Fixing Poor Control Surface Performance on a Transonic Missile - A Case Study of Combining Cost-Effective Wind Tunnel Testing and CFD Analysis

C.P.Crosby[1] & S.G.Gobey[1] *

1 Aerodynamics Department, Kentron, PO Box 7412, Centurion, 0046, South Africa,
corresponding author, charles.crosby@kentron.co.za

Abstract

A combination of simplified CFD analysis and wind-tunnel tests were used to redesign the pitch control surfaces of a transonic missile in order to meet particularly challenging pitch control requirements. Limited resources precluded using fully "qualified" and calibrated CFD models and wind tunnel tests. Despite these limitations, the redesign was successful. Close cooperation between CFD practitioner, wind-tunnel test engineer and aerodynamic designer allowed insights into complex flow physics to be shared and a satisfactory design solution to be found at low cost. It is concluded that the "safety net" of a later detailed wind-tunnel test can and should be used to determine the level of detail required from analysis and tests at the design stage. Sacrificing detail at this stage can allow a greater variety of solutions to be investigated. Quality of insight into the flow physics does not appear to suffer much from "coarse" CFD or wind-tunnel testing. This experience has rather shown that the greater number of solutions that can be investigated results in improved insight, and a better design.

Introduction

In the authors' experience, there appears to be a view in industry that the aerodynamic designer has the following tools at his disposal:

- "Classical" exact analytical methods
- Semi-empirical methods such as ESDU or Datcom
- Computational Fluid Dynamics
- Wind-tunnel testing

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* Names listed in alphabetical order

In keeping with this doctrine, both CFD and wind-tunnel testing are performed in ways that are most likely to guarantee high quality results. There is a large body of literature explaining in some detail how wind-tunnel testing should be performed in order to obtain quality results. In contrast there is much literature on the theory of CFD, but not much that will help the CFD practitioner in terms of how he should apply his commercial CFD tools. In many cases, the CFD practitioner must rely on the CFD code vendor's literature. Nevertheless, a recurring theme is "validation". The CFD practitioner is widely urged and expected to validate his results in order to ensure quality. The use of wind-tunnel data to validate CFD is perhaps the most widely seen combination of CFD and experimental work. However, this is not "integrating" CFD and experiments.

The practitioner faced with the realities of limited resources and pressure from project managers is in a difficult position. Trying to do the CFD work in accordance with normal CFD industry good "practices" may well result in validated high quality CFD results only becoming available some time after the airframe is already in production. It is thus necessary to consider quality requirements, and ways of meeting these requirements, very carefully. There is inevitably a trade-off between quality and quantity of CFD results. Enforcing strict quality requirements seriously limits the number of flow conditions or design variants that can be analysed. If the desired outcome of a project is merely high quality CFD, decisions obviously have to be biased toward quality rather than quantity. A specialised CFD consultant is most likely to encounter this situation. However, in an aerospace company, the success of a project is measured in terms of the performance and cost of the final product or airframe. The exact path followed to arrive at the successful design is immaterial.

At this point it is worth remembering that neither CFD nor wind-tunnel testing need to be considered as discrete points on the range of tools available to the aerodynamic developer. Useful techniques encompassed by the term "wind-tunnel test" range from an un-instrumented tufted wooden model in a class-room smoke tunnel all the way to a pressure tapped, numerically machined, dynamically scaled model in a pressure tunnel with LDVA. In similar fashion CFD can encompass everything from simple two-dimensional panel methods all the way up to multi-million cell, multi-equation turbulence model Navier-Stokes codes. Even a single class of CFD method, such as compressible Reynolds-Averaged Navier-Stokes on a multi-block structured grid, can cover a wide range. Simplifying the model by ignoring downstream detail and accepting a relatively coarse mesh can result in a CFD model that will give an answer about 10 times faster than one including all detail and ensuring grid-independent results. The "coarse" model will most certainly not meet CFD quality standards, but if the determining metric is the success of the final airframe, these standards are of little importance in their own right. The question is if these coarse results help to achieve a successful airframe. The case study presented here illustrates that the answer can be "yes", provided that CFD and wind-tunnel experiments are integrated sensibly.

A Case Study of Using Cost-Effective CFD and Wind-Tunnel Testing in Design

Design Requirements

An aerodynamic design was required for a new transonic missile. Due to obvious security considerations, actual design requirement values can not be given, but the most important requirements can be summarised as the following:

- Unusually high manoeuvrability
- Very strict packaging dimensions
- Low control surface hinge moments to keep servo costs low

As ever, these requirements were in conflict with each other. The aerodynamic design of the control surfaces thus became a critical element of the airframe development.

Preliminary Design and Performance

In order to meet the design requirements, tandem canards, consisting of a movable surface mounted just aft of a fixed surface, were selected as pitch control surfaces, as shown in Figure 1. Early in the conceptual design phase, a very small (1:13) scale model was wind-tunnel tested. This test revealed that elevator effectiveness was insufficient to meet the manoeuvrability requirements. At this stage of the project there was no suitable CFD capability available to investigate the issue further. The canard layout was then developed empirically through three more design iterations. These developments improved the performance, but the design still could not meet the requirements. Similar close-coupled control surfaces systems had been used successfully by the same aerodynamic design team on other missiles, and it was concluded that the shortcomings were most probably caused by profile inaccuracy and low Reynolds number. As it is impossible to manufacture very accurate aerofoil profiles inexpensively at this scale, this would appear to be a reasonable conclusion.

The next phase of the project involved wind-tunnel testing of a far more accurate 30% scale model. Figure 2 is a plot of pitching moment coefficient versus angle of incidence from this test series, as measured at a high subsonic Mach number. The different lines represent different control deflections. A total loss of elevator control effectiveness is evident from this graph. These results show that the “control power collapse” observed on the small model was not an artifact of the wind tunnel test, but a real design flaw.

Using CFD and Wind Tunnel Testing to Understand the Problem

In order to satisfy the demanding packaging and manoeuvrability user requirements, a canard redesign was undertaken to delay control power collapse to a significantly higher incidence angle. This kind of control power collapse is to be expected for a canard controlled missile in

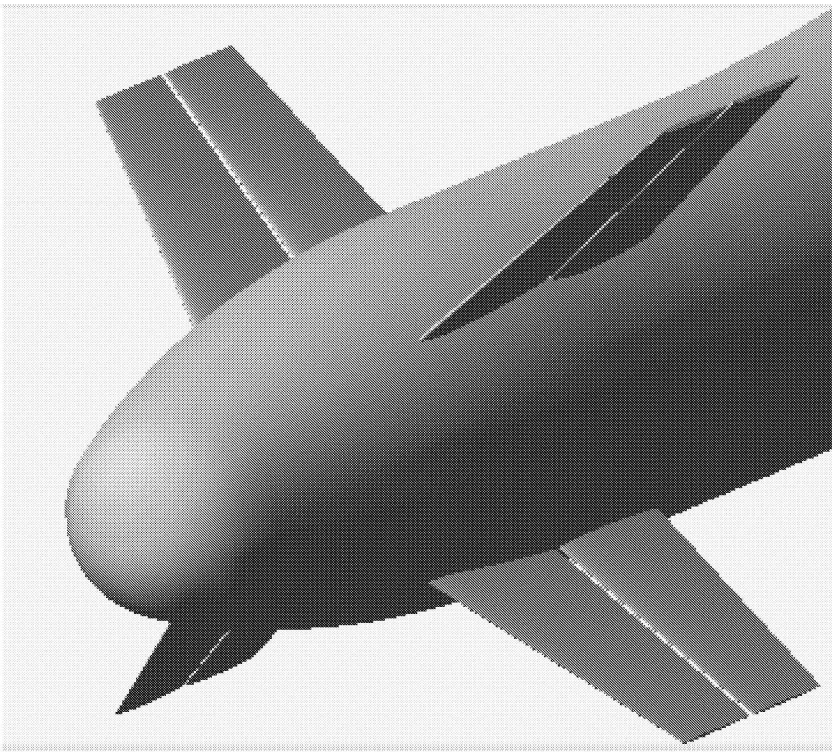

Figure 1: Layout of pitch control surfaces

subsonic flight. In this case however, it occurred at much smaller angles of incidence and control deflection than predicted by normally accurate design methods. Finding solutions to this kind of unexpected result is of course the everyday task of a practicing aerodynamicist, and there are several empirical approaches that can be followed. Nevertheless, empirical "rules of thumb" or heuristics do not guarantee either better understanding or even a better design.

By this stage in the project, a usable CFD capability had been established, in the form of the commercial solver CFD-FASTRAN, running on a workstation with a 1.0 GHz class x86 processor[1] Although it was hoped that the CFD capability would be useful for finding a design solution, the limitations of this capability were also recognised. Because the performance shortcoming had already been evident in early small-scale tests, it was concluded that it was probably caused by an unsubtle characteristic of the design. A logical extension of this argument was that highly detailed modelling would probably not be required.

This is already an example of integrating knowledge gained from experimental work into the planning process for a CFD study. If the unwanted effect had been absent from the early small-scale tests, it would have indicated a more subtle phenomenon, which would have required more care and detail in modelling.[2]

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[1] In year 2000 terms, a top-end PC

[2] Modelling a major pitch control shortcoming like this is easy. Modelling yaw disturbances is far more difficult, requiring much more detail.

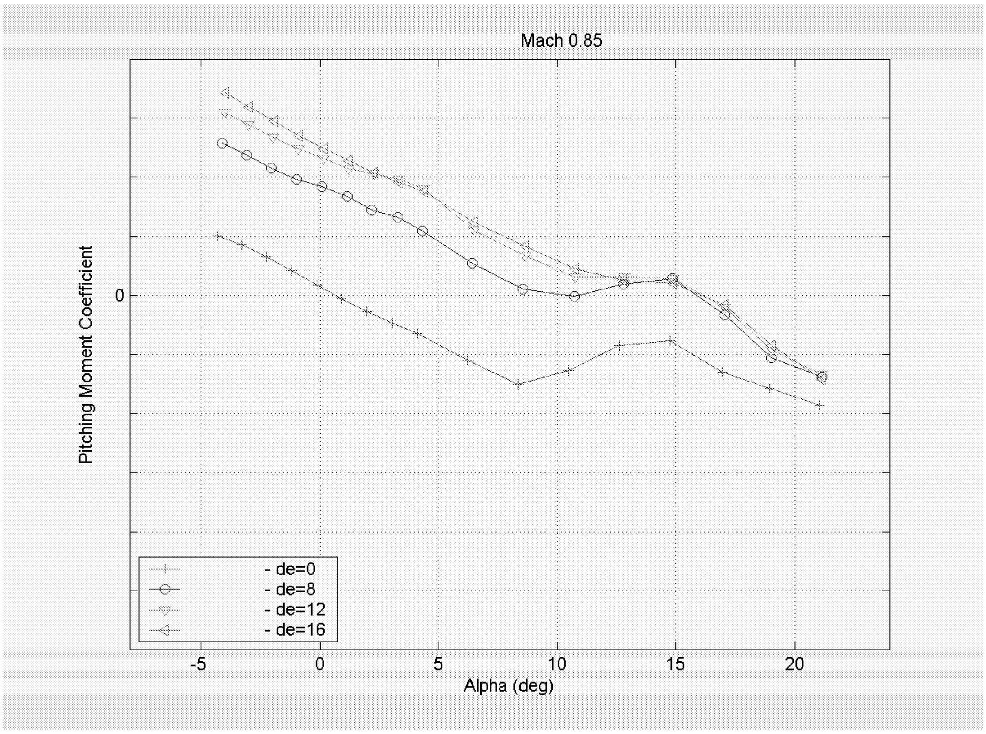

Figure 2: Loss of elevator control effectiveness

Understanding the Problem

As ever in this sort of situation, several theories about the root cause of the problem were suggested. Unfortunately, no flow visualisation of the wind-tunnel test was available. It thus seemed logical to use CFD to supply the flow-visualisation initially. At this stage, a conscious decision was made to depart somewhat from "accepted good CFD practice", and to ignore the normal rules for ensuring quality CFD results. This decision needs some justification:

- If a flow phenomenon is caused by a major, primary effect, this phenomenon will also be present in a "coarse" simulation
- It can take an extremely long time time (especially on the equipment available) to obtain a CFD solution that accurately matches tunnel data. By the time this solution has been obtained, it may be too late to influence the design!
- Coarse grids run quickly. Quick runs allow many flow situations to be investigated. Intelligent inspection of many flows can lead to better understanding of the flow.
- Good understanding of the flow should result in a good design
- Quick runs also allow many possible designs to be evaluated

There is obviously a risk involved in doing deliberately "bad" CFD like this. However, in the real world of aerodynamic development, CFD is not performed in isolation. Any revised design suggested by CFD analysis would initially be evaluated in another "rough" wind tunnel test, and later on in a major detailed wind-tunnel test. These tests thus perform the duty of a quality "safety net". The worst that can happen is that time will be wasted on developments along an aerodynamic blind alley.

Simplified Modelling

There is always a great temptation to model virtually everything at the highest level of detail allowed by available infrastructure. With the very limited capability available at the time, the CFD half model used for this study consisted of the forward part of the missile body and a single set of canards only. The aft body and wake were not modelled.[3] An example of a typical grid is shown in Figure 3. Significant characteristics of this grid are as follows:

- About 190 000 cells
- Minimal downstream detail
- Far-field boundaries are very close in
- Many high aspect-ratio cells

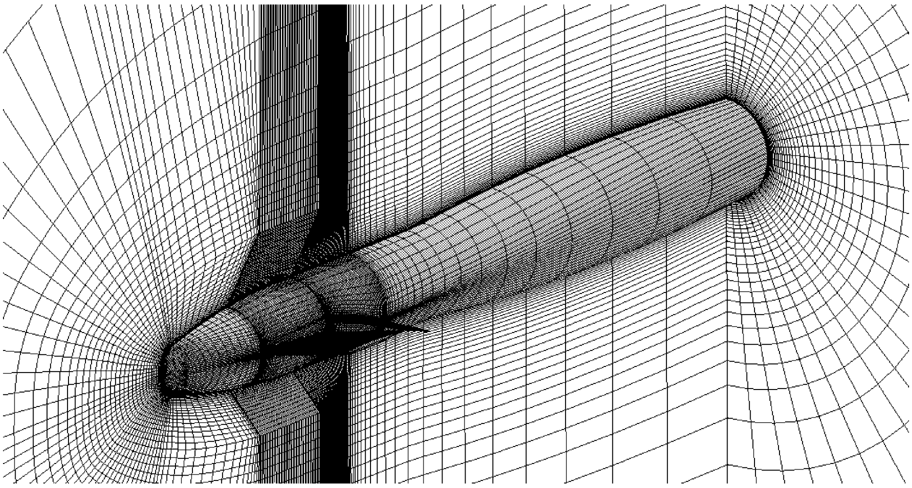

Figure 3: Example of grid used in this study

The shortcomings of such a grid are obvious. However, being very small, it was possible to run enough simulations in an acceptable time to produce graphs as shown in Figure 4.

The results of Figures 2 and 4 cannot be compared directly. The rear body and fins were not included in the CFD model, hence no meaningful pitching moment can be calculated. The normal force on the canards only can not be obtained directly from the wind-tunnel data either. However, the loss of control effectiveness at about 10° incidence can easily be identified in both graphs. It would be inappropriate to describe this as a good agreement. Nevertheless, Figures 2 and 4 indicate that a major feature of the flow in the wind tunnel is captured in the CFD model,

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[3] Not modelling the wake is a great time saver. Much convergence difficulty comes from the shear layer, yet it has no significant effect on the control surfaces.

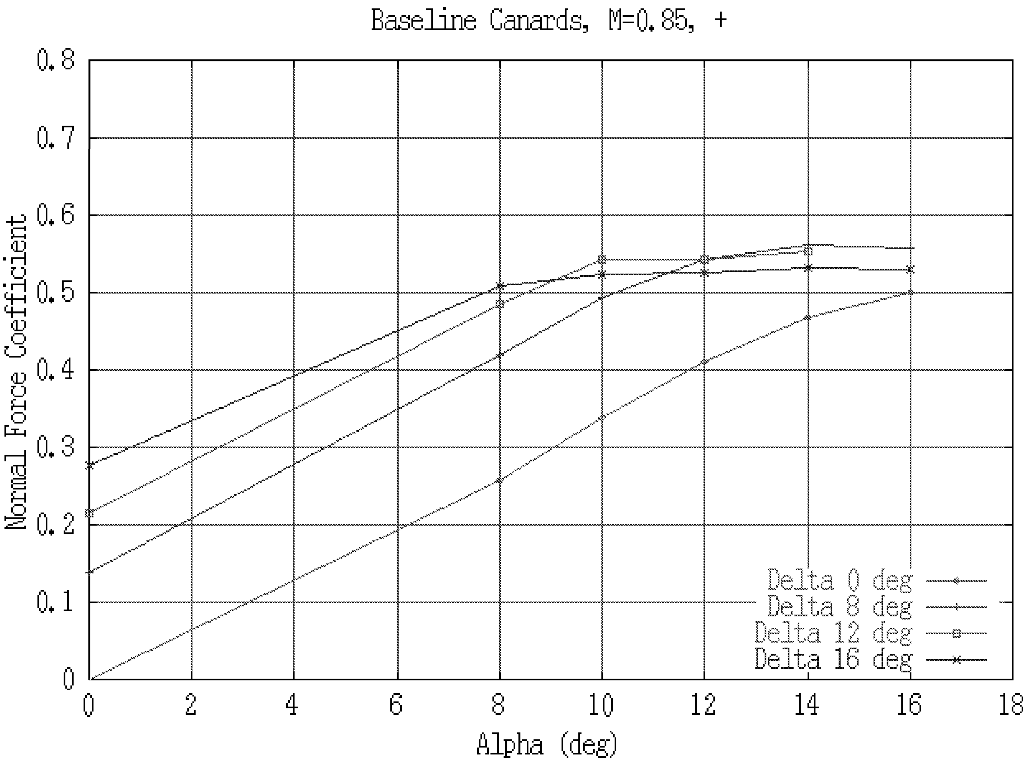

Figure 4: Canard normal force as predicted by CFD

and it is thus reasonable to inspect the CFD flow-field in order to understand this characteristic. The streamline plot of the flow-field shown in Figure 5 indicates massive flow separation.

Fixing the Problem

Both quantitative and qualitative inspection of the CFD results indicated that the crude CFD model had revealed the main causes of the poor control performance:

- The combination of high incidence and deflection angle caused premature flow separation on the control canard - a typical characteristic of canard elevators
- The shape of the missile nose caused significant upwash, thus increasing effective incidence angle and aggravating flow separation
- In subsonic flight the high pressure on the lower surface of the deflected control canard was feeding forward and causing separation of the upper surface flow on the fixed canard

Improvements to the design were reasonably straightforward, and were evaluated in step-by-step fashion using CFD. These evaluations were based almost entirely on interpretation of the visualised CFD flow fields. Starting from the chaotic flow of Figure 5, the design was progressively tweaked to finally obtain the much more ordered flow of Figure 7. Quantitative evaluation of a design's performance was only done once the flow field looked acceptable. This

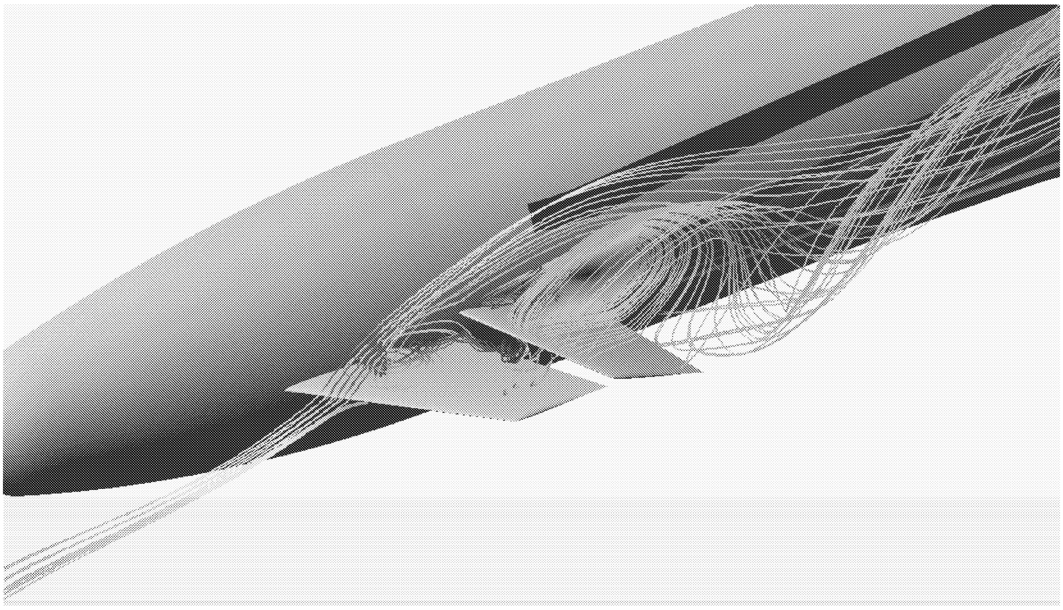

Figure 5: Streamline plot of unmodified design illustrating major flow separation

is an often-overlooked unique strength of CFD analysis. Although wind-tunnel flow visualisation is a well developed science, the CFD user has the opportunity to do a very detailed inspection of the characteristics of the flow. This is especially valuable if the CFD analyst, wind-tunnel test engineer and aerodynamic designer can work closely together to get a full understanding of complex flows. The design changes that clearly improved the appearance of the flow field were:

- Increase control canard leading edge sweep to delay flow separation to higher angles
- The additional sweep back reduced the control canard lower surface pressure, thus reducing the adverse interference on to the fixed canard
- The gap between the canards was increased to reduce interference
- A boundary layer fence was added to the fixed canard to delay flow separation to higher angles

After five design evolutions the CFD results were much improved, as shown in Figure 6. Some CFD calculations were also performed at M=0.3, to facilitate comparisons with a planned "crude" low-speed wind-tunnel test.

The streamline plot for the modified design is given in Figure 7. The airflow is much more orderly, and dominated by vortices.

As a first step toward accepting the modified design as successful, a simplified version of the airframe was tested in a low-speed wind-tunnel. Several new canards were evaluated in this test, and to keep costs low these control surfaces did not even have proper aerofoil profiles. Following a similar philosophy to the simplified CFD analyses, accuracy was sacrificed in favour of testing a large number of different designs. The validity of testing with simplified aerofoil profiles is demonstrated in Figure 8. This is not always a valid approach, but in this case, where

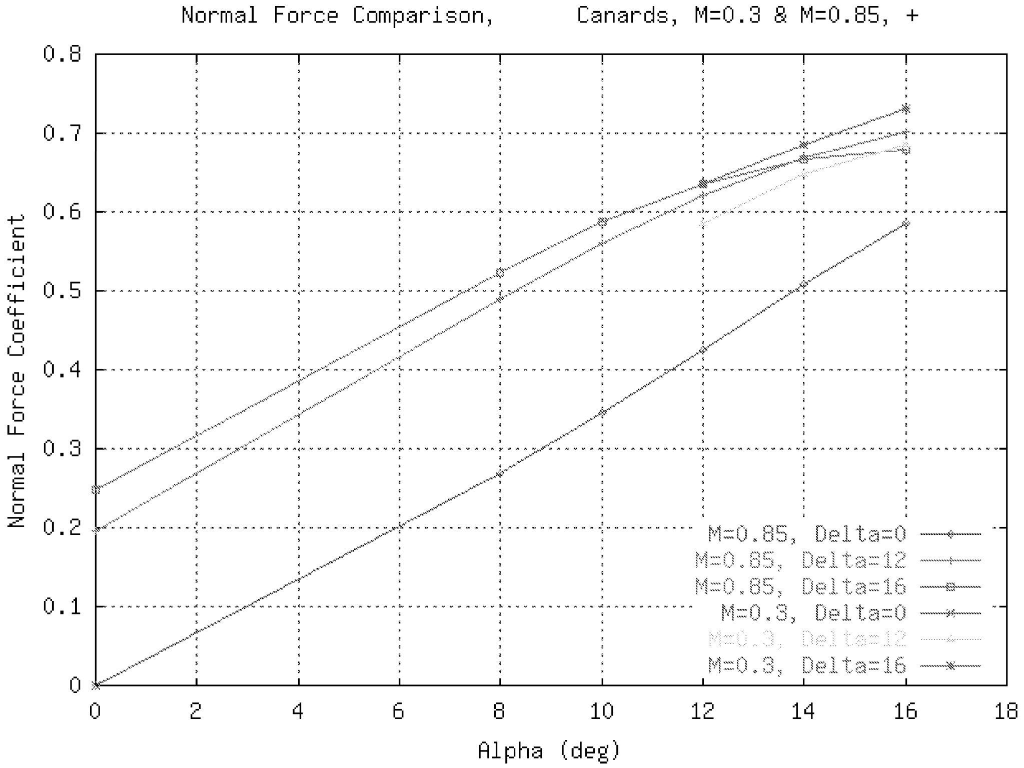

Figure 6: CFD results for modified canard

the control fins are of low aspect ratio, the aerodynamic performance is determined much more by planform than by profile. CFD can be used to good effect to plan a simplified test like this, by determining which parameters are candidates for simplification.

Data from the low-speed tunnel at M=0.3 are compared to data from the transonic tunnel at M=0.6 for an identical version of the model in Figure 9. This illustrates that the low-speed test is capable of capturing the relevant fluid dynamic characteristics.

The improvement in pitch-control characteristics is illustrated in Figure 10.

An important consideration is that the "crude" approach to the CFD study was only acceptable because of the knowledge that wind-tunnel testing would also be performed. In similar fashion, the "crude" wind-tunnel test was only viable because of the understanding of the underlying flow physics that had been obtained from the CFD study. Both of these rough methods required a "safety net", in the form of a highly detailed and very expensive characterisation wind-tunnel test series to be performed later in the development program.

Barking up the wrong tree

At some stage in the CFD development of the modified design a boundary layer fence was added to the fixed canard in order to delay flow separation. It improved the performance, and was also used on the later evolutions. However, in the low-speed test it was found to degrade rather than

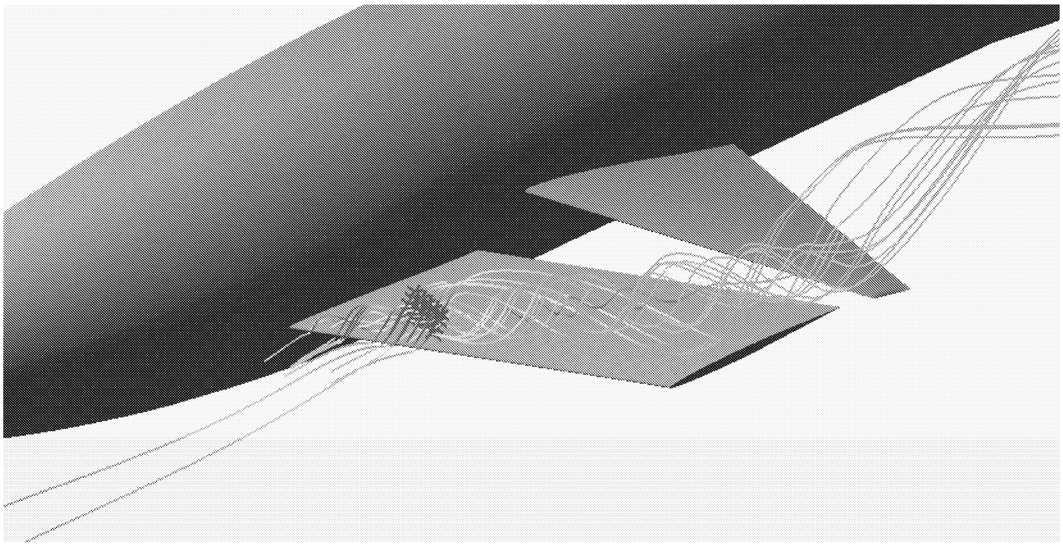

Figure 7: Streamline plots for modified design

improve the performance. CFD analyses were then performed at the low Mach-number without the fence, and confirmed that it was degrading performance. CFD analyses at M=0.85 then also confirmed that the fence had been a mistake.

The slightly embarrassing story of the boundary layer fence illustrates that it is easy to follow blind alleys when developing a design in "sequential" fashion. It is perhaps necessary at times to introduce a major perturbation[4] in order to highlight obvious mistakes. However, it also illustrated the ability of a relatively crude CFD investigation to reproduce wind-tunnel trends.

Validation of the Modified Design

The elevator control effectiveness of the modified design as obtained from a highly detailed wind-tunnel test is given in Figure 11. Comparison with Figure 2 shows that control power collapse has now been delayed to a significantly larger angle of incidence. There is now sufficient elevator control available to satisfy the manoeuvring requirement.

It can be concluded that a design of good quality has been achieved, despite the use of CFD and wind-tunnel tests of dubious quality. In the opinion of the authors, the success of the modified design can be attributed at least indirectly to the CFD and wind-tunnel short cuts taken during the development. Although these short-cuts are very risky when considered individually, the risk is substantially reduced when they are integrated. Simply put, crude CFD and cheap wind-tunnel tests are unlikely to make the same mistakes.

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[4] A mutation in genetic optimisation terms

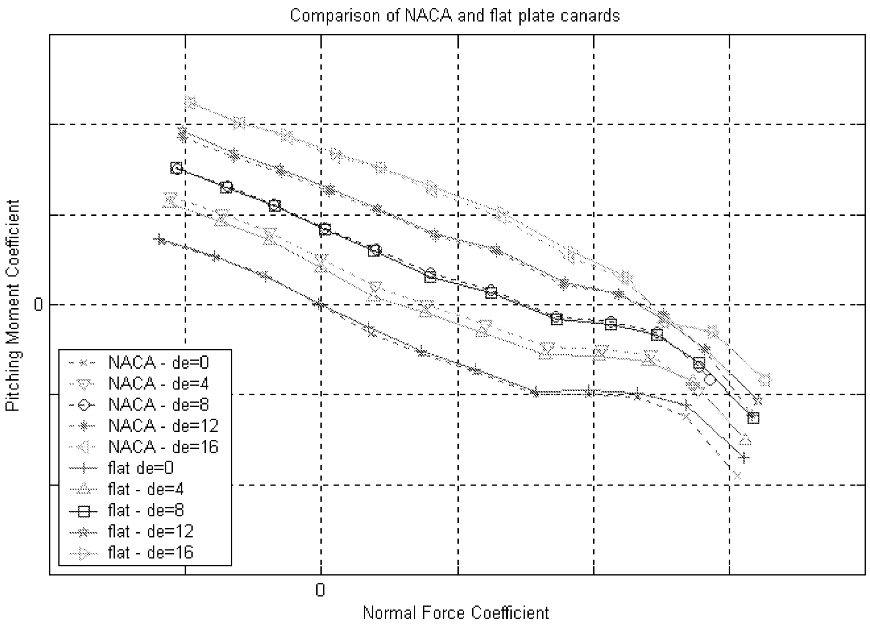

Figure 8: Wind-tunnel test data comparing simplified canards to proper aerofoil profiles

Conclusions

- Inexpensive, small-scale wind tunnel tests can give misleading results, but CFD should be used to determine the cause of unexpected results before jumping to conclusions
- CFD simulations do not always need to be performed to high levels of geometric detail and grid refinement in order to capture the most important characteristics of a complex flow field
- Qualitative inspection of CFD flow fields should be taken seriously, as it is an invaluable aid to understanding the complex flows encountered in the real world. Development without this understanding is mostly a shot in the dark.
- Given the "safety-net" of a very detailed and accurate wind-tunnel test to be performed later in the project, much time and money can be saved by performing some earlier CFD work and wind-tunnel tests at much lower levels of detail and refinement. This allows more designs to be evaluated under more conditions for the same cost.
- If CFD and experimental work are integrated, it is feasible to accept more quality risk than when they are used separately
- The aerodynamic designer, wind-tunnel test engineer and CFD practitioner need to discuss the relevant flow phenomena, aerodynamic characteristics and design decisions on a daily basis
- When using CFD, it is entirely possible to pursue blind development alleys by over-concentrating on a single characteristic of the flow. However, even inexpensive, "crude"

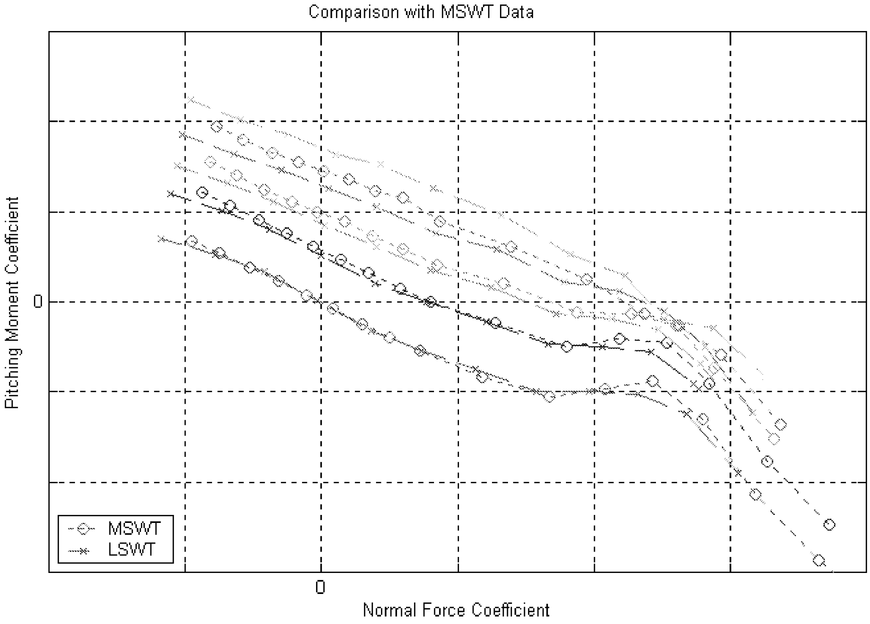

Figure 9: Comparison of data for the same model, as tested in different wind-tunnels at different Mach numbers

wind tunnel testing can easily rectify this, by virtue of its ability to quickly compare candidate designs at a variety of flow conditions.

- It is the quality of the final design that matters. In the intermediate stages, quality control is merely a means to an end, and can be interpreted flexibly.

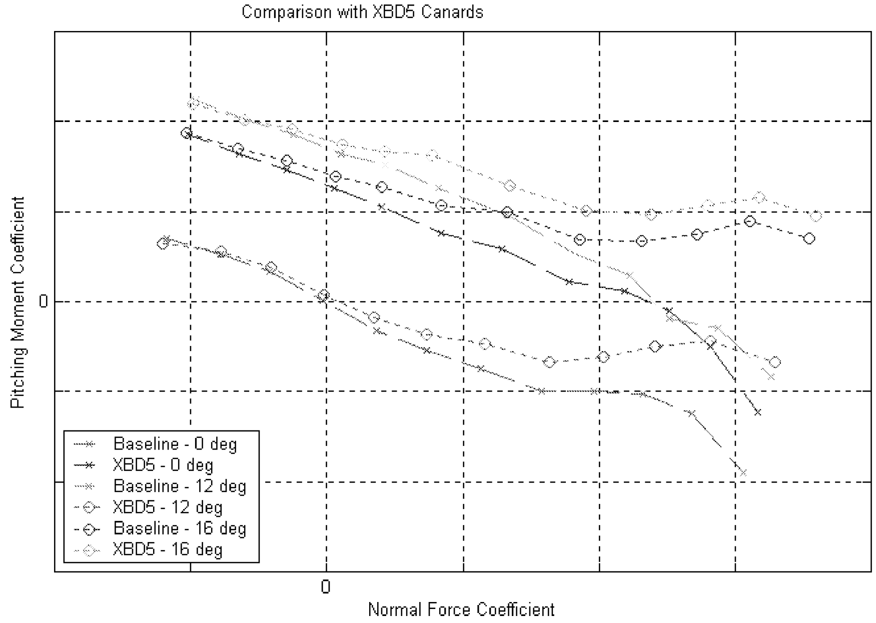

Figure 10: Improvement in pitch control characteristics as measured in a simplified low-speed wind-tunnel test

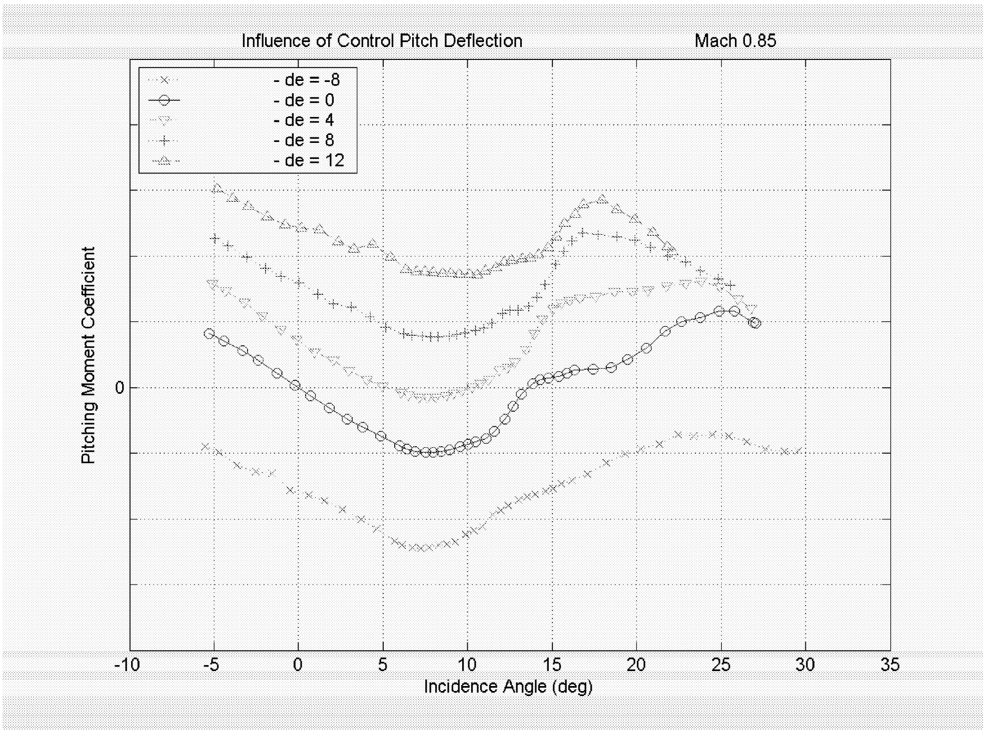

Figure 11: Elevator control effectiveness from detailed wind-tunnel testing