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An integrated computational/experimental approach to X-31 stability & control estimation

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ABSTRACT

A comprehensive research program designed to investigate the ability of computational methods to predict stability and control characteristics of realistic flight vehicles has been undertaken. The approach to simulating static and dynamic stability characteristics for the X-31 configuration was performed by NATO RTO Task Group AVT-161, which resulted in an integrated computational and experimental study. The stability characteristics of the vehicle were evaluated via a highly integrated approach, where CFD and experimental results were used in a parallel and collaborative fashion. The results show that computational methods have made great strides in predicting static and dynamic stability characteristics, but several key issues need to be resolved before efficient, affordable, and reliable predictions are available.

1. Introduction

Stability and Control (S&C) engineers have long used an iterative process combining semi-empirical lower-order, wind tunnel, and flight test modeling techniques to determine the aerodynamic characteristics of new fighter aircraft. Despite their greatest efforts using the best available predictive capabilities, nearly every major fighter program since 1960 has had costly nonlinear aerodynamic or fluid–structure interaction issues that were not discovered until flight testing [14,30,31,43,46]. Some examples include the F-15 [70], F/A-18 [70], F/A-18C [47], AV-8B [70], and the B-2 Bomber [36]. The F-15, F/A-18A, and AV-8B all exhibited significant aeroelastic flutter [70], while the F/A-18C experienced tail buffet at high angles of attack due to leading-edge extension vortex breakdown [47], and the B-2 Bomber experienced a residual pitch oscillation [36]. The development costs of each of these aircraft could have been drastically reduced if these issues had been identified earlier in the design process.

Several tools can be used to predict the S&C characteristics of an aircraft, including flight and wind tunnel testing, semi-empirical lower-order modeling and computational fluid dynamics (CFD). Flight testing is the most accurate of these methods, but is also the most expensive and cannot be used during early stages of the aircraft development process because the aircraft configuration typically is not finalized. Wind tunnel testing is also fairly accurate, but suffers from scaling issues, along with difficulty modeling unsteady dynamic behavior. Wind tunnel testing is also expensive, although cheaper than flight testing. Semi-empirical lower-order modeling has less fidelity than flight and wind tunnel testing and is incapable of reliably predicting unsteady nonlinear aerodynamic behavior. A reasonable compromise between flight and wind tunnel testing and semi-empirical lower-order modeling is CFD simulation. Modern CFD techniques have a relatively high level of fidelity and have successfully modeled the nonlinear aerodynamic behavior of aircraft at full scale Reynolds numbers. This method reduces some of the major uncertainties associated with sufficiently modeling physical space. However, it comes with an additional cost in execution time that results from computer performance and small physical time step requirements to accurately capture the flow physics. This is exaggerated by the low frequency nature of most of the aerodynamic motions that result in nonlinear behavior of interest. Researchers at NASA Ames, for example, have attempted to perform a “brute force” approach to filling a stability and control

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Nomenclature

a	Speed of sound	[m/s]
b	Wing span	[1 m]
c_r	Root chord	[1 m]
c_{ref}	Reference chord	[0.51818 m]
C_ℓ	Rolling moment coefficient, $\equiv \ell/(q_\infty Sb)$	
C_m	Pitching moment coefficient, $\equiv m/(q_\infty S c_{ref})$	
C_n	Yawing moment coefficient, $\equiv n/(q_\infty Sb)$	
C_p	Pressure coefficient, $\equiv (p - p_\infty)/q_\infty$	
C_Y	Side force coefficient, $\equiv Y/(q_\infty S)$	
k	dim'less frequency, $\equiv 2\pi \cdot f_0 \cdot c_{ref}/V$	
ℓ	Rolling moment	[N m]
L	Lift	[N]
M	Mach number, $\equiv V/a$	
m	Pitching moment	[N m]
∞	Free stream condition	
n	Yawing moment	[N m]
p	Pressure	[N/m^2]
q	Dynamic pressure $\equiv \rho \cdot V^2/2$	[N/m^2]
S	Wing reference area	[m^2]
s	Wing half span	[m]
V	Free stream velocity	[m/s]
x	Chordwise coordinate	[m]
y	Spanwise coordinate	[m]
z	Vertical coordinate	[m]
α	Angle of attack	[deg]
β	Angle of sideslip	[deg]
ρ	Density	[kg/m^3]
θ	Pitch angle	[deg]
ψ	Yaw angle	[deg]
φ	Roll angle	[deg]

database for vehicle design [11,49,56]. They found that a reasonable database for static stability and control derivatives would include on the order of 30 different angles-of-attack, 20 different Mach numbers, and 5 different side-slip angles, each for a number of different geometry configurations or control surface deflections [49]. They envisioned that a few hundred solutions can be obtained automatically and the remainder of the parameter space is filled using an interpolation procedure or neural networks. Clearly, a high-fidelity tool capable of reliably predicting and/or identifying configurations susceptible to handling quality instabilities prior to flight testing would be of great interest to the S&C community. Such a tool would be well suited to the aircraft design phase and would decrease the cost and risks incurred by flight testing and post-design-phase modifications.

Considering today's performance of computers and CFD codes, the routine calculations of hundreds of maneuvers in a reasonable time frame are unrealistic. In order to accurately and reliably predict the stability and control characteristics of an aircraft prior to the costly flight test phase, CFD has to be combined with predictive modeling of lower complexity. The vision of using CFD in the initial aircraft design phases initiated several projects within S&C, CFD, and wind tunnel communities, including Computational Methods for Stability and Control (COMSAC) [31] and Simulation of Aircraft Stability and Control Characteristics for Use in Conceptual Design (SIMSAC). These groups have met with varying degrees of success, and also helped to formulate the creation of a NATO Research & Technology Organization (RTO) task group that would investigate some of these issues.

2. AVT-161 Task Group

The NATO RTO AVT-161 Task Group was established to determine the ability of computational methods to accurately predict both static and dynamic stability of air and sea vehicles. Whereas this paper will concentrate on the air vehicle application within the Task Group, the overall approach is to identify major synergy in terms of physical modeling, fluid structures, or transition effects. The Task Group joins together three major avenues of interest: the experimental part to provide highly accurate static and dynamic validation data; the CFD community who is trying to predict the steady state and dynamic behavior of the target configurations; and the S&C group which is analyzing the experimental and numerical data. The objective of the group is to provide best practice procedures to predict the static and dynamic behavior especially for configurations with vortex-dominated flow fields where nonlinear effects have a significant impact. These nonlinear regimes are the areas where typical linear S&C methods fail, or where wind tunnel data are only available for non-full-scale flight flow regimes. Currently these deficiencies can only be addressed through costly flight testing. Because of this, the main focus of the task group is the prediction with CFD methods rather than enhancing existing S&C system identification methods. The AVT-161 Task Group partners and their contributions are listed in Table 1.

2.1. Background

AVT-161 began as an outgrowth of previous RTO Task Groups which also investigated the ability of CFD to predict complex aerodynamics. These previous groups (AVT-080 and AVT-113) studied the ability of various CFD prediction methods (including Euler and Navier–Stokes prediction) to accurately predict vortical flows on vehicles at medium to high angles of attack. AVT-080 focused on determining the ability of CFD to predict vortical flow structures on delta wings [27,48,65,68]. In AVT-113 [33,34] the focus was on experimental and numerical investigations on delta wing configurations with various leading edges from sharp to different round radii. AVT-113 started from given fundamental wind tunnel data provided by NASA [44] followed by several pre-test CFD results which supported the wind tunnel investigations with advanced experimental methods. All of these investigations resulted in improved understanding of the flow physics and new best practice methods for computational simulation of vortical flows. The results of the AVT-113 Task Group have been presented at the AIAA Aerospace Science Meeting in 2008 within experimental [15,26,38,42,45] and numerical sessions [16,19,23,24,29,50,58,62]. The second target configuration of the AVT-113 Task Group was the F-16XL CAWAPI configuration. A special section of the *Journal of Aircraft* also included several papers on the F-16XL by Lamar and Obara [40], Boelens et al. [8,9], Görtz et al. [28], and Fritz et al. [25]. A summery of lessons learned was given by Rizzi et al. [54].

Since the overall goal of AVT-161 was to determine the ability of modern CFD tools to adequately predict static and dynamic S&C parameters for modern aircraft, two candidate configurations were chosen: a generic UCAV (Stability And Control CONfiguration, SACCON) and the X-31. Both AVT-161 Task Group target configurations possess a delta wing planform with medium sweep leading edges (between 45° and 57° sweep angle), and with leading-edge nose radii varying from sharp to medium and large roundness. The approach is to provide most (if not all) flow features common to typical UCAV and fighter aircraft configurations, and to investigate the aerodynamic challenges which have to be captured by computational methods.