

Design Issues Associated with Full-Scale Application of Active Control of Vortex Flows

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Nomenclature

AoA	angle of attack
C.P.	center of pressure
C_Y	sideforce coefficient
C_n	yawing moment coefficient
D	forebody diameter
FCS	flight control system
PIO	pilot-induced oscillations

Introduction

Control technology is becoming one of the most pervasive aspects of vehicle design and operation. The engine, subsystems, weapons, etc., etc. all have their individual control systems in addition to the flight control system (FCS) of the aircraft overall. In addition, the basic FCS itself is expanding continually with aspects such as thrust vectoring. Research has indicated promising results from the control of the flow fields over an aircraft, and the vortical flow fields in particular. First, the manipulation of forebody vortices to create a lateral force has indicated the potential for significant yaw control at elevated angles of attack (AoA). Benefits can also come from preventing uncommanded asymmetric vortex behavior, which is known to create forces and moments sufficient to cause aircraft to depart from controlled flight. The consideration of vortex flow control includes aspects of both the aerodynamic aircraft model and also use as a control effector. Both of these effects, plus high-angle-of-attack aerodynamics in general, are known to be very non-linear. In addition, experience has shown that the full-scale characteristics are frequently not as predicted.

There is a need to address the integration of effects such as those described above into the design of a full-scale aircraft, and especially the flight control system (FCS). Another relevant factor is the current emphasis on modelling and simulation based acquisition. There has to be an assumption that the models are sufficiently accurate. A basic question that must be addressed is the validation of analytical methods used to model the predicted characteristics. If the methods have been validated against wind tunnel data, then they are subject to the same uncertainties as the basic small-scale measurements. Only if they have been validated against full-scale flight data should analytical methods be considered accurate, at least within the range of measurements.

The object of this paper is to review some recent published research data from the viewpoint of how the results would be interpreted in the application to a full-scale design. Second, flight test experience with both passive and active vortex control devices is presented. We then discuss issues with designing a flight control system to include that capability. There needs to be consideration of the required control design technology. The overall intent is to help communication between researchers and aircraft designers, and to question whether the traditional techniques in those communities should be revised for future developments.

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Recent Vortex Control Data

Typical information is available from a symposium that was held a year ago, Reference 1. It had a stated objective to review the current status of active control and evaluate the short term and long term potential. For some of the technology areas presented, passive control has reached limitations and active control is showing the potential for significant performance improvements, just as it did with flight controls in the 1970s. Technology developments over the past decade, particularly in the areas of micro-electronics and advanced materials and sensors, have made new applications of active control technology possible. There was a keynote presentation discussing Micro Electro-Mechanical Systems (MEMS) applications to Active Control Technology (Reference 2). This was a very interesting presentation, showing the possibilities of this new technology, including a flying demonstrator with leading edge vortex control on a delta wing configuration. One very important message in this presentation was that it is not possible to "just shrink traditional design". The premise was that small-scale design raised unique issues relative to the traditional experience and databases. Throughout this paper, it is taken as a given that the reverse is even more true, i.e. the full-scale application of wind tunnel data requires special attention in critical areas.

One session addressed aspects of controlling the position of forebody vortices in order to augment aircraft yaw control at moderate to high angles of attack. The first paper (Reference 3) showed the yawing moment obtained from a nose piece fitted with strakes as a function of angle of rotation about the longitudinal axis. The results were obtained on a 1:7.5 scale wind-tunnel model of the X-31 research aircraft, which loses rudder effectiveness completely at 50 degrees angle of attack. The rotating nose had effective yaw control starting at approximately 35, peaking around 50 degrees and then decreasing towards zero, i.e. very non-linear with α . The results showed a reasonable variation of yawing moment with strake rotation, with the effectiveness peaking about 45 degrees. With the strakes at the vertical position, 90 degrees rotation, however, there was a significant yawing moment rather than zero. Although this position would not normally be used in a control system, it shows a large effect from what must be a small model asymmetry. The author stated that a full-scale wind tunnel test is proposed, which should answer some but not all questions of scale effect.

The second paper (Reference 4) discussed vortex manipulation using forward blowing jets. Results were presented that extended earlier work on an ogive cylinder to a circular fuselage/delta wing model. There was effective yaw control that was essentially linear with blowing duty cycle. The authors pointed out the non-linearity and reversals of effectiveness with both angle of attack and momentum coefficient. Data from this reference is discussed in more detail in a later section.

The third paper (Reference 5) showed similar results of blowing on a conical forebody at elevated angles of attack, again with a periodic left/right reversal of blowing coefficient. These results also showed good linearity with this control variable. One example of the sensitivity of the results was the large yawing moment without blowing, which is presumed to be due to model asymmetry. An interesting result showed that 66% of the blowing duty cycle was required to produce zero yawing moment at one angle of attack. A plan for future work was presented, covering an active control concept with vortex detection.

All three papers showed interesting conceptual model results that have extreme sensitivities to one or more parameters, and this is considered to be typical. There is an extremely low probability that the full-scale flight characteristics would match the model predictions. This means that use of the model results for design of a full-scale flight application could be very complex and great care would be needed during flight testing. There would be a very high risk of control law gain errors or even sign reversals in the sensitive areas of those parameters. In addition, all of the references showed interactions in the pitch and roll axes, making the full-scale control system design a multi-dimensional problem.

Flight Test Experience

First, we can consider the possibilities of reduced emphasis on flight testing in favor of more emphasis on modelling and simulation. Reference 6 discusses the rationale for these trends, but also provides an indication of the recent state of the art in predicting aircraft characteristics. It contains seven pages of "Unanticipated Characteristics Discovered in Flight Test". The discussion covers experiences with a wide range of aircraft, commercial and military, fighters and transports, plus a wide range of characteristics. The anomalies also range from nuisance to significant, but there are many instances of failure to predict the aerodynamic characteristics, especially drag. Of primary interest to the current paper are the many instances of unpredicted vortical behavior. One effect that happened on more than one aircraft was the impingement of vortices on twin vertical tails. It may be expected that there is now more awareness of the need to assess vortex activity, and also to control it as much as possible. More important, however, are the number of instances of unexpected behavior at elevated angles of attack - the primary region where active control of vortex flows would apply. Results from two vortex control flight test experiments are discussed next with the potential problems that would need to be considered for system application.

Passive forebody chines

Flight experience with passive devices, i.e. chines, on the forebody of an F-16 is discussed in Reference 7. The airplane was fitted with a pitch and yaw thrust vectoring exhaust nozzle so that there was sufficient control to conduct a safe investigation of flight at high AoA. A "mini experiment" was added to the program to investigate chines that were designed to increase the directional stability of the F-16 at high AoA. The flight control system for the vectored-thrust configuration was not modified in any way to account for the chines.

A number of steps were taken to ensure credible results without a formal system identification effort. Wind tunnel data was acquired on the exact geometry of the chine and flight-test nose-boom. These results showed that the baseline configuration was directionally unstable between 31 and 48 degrees AoA without chines. With the chines, directional stability was never negative but was approximately neutral at 40 degrees before recovering.

An existing aero model for this variable stability test aircraft was considered to be accurate enough for this analysis, except that it did not include any thrust vectoring effects. The model was first used to derive calculated full-scale effects of the vectoring nozzles from the flight results without chines. Then, knowing the full-scale effectiveness of all the controls, it was possible to calculate the new aerodynamics with the chines. Although not as rigorous as a formal system identification program would have been, it was felt that this comparison of flights with and without the chines allowed their characteristics to be derived with some confidence. There was, however, some judgement required in the analysis because of slightly differing flight conditions and pilot inputs. The conclusions in that reference will now be discussed in terms of designing a control system around such effects.

In the longitudinal axis, the baseline configuration experienced an uncommanded increase in pitch acceleration during a test maneuver to slowly pitch the aircraft up. This did not happen on the chine configuration, which appears like an unexpected benefit not a problem. It could be transparent to a simple response command system. If, however, the FCS had been designed to compensate for some adverse characteristic that was not present, then there would be the possibility of creating a similar adverse effect in the opposite direction.

In the directional axis, the chines were actually destabilizing at 30 degrees AoA in contrast to the effect predicted by the wind tunnel results. At 45 degrees AoA, however, they produced a stabilizing effect comparable to the wind tunnel. This unpredicted and highly non-linear change in stability with AoA would certainly cause problems in designing the FCS if it were designed to augment the stability. The

aircraft in this experiment had excess control power with the thrust vectoring nozzles, but that might not always be the case.

Pneumatic forebody jets

A flight experiment with pneumatic vortex control was reported in Reference 8. In this case, jets were positioned on the nose of the X-29 for a proof of concept demonstration. The position and orientation to generate yaw control at elevated angles of attack were based on extensive wind tunnel testing. One flight test result quoted is that the yaw control was "... in some cases twice as powerful as predicted, is more good news. Lower blowing coefficients, using even less engine bleed air, are apparently feasible". Of course, for application of these results to a new design this knowledge may not be available until the aircraft is in flight test! Especially important if this result were found in flight, a doubling of the control power is equivalent to the standard 6db gain margin for minimum stability. It could certainly be a problem if such a control were being used for stabilization. In addition, a command gain that is too high has been a factor in most PIO occurrences. A control effectiveness double the predicted value would certainly be a problem for pilot control. If it were a gradual increase, it may be identified during build-up flight testing and allow for control system modifications. On the other hand, if the vortex migration caused a sudden switch in effectiveness it would certainly be more of a problem.

Design Issues

If active vortex flow control were being considered for a new system, then we might expect that a concept would be chosen from previous research. Wind tunnel testing would be performed to develop the final design configuration. That set of wind tunnel data may or may not yield an accurate model of the real aircraft. In this section we discuss a particular set of data in more detail, from Reference 4. The authors correctly point out that "Furthermore, it is difficult to implement suitable control laws due to the severely non-linear response of the vortices, and thus resulting loads, to the control variable". In most past work, this control variable was the blowing momentum coefficient. The objective of the work in Reference 4 was to exploit the inherent bi-stability of the vortex configuration at elevated angles of attack, and avoid the typical non-linearities. The approach taken was to use oscillatory (i.e. left and right) jets on the forebody of a model aircraft. The duty cycle varied from 100% blowing on one side (steady) through the complete range of blowing varying amounts on both sides to 100% on the opposite side. With this duty cycle as the control variable, the majority of the results did show linear control effectiveness.

Now we examine that same data with respect to the design problem. Figure 1 shows the yawing moment and sideforce due to blowing on an ogive cylinder at different angles of attack. From zero effect at 30 deg, steady port-side blowing produces a negative yawing moment at 40 deg and positive values at 50 – 70 deg. Starboard-side blowing produces equal and opposite values. There is certainly a linear variation with duty cycle except at one value, but it is the variation with AoA that could cause problems. If we used angle of attack as a schedule parameter, then there is a potential problem in the area of the zero crossing between 40 and 50 deg. It is unlikely that the full-scale characteristics would be exactly the same, leading to the probability of a wrong sign on the control effectiveness. If this happened in flight, then it would obviously cause a problem. A simple error feedback would drive the controller to its maximum value and increase the error. The design answer would require appropriate monitoring of aircraft center of gravity relative to the model reference center.

The preceding discussion used data from an ogive/cylinder configuration, but the majority of the results in Reference 4 are for a representative aircraft configuration with delta wing and vertical tail. Figure 2 shows typical yawing moment results and again the control effectiveness is quite linear. The analogous port-side blowing, in this case, results in zero at 25 deg, negative yawing moments from 35 - 55 deg and a positive value at 65 deg. The qualitative effects are similar for the two configurations, in that yawing moment is initially negative changing to positive with increasing AoA. This means that the center of pressure of the sideforce moves from aft to ahead of the moment reference center. It should be pointed out

that the moment reference center for this model configuration is in a reasonable location for an aircraft center of gravity. In terms of a simple comparison, the ogive/cylinder moment reference center is 3.5D aft of the nose and 8.15D for the aircraft configuration. The moment zero crossing has shifted from around 45 deg to over 60 deg and at a much further aft location. Private communication with one of the authors of Reference 4 yielded: "I certainly agree that there is a high potential for major 'surprises' in applying wind-tunnel data for vortical flows to full scale. Even in our relatively limited work on this scheme we have seen great sensitivity to Reynolds number and to blowing momentum coefficient. We suspect that these sensitivities are also strongly configuration-dependent. For example, included apex angle may well be very important. In fact the apex angle of our ogive-cylinder model was 60 deg. While that of the delta-wing model was only 25.6 deg. This, in addition to the presence of the delta wing, might have had something to do with the different movement of the centre of pressure for sideforce for the two models". Thus, the application of these results to a full-scale vehicle would require investigation of whether it was the influence of the wing, the effect of nose angle, or even a combination of both. In addition, any of those possibilities could be a function of Reynolds number.

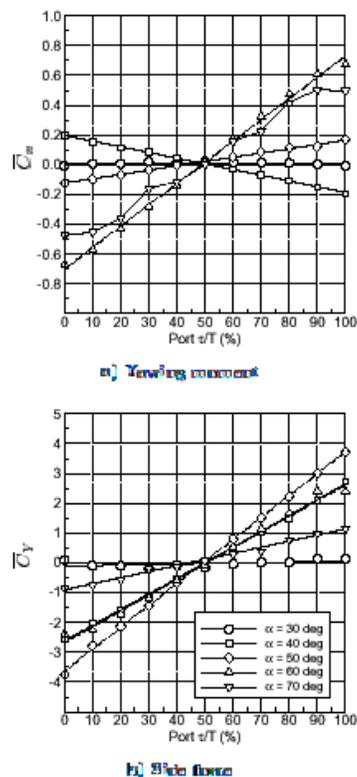


Figure 1. Variation of yawing moment and sideforce with duty cycle for an ogive/cylinder model (Ref. 4)

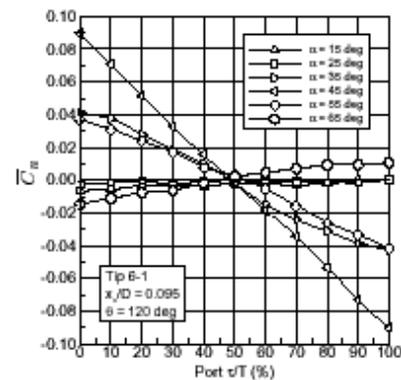


Figure 2. Variation of yawing moment with duty cycle for a delta-wing model (Ref. 4)

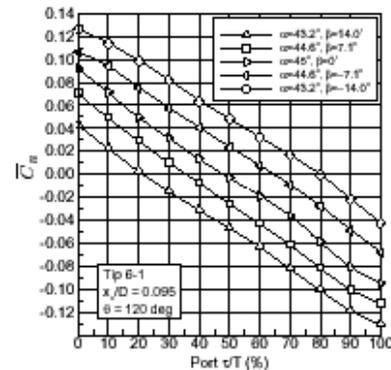


Figure 3. Effect of sideslip angles for the delta-wing model (Ref. 4)

Finally, figure 3 shows the results from reference 4 of the effects of the blowing at sideslip angles between +14 deg and -14 deg. It shows very linear and well-behaved characteristics, with the blowing producing yawing moments more than twice the value from those values of sideslip angle. If this result extrapolated to full-scale characteristics, it would be good news.

This discussion of the wind tunnel results from Reference 4 is for illustration purposes only. It should be considered typical that vortex control involves non-linearities and sensitivity to the control variable. It should also be expected that full-scale aircraft characteristics will be different from predictions based on scale model wind tunnel data. These differences are probably going to be configuration dependent,

because of the vortex interactions with the other parts of the airframe. Again, there may be differences in the basic aerodynamics or in control effectiveness. It might suggest that the largest scale of wind tunnel test would be beneficial, with special attention to the formation and location of all the vortices.

Flight Control Technology

The discussion in this section is supported, in part, by Reference 9. The report includes a discussion of the causes of various problem areas in flight control design. A pilot command gain that is too high has frequently been a problem, leading to PIOs. This has occurred when the command gains have been based too much on simulation, and an accident happens in flight. Now if we consider that the control gain also may be much higher than predicted, the design problem is much harder. By contrast, although sensitivity analyses are standard procedure, consideration of an opposite sign on the control effectiveness is probably not.

Non-linearities represent another factor that has been involved in many aircraft accidents. The design process typically commences with linear models to develop the initial control system. One of the best practices in Reference 9 is to include consideration of non-linearities as early in the design as possible. As an example, the discussion above from Reference 4 could indicate that the FCS designer has a linear control derivative. The more classical methods would schedule this with AoA, etc. The data from Figure 2 is shown as maximum yawing moment vs angle of attack in Figure 4 (with the assumption of a zero crossing at 60 degrees for illustration). The value of maximum yawing moment is equivalent to a control derivative and the linearity with duty cycle would appear to make that a reasonable approach. We can assume that vortex control is not effective below about 30 degrees AoA. A designer could schedule a command gain with increasing angle of attack up through about 55 degrees. The region between 55 and 65 requires extra scrutiny, i.e. the data may be valid as the vortex interactions with other parts of the airframe could change to cause this reversal. If it is required to use this form of control to higher angles, then the designer has to schedule a command gain through this region. A command gain would tend to increase as control effectiveness reduces, but a deadband or transition gain would be required around the zero point. It is common in FCS design to perform a sensitivity analysis where the control effectiveness is considered to vary \pm a certain percentage around the nominal value, often based on historical accuracy of wind tunnel measurements. The design team might decide that the confidence in measured yawing moment was $\pm 10\%$, which is shown applied to the peak value of the yaw control in Figure 4. Analysis based on this approach would ensure no stability or control problems with variations in this range. The

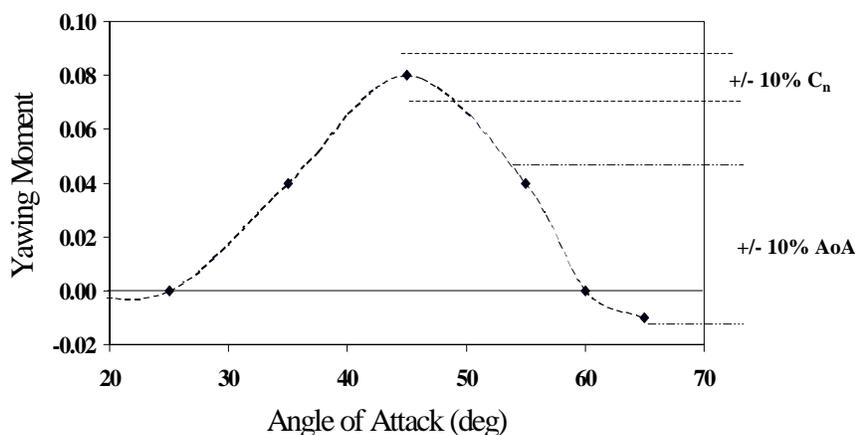


Figure 4. Variation of yawing moment with AoA

result would be much different, however, if a more cynical designer judged that there was a +/-10% uncertainty in the angle of attack at which the zero crossing occurred. As illustrated in Figure 4, this gives approximately six times the magnitude of control variation or a change in sign. Modern control design methods typically include a robustness analysis giving the variation of model characteristics within which the system remains stable. The reversal in control effectiveness would give a real possibility that the exact full-scale point would be different from wind tunnel results. This could give control effectiveness of the wrong sign in this angle-of-attack region, which is definitely not covered by the typical robustness analysis. It is suggested that an 'uncertainty analysis' is required, i.e. consider the possible error in angle of attack at which the control reversal occurs.

One of the Best Practices in Reference 9 relates to modelling and analysis of the unaugmented vehicle: "Before beginning any control law design, it is important to study and fully understand the dynamics and the non-linearities of the unaugmented vehicle, including those of the FCS hardware, the air data system and the powerplant. It is also important to understand how these are likely to affect the aircraft's control characteristics as its operating condition varies. If this is not done then there are likely to be some nasty surprises later in the design process, which will require re-work". There follows eight specific recommendations, some of which concern the discussion in this paper.

It is also stated in Reference 9 that no correlation had been found between the documented problems and the flight control design methodology. This is a result of the methods that had been used in those flight vehicles. In fact, crashes have occurred due to FCS design problems with aircraft where the FCS was designed with classical methods, and also aircraft designed with modern methods. The causes were independent of the method used. Now, if we consider the problem of differences between model predictions and the full-scale aircraft characteristics, then even most modern methods would be susceptible. Reference 10 is a comparison of a number of multivariable techniques, all of which would have problems with significant plant model errors. To quote from that reference: "The only reliable way to design for robustness with respect to real variations appears to be to cover them with a larger set of complex uncertainties and then to use one of the available methods to provide robustness with respect to the larger set. However, there are no guarantees that it will succeed in any specific application". If the aircraft FCS designer anticipates problems such as those discussed above, however, then it may dictate aspects of the design methodology. An analysis of sensitivity to uncertainties will be required and is commonly done. It is not common, however, to consider the possibility of a wrong sign on control effectiveness in either classical or modern control methods.

The latest developments in adaptive control do promise to be independent of the details of the plant model. Reference 11 discusses new adaptable reconfigurable logic. In this case the basic design methodology is based on dynamic inversion, which cancels (inverts) the aerodynamic plant model, and then produces the required flying qualities with the addition of appropriate pre-filters. The method would not account for errors in the plant model nor for control sign errors by itself. With the addition of the adaptive feature, there is an algorithm to continually identify the actual plant characteristics. Then it would be expected that a model feature of incorrect sign would be readily identified and the required adjustments in control gain made. Reference 12 presents supporting technology for parameter estimation in the case of redundant control effectors and non-linearities. Heuristically, we might expect that this technology approach would be robust in minimizing any effect of the actual control effectiveness being opposite in sign to the predicted value {provided the design algorithm did account for an initial adjustment going in the wrong direction!}. A longer term approach may lie in the use of neural networks. Much research is underway, e.g. References 13 and 14, but much work remains to be done. There may not be an absolute guarantee that a machine or a neural network will ever do what you really want it to do as opposed to what you told it to do.

Conclusions

This paper has discussed instances of where the control of vortex behaviour has had unexpected results. In each case the actual full-scale flight characteristics were very different from wind tunnel data. Any strong sensitivity of aerodynamic or control characteristics to any parameters is going to be a design problem because the real full-scale characteristics are likely to be different. Increased modelling effort will be needed in the future, in order to be able to accurately represent the physical observations. The models will need to be validated as increasing amounts of data and understanding are gained. The models should have estimates of parametric uncertainties, to allow more rigorous system studies to be performed - especially before any flight testing. It is suggested that viewing the underlying cause as uncertain can give different answers from a conventional sensitivity analysis, i.e. only considering that the parameters lie within a confidence bound.

The lessons learned from applying active control technology to flight controls over the last three decades, are equally relevant to any other active control application. The research community needs to be aware of the lessons learned in order to avoid implementation and testing difficulties that are not usually apparent when new concepts are in their infancy. One consideration for the researchers is to explicitly identify areas where the aerodynamic characteristics could be extremely sensitive to the configuration details. This may involve identifying detailed interactions of the vortices with different parts of the airframe, especially where the result could be a discrete change in a characteristic. As always, complete documentation is essential but also things that did not appear to work can provide useful information.

At the same time, the flight control system designers must understand the underlying physics of the dynamic plant that they "are given by the aerodynamicists". There is always a question of linearization of the aerodynamic model. The subject of this paper, and the symposium, is the consideration of a non-linear effect, by definition. Active control of vortex flow at high angles of attack may be considered close to application for a full-scale project, but it is suggested that extreme attention to detail will be required. The more knowledge {not just data!} that is available and considered then the better the results will be.

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