircraft industry and the airlines to determine if and when laminar flow is economically feasible.

Turbulence management represents another class of means for reduction of friction drag or, more in general, for turbulent boundary layer manipulation (Chart 7). For aeronautical application of (turbulent) friction drag reduction devices *'riblets'* and '*Large Eddy Break-Up Devices (LEBUs')*, in that order, are probably the most important(13). Both riblets and LEBUs recognize the knowledge that the large eddies in the boundary layer cause most of the turbulent friction drag. In the case of riblets the development of large eddies is constrained by longitudinal, stream aligned, V-shaped grooves. In the case of LEBUs the boundary layer flow is streamwise-periodically straightened by small, surface-parallel, wing-like devices in the boundary layer.

	DOC/ Fuel		Maintenance/ vulnerability	Cost of Ownership
	C_D	C_{Lmax}		
Riblets	+		-	-
LEBUs	+		- -	-
'smart' vortex generators	- ?	+	- ?	-

Chart 7. Applied Aerodynamic Concepts (2): Turbulence Management

Research on riblets and LEBUs has been going on for more than a decade and it has been demonstrated, both in the wind tunnel and in flight that net friction drag reductions up to about 5% can be realized. It seems, however, that due to increased cost of ownership (manufacturing, in particular for LEBUs) and high vulnerability (maintenance cost) the net overall economics are in the red.

Vortex generators represent another means of turbulence management, with a different objective. They have been and are still widely used for (locally) postponing boundary layer separation and, through this, for improving low-speed and/or high-speed stall characteristics. The mechanism is to make the boundary layer more resistant to separation due to adverse pressure gradient by generating streamwise vortices near the edge of the boundary layer that 're-energize' the boundary layer flow. This at the expense of additional drag resulting from the increased surface friction of the boundary layer flow as well as the frictional resistance and vortex drag of the generator devices themselves.

The more recently developed concept of *'smart' vortex generators* is a little more closely related to the notion of turbulence management. The basic idea here is to postpone separation by stimulating the development of (very) large eddies within the boundary layer through small generating devices with less additional drag. Both mechanical(14) as well as pneumatic(15) (small jets) devices have been proposed for this purpose.

In the author's opinion the concept of 'smart' vortex generators is sufficiently interesting for further investigation. Of particular interest is the question whether, if adopted from the outset as an additional 'variable' in the design space of an aircraft (rather than as a 'deficiency curing' device that is applied afterwards), 'smart' vortex generators would lead to better overall aerodynamic/economic performance.

Wing tip devices, in particular *winglets,* have been with us for quite some time (since the late 1970s). It is generally, but not (yet?) universally recognized that they offer a cost effective way of (induced) drag reduction (Chart 8); but only so if there is a geometric or structural constraint on wing span. The latter is, e.g., the case for the Ultra-High Capacity Aircraft due to airport gate spacing limitations. Without such constraints a plain span extension appears to be the best solution.

Although the fairly large variety of winglet shapes on current aircraft suggests that there is (still)

	DOC/ Fuel		Cost of Ownership	Ops./ flex.	Noise
	C_D	C_{Lmax}			
wing tip	+$^{1)}$		-		
flap tip	+?/-?$^{2)}$	+?	-	?	+?

1) only when constraint on span
2) reduction of induced drag (take-off/climb) increase of friction drag

Chart 8. Applied Aerodynamic Concepts (3): Tip devices

no complete consensus between designers on the 'best' shape, there is probably not much room for further improvement.

A related, more recent concept is that of *flap tip devices.* It has been conjectured (in the early 1990s, by this author) that winglet type devices, mounted at the tip of a trailing-edge flap (fig. 5) might offer several aerodynamic and operational advantages (Chart 8):

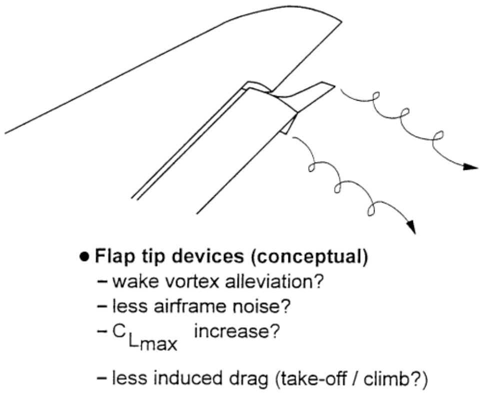


Figure 5 Winglet type flap tip device

1) a reduction of induced drag in the take-off/climb configuration (good for fuel burn, noise and emission)
2) possibly a reduction of trailing vortex intensity in the landing and take-off configurations (allowing reduced separation time/distance between landing and starting aircraft)
3) a reduction of airframe noise in the landing configuration (flap edges are one of the main sources of airframe noise)

While the first of these conjectured advantages is of interest for all types of aircraft, the second and third would be particularly relevant for the Ultra-High Capacity Aircraft.

Negative aspects would, ofcourse, be increased structural and manufacturing complexity and added wetted surface, i.e. friction drag. The latter might, however, be limited if the flap tip devices could be integrated with flap track fairings.

To the author's knowledge the flap tip device concept has not been explored to any significant extent[§]. The conjectured (potential) advantages do, however, justify serious research on the topic[†].

Another 'hi-tech' concept for aerodynamic efficiency improvement that, in various forms, has been around for a while, is that of the *adaptive* or *variable camber wing.* The basic idea is to widen the envelope of (efficient) operating conditions of an aircraft wing by introducing variable wing section geometry(19). In early versions of the concept the variable geometry capability was usually limited to flap-like leading-edge and trailing-edge devices. More recently the advent of new materials and 'smart structures' would allow elastic shape deformation driven by 'smart' sensors and actuators (fig. 6).

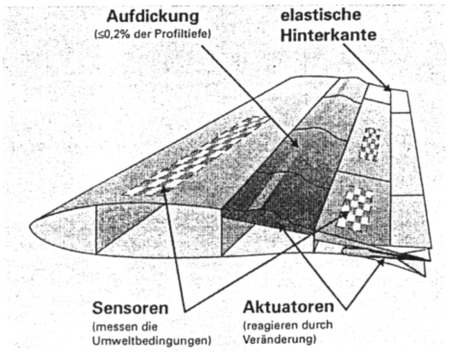


Figure 6 Adaptive wing concept
(courtesy DLR)

While there is no doubt that variable geometry can improve aerodynamic efficiency and little doubt that this can, technically, be realized, it is, (like (hybrid) laminar flow), highly questionable whether it is economically feasible. Chart 9 summarizes the 'pro's and cons'.

- adaptive wing

DOC/Fuel (L/D)	Maint./ Vuln.	Cost of Ownership	Ops./flex.	Safety
+	-	--	+	-

- SBLI control

+	-?	-	+?	-?

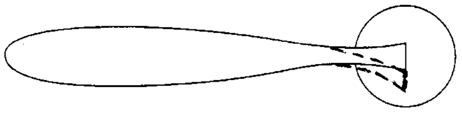
Chart 9. Applied Aerodynamic Concepts (4): Adaptive wing

[§] In February 1997, at a 'repeat' presentation of this Lanchester lecture for the Bristol Section of the Royal Aeronautical Society, Dr Fiddes of Bristol University pointed out that some aerodynamic research on flap tip devices was done in the UK in 1986/87(16). The results of this work confirm the conjectured aerodynamic potential.
In May 1997, the author noticed an AIAA paper(17) confirming the conjectured potential of flap tip devices for airframe noise reduction.

[†] Work of this nature was, eventually, done at NLR(18). The results confirm an improvement of L/D and a small increase in C_{Lmax} in take-off/climb and a significant reduction if not elimination of flap tip noise. The effect on wake vortex intensity was found to be negligible.

A related subject is that of (local) *Shock-Boundary-Layer-Interaction (SBLI) Control*(20). Objective is to reduce the strength of shock waves and related adverse boundary layer effects for the purpose of reducing drag and/or postponing separation/buffet phenomena. This is to be realized through either local, elastic shape deformation like in the case of the elastic wing (fig. 6) or by active or passive ventilation, through sub-surface cavities, of boundary layer air from aft to forward of the shock. As in the case of the elastic wing there is little doubt that SBLI control offers aerodynamic advantages. Whether it is feasible from the economic and other points of view is equally questionable (see Chart 9)§.

A less complex concept for improvement of aerodynamic efficiency with, however, probably also less potential for aerodynamic improvement is the *diverging trailing-edge airfoil* (Chart 10).



DOC/Fuel			Cost of Ownership
(L/D)	C_{Lmax}	weight	
+?	+	-?	-?

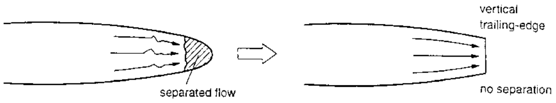
Chart 10. Applied Aerodynamic Concepts (5): Diverging Trailing-Edge Airfoil

The purpose of a diverging trailing-edge, which is applied in combination with aft camber, is to postpone boundary layer separation by decreasing the trailing-edge pressure and, through that, the aft pressure gradient. Hence, the divergent trailing edge represents a means for increasing C_{Lmax} and/or $C_{Lbuffet}$.
It was indeed, to the author's knowledge, first proposed as a means to expand the manoeuver envelope of fighter aircraft(22). More recently it has been suggested that divergent trailing-edge airfoil sections might also have benefits for civil transport aircraft(23).The latter would be the case if:

1) the increase in $C_{Lmax}/C_{Lbuffet}$ is traded for a reduction in wing area
2) the amount of trailing-edge divergence is limited so as not to generate too much additional base drag.

Because the divergent trailing-edge concept does not seem to introduce significant negative effects it is probably worthy of further exploration.
Not really a (new) aerodynamic concept but worth mentioning in this context is *multi design point (wing) aerodynamic optimization*, I.e. the process of finding the wing shape that represents the best balance between the usually conflicting requirements of cruise and off-design conditions. Recent developments in computational fluid dynamics and optimization theory are offering interesting possibilities for more rigorous and more efficient approaches (see also section 3.2).

A potential for a modest reduction of fuselage drag seems to be present in better aerodynamic *rear-fuselage shaping*. While many transport aircraft have a cone-like rear-fuselage shape, there are indications that a shape with a finite-length trailing-edge shape offers some advantage in terms of drag(24). The mechanism would be that the excessive growth of the boundary layer displacement thickness and associated separation, through the converging boundary layer flow towards the rear tip of the cone is avoided by spreading the boundary layer material over a vertical trailing-edge of some finite length (Chart 11).



(MD 80/90, 777, (F28, F100))

DOC/Fuel	Cost of Ownership
C_D	
+	?

Chart 11. Applied Aerodynamic Concepts (6): Rear-Fuselage Shaping
(avoiding boundary layer convergence/separation)

The concept has been adopted on the later MD series of aircraft and more recently on the Boeing 777.

Propulsion/airframe integration is an area that continues to receive attention (Chart 12).

	DOC/ Fuel	Cost of Ownership
Propeller (S/R) swirl recovery (wing/nacelle optimization)	+?	-
Thrust vector modulation	+?	-
Wing/pylon/nacelle optim.	+	

Chart 12. Applied Aerodynamic Concepts (7): Propulsion/airframe integration

---

§ For a recent survey of adaptive wing and flow control technology: see(21)

For the Advanced Turboprop aircraft there are probably possibilities to reduce the induced drag with installed (single rotating) propellers by properly shaping the nacelle and local wing twist and sections. Exploratory computations with an induced drag minimization code[(25)] have indicated a potential for a reduction of the induced drag of 9% if a properly laterally loaded pylon is positioned in the propeller slipstream to recover some of the swirl of the propeller (fig.7). It can be conjectured that a properly shaped nacelle can assume the same role.

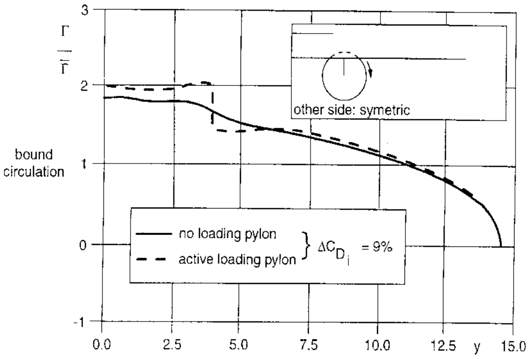


Figure 7 Spanwise distribution of circulation for minimum induced drag of a wing with and without pylon in propeller slipstream

For jet aircraft with (under)wing mounted engine nacelles *thrust vector modulation* might be an option to improve the take-off and landing performance. Many if not most of such aircraft exhibit flaps with spanwise interruptions to avoid that the jets hit the flap. Such interruptions are detrimental to induced drag as well as maximum lift. They could be avoided by a modest downward deflection of the jets. Whether this is technically possible can not be judged by the author. However, it would seem that a mechanism that integrates thrust vector modulation and thrust reversing functions is worth studying.

Improved aerodynamic integration of wing, pylons and engine nacelles for minimum drag in cruise is, ofcourse, a subject of continuing general interest and research. In wind tunnels such research, involving engine simulators, is costly and time consuming. *Computational Fluid Dynamics* (CFD) already offers possibilities for detailed analysis of wing-pylon-nacelle interference (fig. 8), but probably not yet with sufficient accuracy.

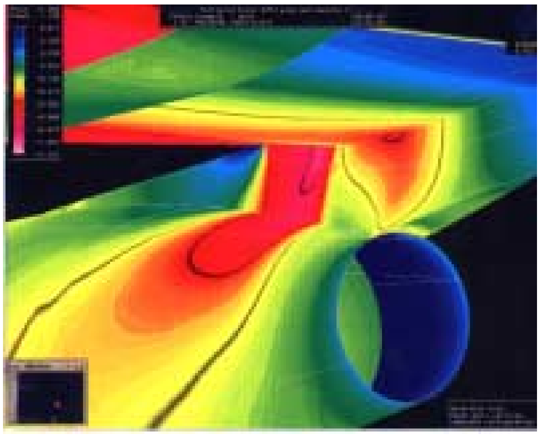


Figure 8 CFD analysis of wing-pylon-nacelle interference: already a powerful tool
(source: NLR, 1995)

Further progress and improvements may be expected when CFD has reached the stage in which accurate drag prediction for complex configurations with propulsion simulation is possible.

Chart 13 lists some topics of a miscellaneous nature. *Active control technology*, including, amongst others, the 'three-surfaces aircraft'[(26)] (fig. 9) can be applied to reduce the total drag under trimmed flight conditions and could also improve passenger comfort ('riding qualities'). There are, however, penalties in the form of increased vulnerability and maintenance and higher cost of ownership. Safety (under malfunctioning of the system) might also be a factor.

	DOC/ Fuel (L/D)	Vulnerability/ Maintenance	Cost of Ownership	Safety	Noise (external)	Comfort
Active control technology	+?	-	-	-?		(+)
Aeroelastic tayloring	+?	?	-	(?)		
Active noise & vibration control	+?	-	-		+	+

Chart 13. Applied Aerodynamic Concepts (8): Miscellaneous topics

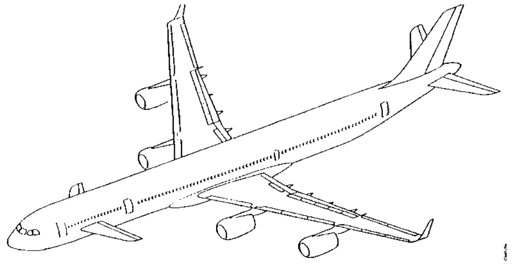


Figure 9 Example of Active Control Technology: the three-surfaces aircraft (courtesy DLR)

Aeroelastic tayloring using suitable composite materials and structures would lead to reduced structural weight and through that to increased L/D. *Active noise and vibration control* of propulsion systems and in the cabin environment holds the promise of reduced external and internal noise and improved passenger comfort.

The *propulsion systems* themselves are of course also subject of continuing improvements. Increasing by-pass ratios of turbofan engines are leading to higher fuel efficiency, lower emission and lower noise, but also require more attention for propulsion/airframe integration. High speed propellers (ducted and unducted) also hold promise for better fuel efficiency and lower emission, but possibly not without higher noise levels.

3.2 Wind tunnel testing technology

An indirect contribution to the economics and other factors of aircraft and their design is offered by improvements in wind tunnel testing technology. Chart 14 summarizes new achievements and trends in facility general characteristics.

The *European Transonic Wind tunnel* (ETW) offers the possibility of full-scale Reynolds number testing at subsonic and transonic speeds. This, at least in principle, implies a lower design risk through a higher accuracy of simulation, but at higher costs than conventional (sub-scale) wind tunnel testing. Higher levels of *automation* in the control of wind tunnels and there systems are leading to improved control of the process of testing and a higher productivity(27). Accuracy may also be improved by better control over tunnel speed, pressure and temperature levels and other independent variables. It has been demonstrated that a*daptive wind tunnel walls*(28) can reduce wind tunnel wall interference, but probably not without consequences for the cost and productivity of testing.

Improvement of instrumentation and measurement systems and the introduction of new measurement techniques (Chart 15) are also contributing to productivity and accuracy, but, and perhaps more importantly, are also providing new possibilities for flow diagnostics. Balances, pressure sensors and their calibration procedures are subject of continuing improvement and automation.

Pressure-sensitive paint(29) is probably one of the most important promising new techniques. It holds the prospect of surface pressure measurements without the need of large numbers of pressure tabs. The importance of the latter is that the complexity, cost and manufacturing time of wind tunnel models can be reduced significantly. Another aspect is that aerodynamic loads on model components by integration of surface pressures can be obtained more conveniently and probably also more accurately. The latter because of a higher resolution of the integrant.

Detailed *wake measurement* techniques using rapidly traversing rakes with *5-hole probes*(30) have been developed in recent years, enabling the determination of viscous drag sources along the span of a wing and other aircraft components as well as determination of the induced drag of a configuration. Figure 10 illustrates an early application of the technique to a wing-body configuration at low speed (Mach 0.18) in the DNW-LST wind tunnel.

	Cost of Ownership (design)		**Design risk reduction**	
	process	**productivity**	**accuracy**	**diagnostics**
Full-scale Re number testing (ETW)	**-**		**+**	
Automated tunnel & systems control	**?**	**+**	**(+)**	
Adaptive walls	**(-?)**	**(-?)**	**+**	

Chart 14. Wind tunnel testing technology (1): Improving facility characteristics

	Cost of Ownership (design)		Design risk reduction	
	process	productivity	accuracy	diagnostics
Improved balances, pressure sensors and calibration procedures		+	+	
Pressure-sensitive paint	+	+	?	+
Particle Image Velocimetry			+?	+
3D wake measurements **- 5-hole probe/rake** **- laser based?**			 +?	 + +
Optical model position and deformation measurement			+	+

Chart 15. Wind tunnel testing technology (2): Instrumentation and measurement systems

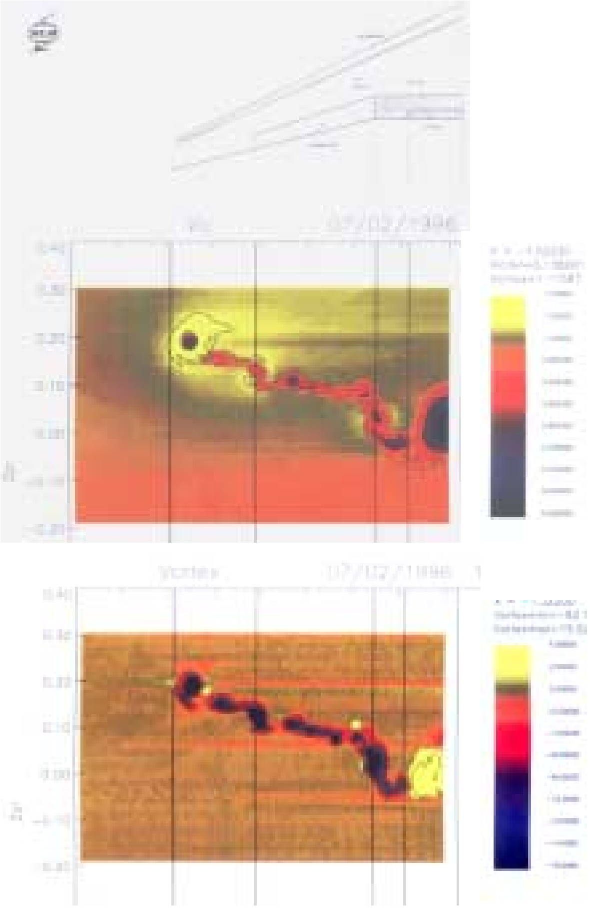


Figure 10 Total velocity and vorticity contours behind a wing as measured by means of 5-hole probes

The upper figure presents distribution of the total velocity (related to viscous drag) and the lower figure that of the longitudinal vorticity distribution (related to induced drag) in a plane at some distance behind the wing. In the author's opinion such techniques provide the aerodynamic designer with new, powerful tools for flow diagnostics.

Among the new non-intrusive measurement techniques *Particle Image Velocimetry*(31) seems to be reaching the stage of readiness for application in production class wind tunnels. It offers the possibility of field measurements of velocity components with a high productivity and is likely to become a competitor for the 5-hole probe technique. This in particular if it could be extended to three dimensions and could be supplemented with a technique for optical pressure measurement in the flow field. The latter would be required if the determination of drag is an objective.

In conclusion of the discussion on wind tunnel testing techniques it is mentioned that optical techniques are also being developed for the 'in situ' and 'on line' *measurement of wind tunnel model deformation* under aerodynamic loads(32). Such capability is particularly important for pressurized wind tunnels in which aerodynamic loads and model deformation are high. Without it, precise information on the actual aerodynamic shape is generally not available, which often constitutes a source of considerable uncertainty.

3.3 Computational Fluid Dynamics

In the past 25 years Computational Fluid Dynamics (CFD) has probably had more impact on the process as well as the quality of aerodynamic design than anything else and it continues to do so. This is not without reason. CFD has opened the possibility of (approximately) analyzing the aerodynamic characteristics of, relative to wind tunnel testing, large numbers of candidate aircraft configurations in early stages of the design process. This capability has changed the role of wind tunnels in aerodynamic design in the sense of utilizing a smaller number of relatively simple 'configuration exploration' models but more emphasis on , more complex, high-fidelity models for verification of the CFD design. As such, CFD has contributed significantly to the quality of aerodynamic design but it can and has also been used to speed-up the design process.

After 25 years CFD is still in full, further development and not in the least because of the trend in persistent performance improvement of computer hardware. As illustrated by figure 11 the speed of computation has, on the averag, increased by a factor of 10 per every 9 years and the current developments in (massively) parallel computers promise even higher rates of growth. In addition, the growth of performance of work stations has led to easy access to high performance computing.

Chart 16 summarizes the benefits of these and other developments in CFD for such *market pull factors* as cost of ownership and design risk.

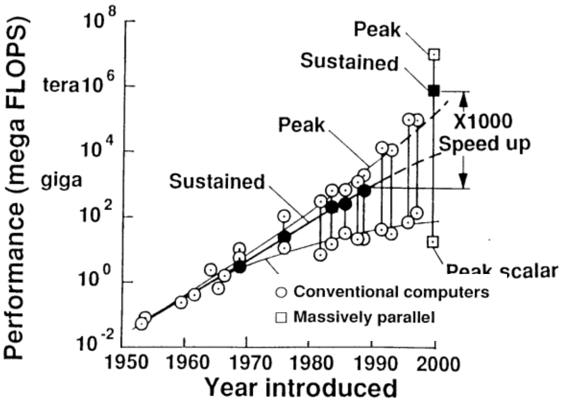


Figure 11 Growth rate of computer performance: Factor 10 per 9 years

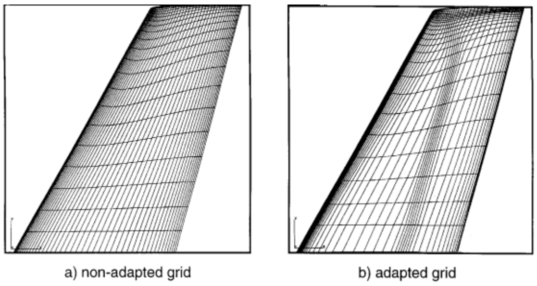
While the growth of computer performance is obviously good for the efficiency of numerical simulations it also allows a larger number of cells of the computational grid. The latter can be used to increase the accuracy of the numerical simulation and, through that, reduce the design risk.

Grid generation has, for some time, been the pacing item in CFD applications, in particular for complex configurations. Higher levels of automation in the generation of block structured grids are therefore subject of continuing development efforts. In addition overlapping (chimera) grid systems and unstructured grids have shown to reduce the grid generation effort significantly, albeit at the price of some loss in accuracy.

	Cost of Ownership (design)		**Design risk reduction**	
	process	**productivity**	**accuracy**	**diagnostics**
(massively) parallel computers	+?	++	++	
more/fully automated grid generation - **block/topology structured** - **chimera (overset)** - **unstructured** - **hybrid**	+	+	+	
Solution adaptive grids	+	+	+	+
Transition and turbulence models for complex flows (RANS)			+	?
algorithms	+	+	+	
LES	(-)	(-)	+	+

Chart 16. Computer Technology and CFD
Effects on reduction of Cost of Ownership and Design Risk (1)

Algorithms for s*olution adaptive grids* have been developed for structured (fig. 11) as well as unstructured grids.



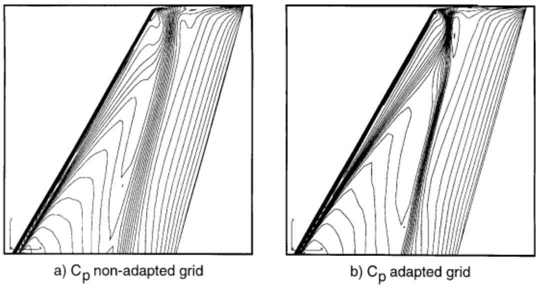
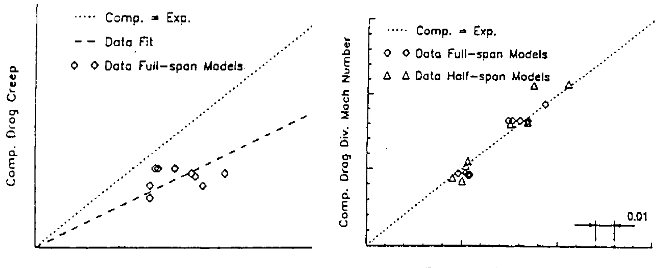


Figure 11 Example(33) of solution adapted (structured) grid
(ONERA M6 wing, M =0.84, α = 3.1^0, Re = 11.7*10^6)

They offer a possibility for a more efficient use of a given number of grid points, a higher accuracy (particularly important for drag) and a better resolution of critical flow features in unexpected locations. For CFD methods based on the Euler equations the benefits are largely limited a sharper capture of shock waves. For methods based on the Reynolds-averaged Navier-Stokes (RANS) equations grid adaptation is almost a 'must' in order to guarantee appropriate resolution of the shear layers. This in particular for situations with separated flow. It is the author's impression that solution adaptive grids are not yet a standard feature on many CFD codes and that more work has to be done to improve the efficiency and robustness of the algorithms.

Improvement of *transition and turbulence models* for the RANS equations, in particular for complex flows with separation on high lift configurations, will probably remain a subject of research for a considerable time to come. Not in the least because *Large Eddy Simulation*, which holds the promise of more universally applicable, sub-grid scale turbulence models, will probably not be feasible for application to complex flows and configurations within the next decade.

Chart 17 lists some further CFD-related topics.
Accurate *drag prediction* through CFD has been a notoriously difficult problem(34). This is due partly to the fact that, at least until the recent past, the available computer did not allow sufficient grid resolution. The absence of suitable methods and algorithms for determining the different components of drag, i.e. boundary layer or 'viscous' drag, induced drag and wave drag has been another reason. Progress has been made however, as illustrated by figure 12.



Statistical correlation of experimental and computed drag-creep at the drag-divergence Mach number for full-span wind tunnel models

Statistical correlation of experimental and computed drag-divergence Mach numbers for various wing/body configurations

Figure 12 Statistical correlation of computed and measured compressibility drag creep (left) and drag divergence Mach number (right)

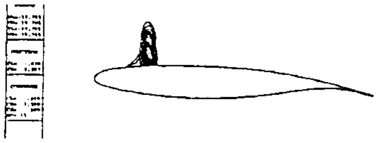
	Cost of Ownership (design)		Design risk reduction	
	process	productivity	accuracy	diagnostics
Drag prediction/analysis schemes			+	+
High-lift (complex) configurations	+	+	+	+
Design & optimization methods (optimal control theory)	+	+	+	+
Multi-disciplinary simulations - Aeroelastics - Flight mechanics	+	+	+	+
Computational Aero-Acoustics	+	+	+	+

Chart 17. Computer Technology and CFD
Effects on reduction of Cost of Ownership and Design Risk (2)

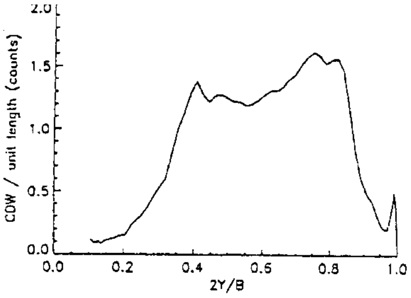
The figure presents a statistical comparison of computed and measured drag data for a number of wing-body configurations. The computational data were obtained with the NLR MATRICS-V code(35). The method is based on the full potential flow model and a simultaneously solved, time-dependent boundary layer model. The figure illustrates that drag divergence due to shock wave formation can be predicted with reasonable accuracy but that ‘drag creep’ is underestimated consistently. It is, however, by no means clear that this difference is only due to errors in the computational results; in the presence of wind tunnel walls, model support systems and boundary layer tripping devices the accurate measurement of drag creep in a wind tunnel is also far from a trivial affair.

A strong point of methods like MATRICS-V is that they also provide information on the distribution of the various drag components along the span of a wing and the spatial distribution of wave drag. Figure 13 gives an example. For the aerodynamic designer this means a new, powerful tool for flow diagnostics.

Spanwise distribution of viscous drag-creep between $M_\infty = 0.60$ and $M_\infty = 0.75$ for the DLR - F4 wing/body at $C_L = 0.5$, $Re = 3{*}10^6$



Spatial distribution of wave drag at approx. 75% span for the DLR - F4 wing/body at $M_\infty = 0.75$, $C_L = 0.5$, $Re = 3{*}10^6$



Spanwise distribution of wave drag for the DLR - F4 wing/body at $M_\infty = 0.75$, $C_l = 0.5$,

Figure 13 Example of computational drag diagnostics: spanwise distributions of wave drag and viscous drag creep and spatial distribution of wave drag

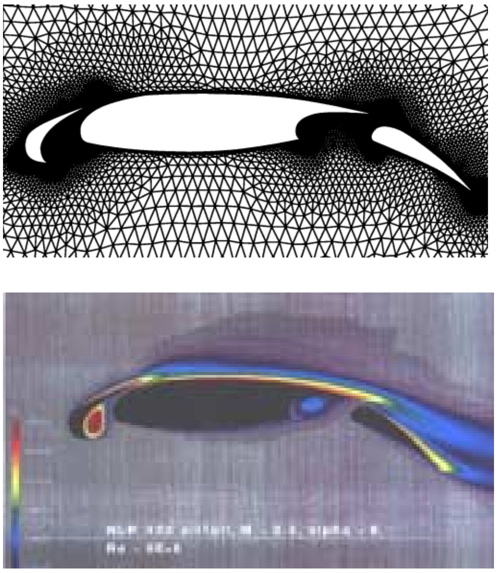


Figure 14 Example of ‘RANS’ simulation on unstructured grid for a ‘2D’ high-lift configuration (source: NLR)

Numerical simulation of the flow about three-dimensional, *complex high-lift (take-off and landing) configurations* on the basis of the RANS equations is one of the remaining frontiers in CFD. The pacing items are grid generation as well as computer power. For grid generation unstructured or hybrid grids are probably the only practical solution. A ‘2D’ example is given in figure 14. Sufficient computer power for applications with three dimensions will probably become available in the next few years. When that has happened it is to be expected that high-lift system design will be able to benefit from CFD in the same sense as supercritical wing design has benefited since the late seventies or early eighties.

Aerodynamic design and optimization methods, in particular for wings, have been subject of research for many years. However it was not until fairly recently that a truly versatile approach based on optimal control theory and the calculus of variation has been developed(36). The technique is, in principle, capable of solving complex optimization problems, such as minimization of drag or the maximization of lift, subject to all sorts of geometric and aerodynamic constraints and for a large number of design variables. It is also flexible, in the sense that it can be developed for different flow models and, if a conventional ‘flow solver’ is available, it requires a only a fairly modest effort to develop the required ‘adjoint solver’ for the optimization problem. Perhaps even more important is the fact that the computational effort involved in solving the optimization problems is also modest: one step in the optimization problem costs about as much time as one ordinary ‘analysis’ calculation and the number of steps required is usually in the order of three.

Figure 15 illustrates an application to a wave drag minimization problem for a wing and figure 16 gives an example of multi (two)-point design(37) for an airfoil section.

The current status of this design technology is that, on the basis of the Euler equations, it has been demonstrated for ‘2D’ and ‘3D’ wings and wing-body configurations. Extension to the RANS equations and other, more complex configurations is, however, in all probability only a matter of time.

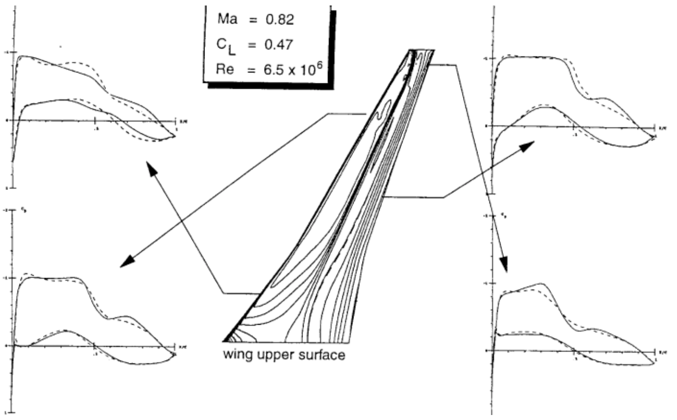
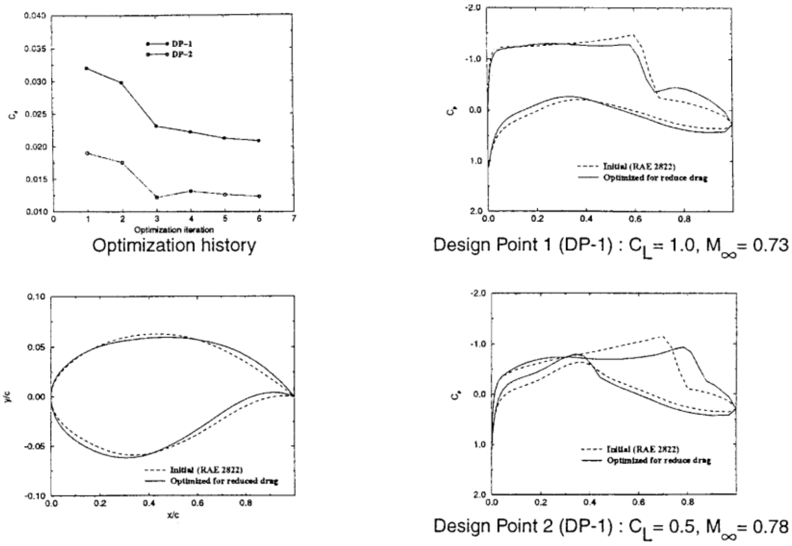


Figure 15 Example of wing design through optimal control theory: wave drag reduction
(source: NLR)



Optimization history

Design Point 1 (DP-1) : C_L= 1.0, M_∞= 0.73

Design Point 2 (DP-1) : C_L= 0.5, M_∞= 0.78

Figure 16 Example of multi-point airfoil design through optimal control theory: wave drag reduction
(source: NLR)

There are a number of areas in the aeronautical sciences that are not specifically of an aerodynamic nature but in which aerodynamics, and CFD in particular, plays a role. CFD has, from its very beginning, played a major role in *structural dynamics and aeroelasticity* and will continue to do so. It is also penetrating in *(flight mechanic) simulations of the stability and control characteristics of complete (flexible) aircraft* with propulsion and control systems. In both cases the role of CFD is, of course to generate the time-dependent aerodynamic loads on the aircraft and its control surfaces. Here also, the growth of computing power creates new opportunities.

Last but not least, the evolving possibility of time-accurate numerical flow simulations has also triggered the development of the new discipline of *Computational Aero-Acoustics* (CAA). New, numerical methods for the calculation or simulation of noise generation and propagation are currently subject of research in many places. Given the still growing importance of noise reduction it is to be expected that the importance (as well as the possibilities) of CAA will also grow strongly in the next decades.

4 Putting it all together….

Having considered both market pull factors and new evolving aerodynamic concepts and technologies (technology push), we are now in a position to judge, or rather estimate, which topics of aerodynamic research and development have the best prospect for contributing to the market position of civil transport aircraft in the next, say twenty years.

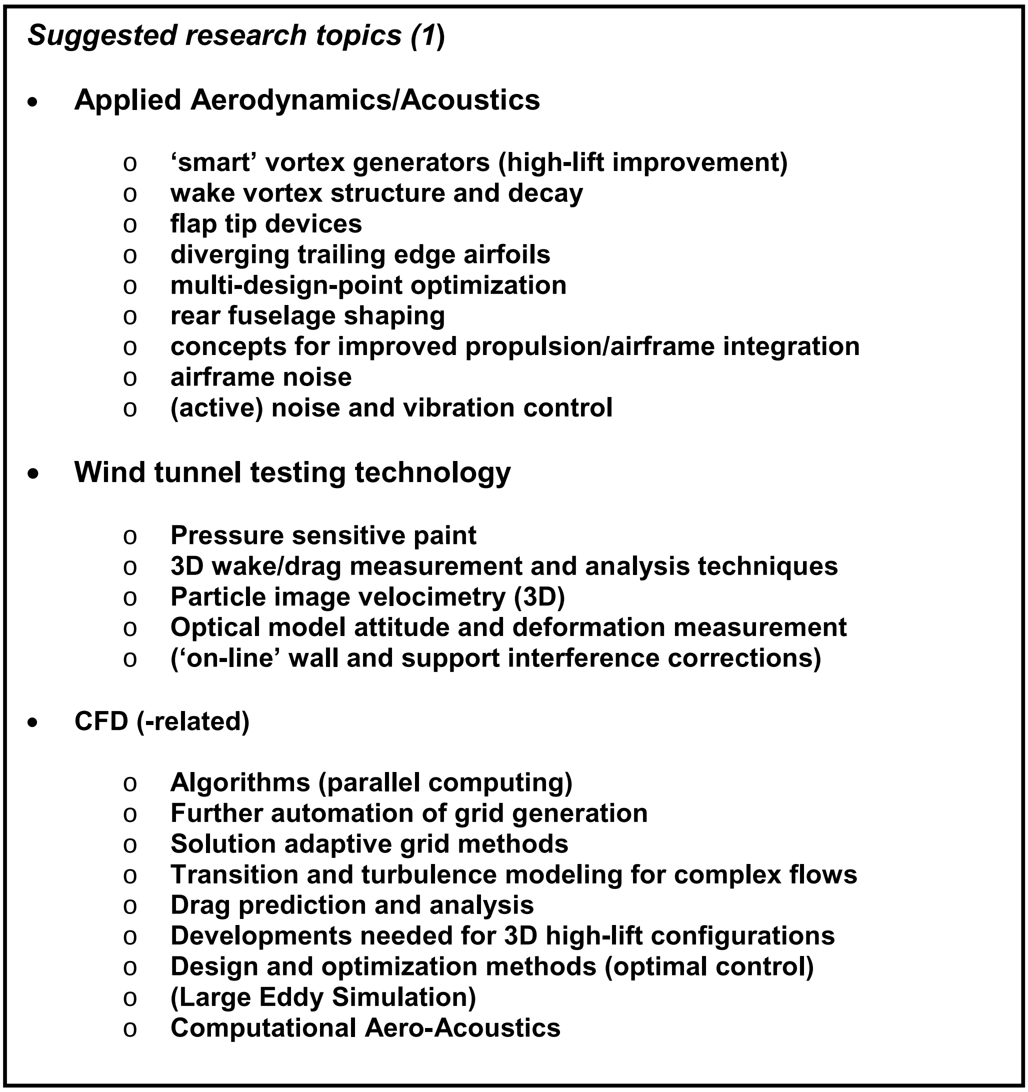
Chart 18 provides a list of suggested research topics that is based on such considerations. It is emphasized that it reflects the personal opinion of the author and not necessarily that of the institute that he is associated with.

The list is limited to subjects that could be addressed by the research community without large-scale participation of the aircraft industry. Topics like ‘(aerodynamic) design for manufacture’ are, therefor, not included. It is also noted that the ordering of the topics does not reflect any priority but rather the order in which they have appeared in the course of this lecture.

After the more extensive discussions in the preceding sections the list of Chart 18 does probably not require much further discussion. The reader may notice that, on the applied aerodynamics side, many of the suggested topics are related to high-lift system improvement. This is not without reason: there is probably nothing more complex in aerodynamics than the flow about an aircraft in take-off or landing configuration and the number of variables in high-lift system design is enormous.

In the area of wind tunnel testing technology the (added) topic of wall and support interference corrections has not been discussed in any detail. It has been added because, in the author’s opinion, it remains a source of uncertainty in wind tunnel testing.

The length of the list of CFD-related topics reflects that, although CFD is now reaching the age of



Suggested research topics (1)

- **Applied Aerodynamics/Acoustics**
    - **‘smart’ vortex generators (high-lift improvement)**
    - **wake vortex structure and decay**
    - **flap tip devices**
    - **diverging trailing edge airfoils**
    - **multi-design-point optimization**
    - **rear fuselage shaping**
    - **concepts for improved propulsion/airframe integration**
    - **airframe noise**
    - **(active) noise and vibration control**
- **Wind tunnel testing technology**
    - **Pressure sensitive paint**
    - **3D wake/drag measurement and analysis techniques**
    - **Particle image velocimetry (3D)**
    - **Optical model attitude and deformation measurement**
    - **(‘on-line’ wall and support interference corrections)**
- **CFD (-related)**
    - **Algorithms (parallel computing)**
    - **Further automation of grid generation**
    - **Solution adaptive grid methods**
    - **Transition and turbulence modeling for complex flows**
    - **Drag prediction and analysis**
    - **Developments needed for 3D high-lift configurations**
    - **Design and optimization methods (optimal control)**
    - **(Large Eddy Simulation)**
    - **Computational Aero-Acoustics**

Chart 18. Summary/ finding the balance:
Suggested research topics

maturity, there are still many opportunities for expanding its role in the aerodynamic design of transport as well as other types of aircraft.

5 Epilogue

When, in the midst of the turmoil created by the bankruptcy of the aircraft industry in my country, I was preparing this lecture, I could not escape wondering what Lanchester would have thought if he would have been in the audience. I think that, confronted with numerous, for him new notions and technologies, he would need the answers to many questions before he could form his opinion on the state-of-the-art and the remaining future of aerodynamics.

In his preface to "Aerodynamics" (1907) Lanchester says:

> "In offering to the public the first installment of the present work, the author desires to record his conviction that the time is near when the study of Aerial Flight will take its place as one of the foremost of the applied sciences, one of which the underlying principles furnish some of the most beautiful and fascinating problems in the whole domain of practical dynamics".

I think, in this spirit, that now, 60 years later, Lanchester would desire to record, with satisfaction, that:

> "the study of Aerial Flight has taken its place as one of the foremost applied sciences, one of which the underlying principles still furnish some of the most beautiful and fascinating problems in the whole domain of practical dynamics, one also of which the challenges and opportunities for further advancements in (economically justifiable) application are equally fascinating".

Mister chairman, ladies and gentlemen,

I thank you for your attention and patience.

REFERENCES

1. ACKROYD, J.A.D. The 31st Lanchester Lecture. Lanchester-The Man, *Aeronaut.J.,* April 1992, 96, (954), pp 119-140
2. Von KARMAN, THEODORE. Lanchester's Contributions to the Theory of Flight and Operational Research, *J.R.Aero.Soc,*Vol.62, Febr. 1958, pp 80-93
3. PRITCHARD, CAPT. The Dawn of Aerodynamics, *J.R.Aero.Soc.,* March 1957, p 152
4. ROGERS, E.W.E. Aerodynamics - retrospect and prospect, *Aeronaut.J.,*Febr. 1982, pp 43-67
5. POISSON-QUINTON, PH. Future SSTs, a European Approach, *Aerospace America,* Sept. 1994, pp38-43
6. ROEDER, JEAN P. Requirements for aerospace research for the development of large civil aircraft, paper presented at the occasion of the 75th anniversary of the National Aerospace Laboratory NLR, Amsterdam, 1994
7. VAN DUINEN, R.J. Requirements for Aerospace Research for the Development of Regional Aircraft, paper presented at the occasion of the 75th anniversary of the National Aerospace Laboratory NLR, Amsterdam, 1994
8. SZODRUCH, J. and ROEDER, J.P. *Eine vision wird Realität - Die Umsetzung von Produkt- und Technologiestrategien,* DGLR-Jahrestagung 1996, DGLR-JT-96-003
9. Private communication. The Boeing Company, 1994
10. RUBBERT, PAUL E. CFD and the Changing World of Airplane Design, AIAA Wright Brothers Lecture, Anaheim, CA, 1994
11. Proceedings 2nd European Laminar Flow Forum
12. ELSENAAR, A. and HAASNOOT, H.N. A survey on Schiphol Airport of the contamination of wing leading edges of three different aircraft types under operating conditions, NLR TP 92185 L, 1992
13. BUSHNELL, D.M. and HEFNER, J.N. Viscous Drag Reduction in Boundary Layers, Progr. In Astron. and Aeron., Vol. 123, AIAA, 1990
14. LIN, J.C.; ROBINSON, S.K.; MCGHEE, R.J.; VALAREZO, W.O.: Separation Control on high-lift airfoils via micro-vortex generators, J.Aircraft, vol. 31, no.6, dec. 1994
15. SEIFFERT, A.; BACHAR, T.; KOSS, D.; SHEPSELOVICH, M.; WYGNANSKY, M. Oscillatory blowing: a tool to delay boundary layer separation. AIAA J. 1993; 31(11): 2052-60
16. WILLMER, A.C.; BARRETT, R.V. and COLEMAN, J.D. The tip flow of a part span slotted flap, Aeronautical J., December 1987, pp 460-469
17. HAYES, Julie A.; HORNE, W. Clifton; SODERMAN, Paul T. and BENT, Paul H. Airframe noise characteristics of a 4.7% scale DC-10 model. AIAA-97-1594-CP, May 1997
18. SLOOFF, J.W.; DE WOLF, W.B.; VAN DER WAL, H.M.M. and MASELAND, J.E.J. Aerodynamic and Aero-acoustic Effects of Flap Tip Fences. AIAA 2002-0848, 2002
19. SMITH, S.B.; NELSON, D.W.; Determination of the aerodynamic characteristics of the mission adaptive wing. AIAA J Aircr. 1990; 27(11): 950-8)
20. ASHILL, P.; FULKER, J.; SIMMONS, M.J. Simulated active control of shock waves in experiments on aerofoil models. Proc. ICEFM, Turin, July 1994
21. STANEWSKY, E. Adaptive wing and flow control technology. Progr. Aero. Sc., Vol. 37, nr 7, Oct. 2001
22. EVANS, Bill (Grumman Aerospace). Private communication, 1973

23. HENNE, P.A. and GREGG, R.D. III: A new airfoil design concept, AIAA 89-2201
24. HENNE, P.A.; Private communication, McDonnell Douglas Comp., 1989
25. VAN DEN DAM, R.F. Constrained span load optimization for minimum drag of multi-lifting-surface configurations. In: AGARD-CP-463 Computational Methods for Aerodynamic Design (Inverse) and Optimization, 1989
26. DLR, private communication, 1995
27. JAARSMA, F.; SMITH, J.; VAN DEN DRAAY, R.K. : A modernised HST of NLR, paper presented the European Forum on Wind tunnels and Wind tunnel Test Techniques, Southampton University, UK, also NLR TP 92420 U, Sept. 1992,
28. Fluid Dynamics Panel Working Group 12: Adaptive Wind Tunnel Walls – Technology and applications, AGARD Advisory Report No. 269
29. CRITES, R.C.; BENNE, M.E.: Emerging technology for pressure measurement - pressure sensitive paint, AIAA Paper 95-0106, 1995
30. HEGEN, G.H. : Calibration of a rake equipped with 18 five hole probes in the LST, test number 5632, NLR TR 96235, 1996.
31. RAFFEL, M.; WESTERWEEL, J.; WILLERT, C.; GHARIB, M.; KOMPENHANS, J.: Analytical and experimental investigations of dual-plane PIV, In: *SPIE Intl. Symp, on Optical Sciences, Engineering and Instrumentation,* Bellingham, WA, USA, 1995
32. DNW, private communication, 1996
33. HAGMEIJER, R. and KOK, J.C.: Adaptive 3D Single-Block Structured Grids for the Computation of Viscous Flows around Wings, In: *5th International Conference on Numerical Grid Generation in Computational Fluid Dynamics and Related Fields,* Starkville, MI, USA, April 1996
34. SLOOFF, J.W.; Computational Drag Analysis and Minimization: Mission Impossible? In: ‘Aircraft Drag Prediction and Reduction’, AGARD Report No. 723, Addendum 1, 1986
35. VAN MUYDEN, J.; BROEKHUIZEN, A.J.; VAN DER WEES, A.J.; VAN DER VOOREN, J.: Flow analysis and drag prediction for transonic wing-body configurations using a viscous-inviscid interaction type method, ICAS paper 94-2.6.5, also NLR TP 94161 L, 1994
36. REUTHER, J. and JAMESON, A. : Aerodynamic shape optimization of wings and wing-body configurations using control theory, AIAA paper 95-0123, Jan. 1995
37. SOEMARWOTO, B.I. : Multi-point aerodynamic design by optimization. PhD thesis, Delft University of Technology, to be published (1996)